

Impact of river engineering on Vistula river channel morphometry near Warsaw (Poland): a 172-year perspective

Abstract

This study investigates the impact of river engineering on the morphometry of the Vistula River channel near Warsaw, Poland, over a 172-year period. This research focuses on the examination of modifications in the Vistula channel between 1843 and 2015 that were associated with regulation, and evaluated their immediate and indirect consequences by analyzing parameters such as channel width, length, sinuosity, presence, and number of channel bars and islands. This study used historical topographic maps and contemporary aerial laser-scanning data to verify changes in the Vistula riverbed in the Warsaw region. Research has found that human-induced transformations directly affect erosion and accumulation, as well as material transport, and that changes in the river channels are most apparent in their cross-section and size of mesoforms.

Keywords

Archival maps • river channel • river engineering • human impact

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Introduction

Contemporary river channel types are heavily influenced by anthropopressure. Human-induced transformations directly affect erosion and accumulation, as well as material transport (indirect catchment use and direct technical regulation of rivers). Straightened channels and stabilized banks exhibit significant changes in morphology (Petts 1979; Klimek 1987; Starkel 2001; Surian & Rinaldi 2003; Wyżga 2003, 2005; Liro 2015; Maaß et al. 2021). Changes in river channels are most apparent in their cross-section, size, shape, and composition of mesoforms (Maaß et al. 2021).

Numerous studies have recognized and illustrated these changes worldwide. Nevertheless, because of the complex responses and local conditions, it is not always possible to predict what will happen in a particular location. Despite many worldwide investigations showing the distribution of changes along rivers due to human impacts, there are still many uncertainties. Therefore, some research problems still need to be addressed. It is not certain what and how much a river will change at a particular location, and because humid and arid systems respond differently, further studies are necessary to reduce uncertainty. In addition, changes identified at the channel, reach, and network levels may have occurred or may have been initiated under different environmental conditions. The extent to which riverbeds react to local environmental conditions has not been fully acknowledged. Furthermore, it is critical to consider the effects of global climate change when evaluating channel sensitivity and determining threshold conditions (Gregory 2006). To ensure successful river restoration efforts, it is crucial to incorporate a channel design that considers geomorphology. A better understanding of human influence on river channel alterations, which vary by culture and over time, would facilitate the design of river channel landscapes – particularly in the context of climate change and adapting to it (Maaß et al. 2021).

Studies into the consequences of engineering works have been conducted on rivers situated in southern Poland and

downstream of the Vistula River (Koc 1972; Babiński 1992; Gierszewski et al. 2015, 2020; Gorczyca 2016; Witkowski 2017). A comprehensive analysis of changes in the channel morphometry in the middle segment of the Vistula River, particularly in the vicinity of Warsaw, has not yet been carried out. The selected 50 km stretch was chosen because of the “Warsaw corset” effect and intense urbanization.

The aim of this study was to determine the significant changes that occurred in the Warsaw area of the Vistula River channel between 1843 and 2015, with a focus on the effects of engineering works. Our primary objective was to identify riverbank positions and other channel features using digitized historical topographic maps and contemporary materials. Our secondary goal was to recognize changes in the chosen parameters, such as the channel planform, width, length, and centerline shifting, as well as the channel sinuosity. Additionally, we attempted to identify parameters that describe the channel structure, such as the number, distribution, and size of channel bars and vegetated islands.

Numerous geological and hydrological studies have been carried out in this section (Biernacki 1975; Falkowski 2007; Popek et al. 2009; Magnuszewski & Gutry-Korycka 2009), but changes in the river's location and mesoforms within the riverbed have not been thoroughly explored.

Historical topographic maps and contemporary aerial laser-scanning data were used in the analyses. Similar studies have been conducted on the Vistula River near Lake Włocławek (Gierszewski et al. 2015), in the Zawadowskie Islands (Kałmykow-Piwińska & Falkowski 2012), and on other rivers (Szymańska & Luc 2010; Amaud et al. 2019; Boothroyd et al. 2020; Vercruyssen & Grabowski 2021; Mandarino et al. 2021; Hajdukiewicz & Wyżga 2023). These works will serve as points of reference when considering the Vistula River transformation in Warsaw.

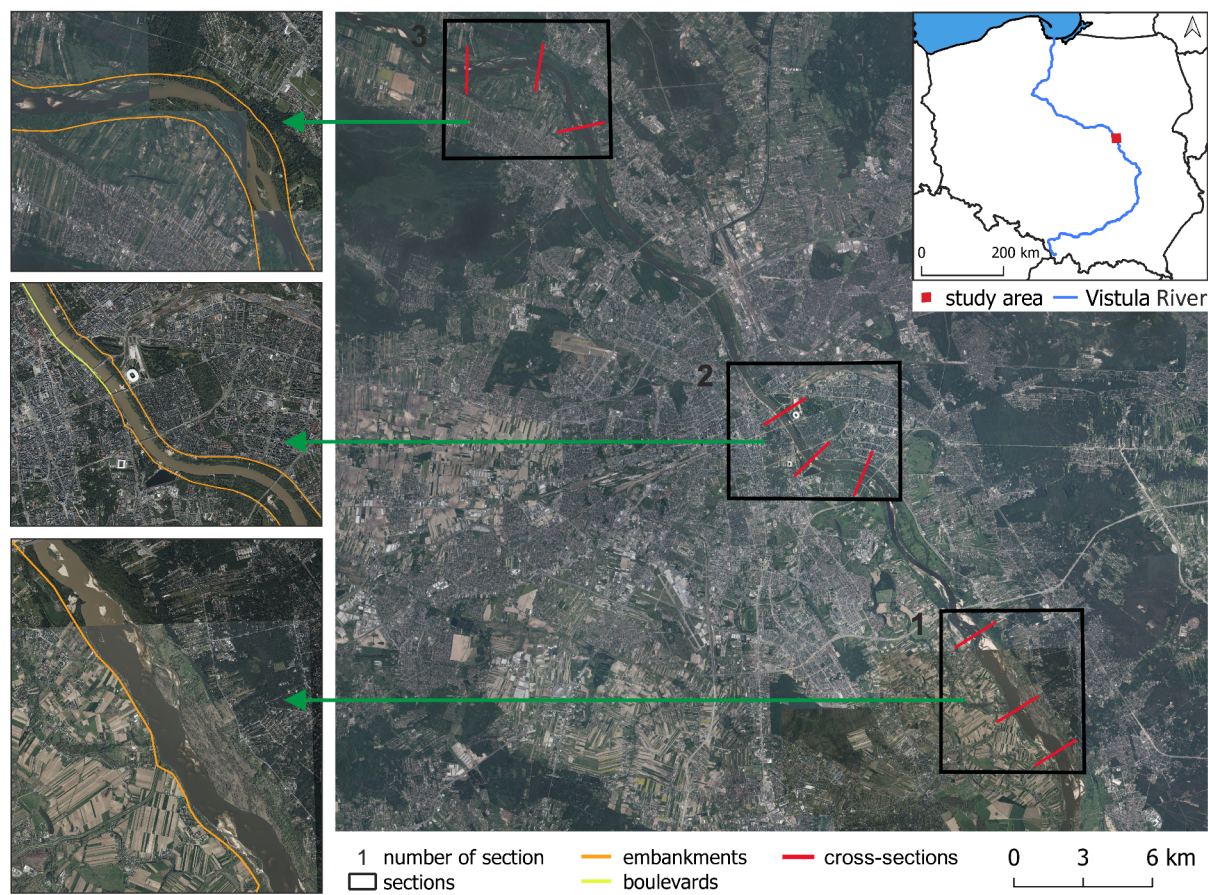


Figure 1. Study area. Source: Geoportal (2024)

Methods

According to the methodology used in fluvial geomorphology (Gurnell et al. 2003; Trimble 2008; Grabowski and Gurnell 2016; Mandarino et al. 2021), a comparison of archival maps (Fig. 2, Table 1), DEMs, and orthophotomaps were used to verify the changes in the Vistula riverbed in the Warsaw region. To facilitate comparison between the historical maps, they were first registered in QGIS software, then rectified using the Georeferencer tool to align them with Poland's CS92 coordinate system. This process is in accordance with the recommended methodology for preparing archival maps for spatial analysis (e.g., Brovelli & Minghini 2012; Lorek 2017). According to Lorek (2017), having too few points can lead to inaccurate results and position errors. To ensure optimal correction, 30–50 control points were implemented per sheet. The geometric accuracy of rectification (RMS error) ranged between 18 m and 33 m. The pixel size of the maps from 1843 and 1915 was 1 m, while that of the map from 1980 was 1.5 m.

The reference layer of the 1980 map was a contemporary orthophoto, which was utilized to calibrate each subsequent older map by comparing it with a younger, already calibrated map. Affek (2012) provides a comprehensive explanation of the calibration process. The rectification may be inexact owing to inaccurate scanning or the imprecision of the maps (Fig. 1), especially the 1843 map. The rectifying process was repeated several times, and the most reliable result was selected for further analysis. These materials were used to determine the length, sinuosity, width, and area of the riverbed, the direction of the centerlines, and the number and size of the channel bars and islands (a

plant-stabilized channel bar) within the riverbed. The Vistula riverbed, sandbars, and stable vegetated islands were manually vectorized using QGIS and ArcGIS. Orthophotomaps were used to minimize rectification and channel structure interpretation errors. Polygons were created to determine the area, length, and longitudinal gradient of the modern Vistula riverbed. The process of vectorizing the extent of the river channel and mesoforms was conducted at a scale that matched the oldest available map.

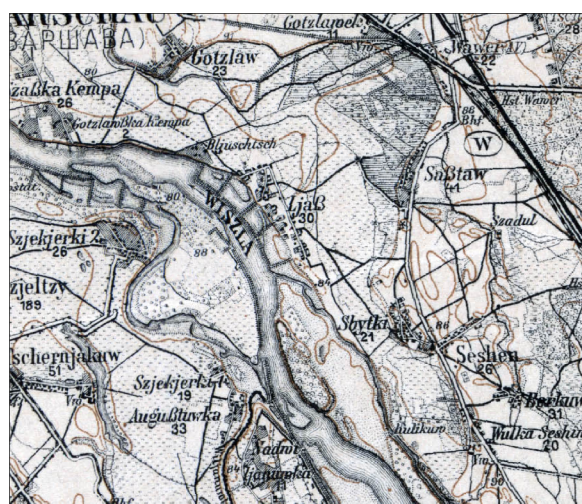
In addition, we compared the width of the river on maps near the water gauge stations with historical data (Magnuszewski & Gutry-Korycka 2009). Based on this, we assumed that the archival maps indicate the state of the river during average water levels. We also related these findings to contemporary levels.

A centerline was determined for the riverbed, allowing for a comparison to be made to observe its displacement, and the curvature index of the river was calculated. To compare the change over time, we calculated the number and area of sandbars and islands. The same techniques were used by Szymańska and Luc (2010), Clerici and Perego (2016), Rinaldi et al. (2016), and Sužiedėlytė-Visockienė et al. (2018). We conducted a detailed study on three sections (Fig. 2) of approximately 9 km each, located within the city (km 507–517), upstream (km 491–500), and downstream (km 529–538). The purpose of this was to enable the changes to be traced – not only in the area where regulatory work was conducted but also in other sections of the Vistula channel that were not directly affected by regulatory structures.



"Topograficzna Karta Królestwa Polskiego", 1843
Kol. IV. Sek. III.; Kol. IV. Sek. IV.
1: 126 000

0 750 1 500 m



"Karte des Westlichen Russlands", 1915
Warszawa-Nord; Warschau-Sued
1: 100 000

0 750 1 500 m



"Varšava/Варшава", 1980
Варшава (лист 1); Варшава (лист 2); Варшава (лист 4)
1: 25 000

0 500 1 000 m



Digital elevation model (DEM), 2015
Spatial resolution 1 m

0 500 1 000 m

Figure 2. Cartographic overview of the Vistula River
Source: Mapster (2024)

Table 1. Maps from archival sources

Title	„Topograficzna Karta Królestwa Polskiego”	„Karte des Westlichen Russlands”	„Warszawa”
Year of publication	1843	1915	1980
Scale	1:126 000	1:100 000	1:25 000
Sheet title	Kol.IV. Sek. III.; Kol.IV. Sek. IV.	Warszawa-Nord; Warchau-Sued	Варшава (лист 1); Варшава (лист 2); Варшава (лист 4)

Source: Geoportal (2024); Mapster (2024); Topograficzna Karta Królestwa Polskiego (2024)

Table 2. Morphometric parameters of the Vistula riverbed 1843–2015. Estimated values

year	1843	1915	1980	2015	1843–2015
sandbars – numbers	87	51	100	51	-36
stabilized vegetated bars (islands) – numbers	13	9	35	61	48
sandbars – area [km ²]	9.028	10.349	5.511	1.842	-7.187
stabilized vegetated bars (islands) – area [km ²]	4.048	4.159	3.041	1.964	-2.084
area of the channel [km ²]	30.558	35.890	27.719	21.035	-9.523
length of the channel [km]	47.361	45.917	45.712	46.297	-1.064
sinuosity of the channel	1.089	1.055	1.051	1.064	-0.024

Source: own elaboration

Study Area

The study area, located in the Middle Vistula Valley and the Warsaw Basin (Kondracki 1980), includes a section of the Vistula River of about 50 km in length, which lies between kilometers 487.5 and 538 of the river's course (according to Rok Wisły 2024) (Fig. 1). The Vistula Valley fragment represents the central lowland. This was cut into old glacial uplands to a depth of 25–55 m. A characteristic feature of the central part of the studied section is the narrowing of the flood terrace and riverbed, which is determined by the geological structure (Biernacki 1975; Falkowski 2007). This narrow section was referred to as a “geomorphological corset.” Glaciotectonically disturbed glacial deposits and Neogene clays occur shallowly in the alluvial basement. The Vistula, in the studied section, has a snow-and-rain regime (Dynowska 1971). The average annual water discharge in the years 1968–2010 was 2,746.5 m³s⁻¹, with extremes of 147 and 59,405 m³s⁻¹ at the Warsaw Nadwilańka gauge station (IMGW BIP 2011). Until the 19th century, the middle course of the Vistula River was unregulated (Ingarden 1921; Falkowski 1990; Magnuszewski & Gutry-Korycka 2009). Prior to regulation, the Vistula was referred to as a braided-anastomosing river (Starkel 2001) or a “wild” river that wanders (e.g., Falkowski 1970; Babiński 1992; Starkel 2001). According to sedimentological analysis (Biernacki 1975; Kałmykow-Piwińska & Falkowski 2012; Polawska 2022), the channel bars are composed of medium and fine sands, with an admixture of gravel.

By the end of the 19th century, the first embankments were built, starting in the center of Warsaw and leading to the suburbs. Work was uneven. The construction of embankments continued in the interwar years and after World War II; the last works, south of Warsaw on the left bank of the Vistula River, were completed in 1970. A total of 49 km of embankments have been modernized since then (Jacewicz & Kuźniar 2000).

Regulation of the Lindley Water Supply Plant channel began in 1885 and has continued for a decade. During this time, local bank stabilization structures were built near ports, water intakes for waterworks, and power plants (Jacewicz & Kuźniar 2000). Following World War II, the Warsaw Vistula Channel became a disposal site for debris from a destroyed city. As a result, the river bankfull cross-section decreased by approximately 50% in comparison with the natural Central Vistula River course, creating the Warsaw corset. Between 1962 and 1963, and in 1968, concrete groynes were constructed to regulate the river channel. The groynes in the Warsaw section have reduced the river width to 224–400 meters (Jacewicz & Kuźniar 2000; Magnuszewski et al. 2012). According to Łajczak et al. (2021), before the initiation of

the regulation works, the width of the riverbed of the entire middle section of the Vistula varied between 1.1 and 1.6 kilometers and measured 600 to 900 meters at below-average levels.

Results

Section 1 (km 491–500 of the river)

Section 1 of the Vistula riverbed, located south of Warsaw and selected for detailed analysis, is natural with numerous sandbars and islands (Fig. 1). The river is between 600 m and 800 m wide. An embankment exists near the left riverbank. On the right, the flood terrace is bounded by a higher Holocene fluvial terrace through the embankment.

The 1843 map reveals 28 channel bars (Fig. 3, Table 2), which is nine fewer than the number recorded in 1915.

The most significant changes from the 19th century can be observed on the 1980 map, where 34 channel bars and 14 stabilized islands are depicted. Presently, there are 18 channel bars and 11 islands in this area. Despite the fact that many channel forms are still evident in this section, their number has decreased by half compared with 1845 (figures 3, 5). The centerline underwent substantial alterations in this section, with the most significant changes occurring between 1843 and 1915. During this time, the channel axis shifted northeastward; only to the south of the section did it shift toward the west (Fig. 4). The examination of cross-sections (A–C) revealed shifts in the channel's width over time (Fig. 5). At figure 5 cross-section A, the width increased from 708 meters in 1843 to 1,325 meters in 1915, before subsequently decreasing to 517 meters. In contrast, cross-section B displays the opposite trend, with the channel narrowing from 1,263 meters in 1843 to 711 meters in 1915, before expanding to 1,233 meters in 1980. As of today, the channel measures 517 meters in width. Furthermore, in cross-section C (Fig. 5), the channel's width increased slightly but steadily from 693 meters in 1843 to 723 meters in 2015.

Section 2 (km 507–517 of the river)

Section 2 is located in the center of the city; the natural narrowing of the riverbed is caused by geological conditions, including the presence of a high moraine plateau escarpment on the left bank and erosion-resistant sediments in the channel bed. In 1843, an archival map showed 13 channel bars and 3 islands, but these were not present in 1915 (Fig. 3, Table 2). Only 5 channel bars were visible in the southern part of the Siekierkowski Bridge and Goław in 1915. In 2015, there were almost no bars in the central part of the section, but approximately

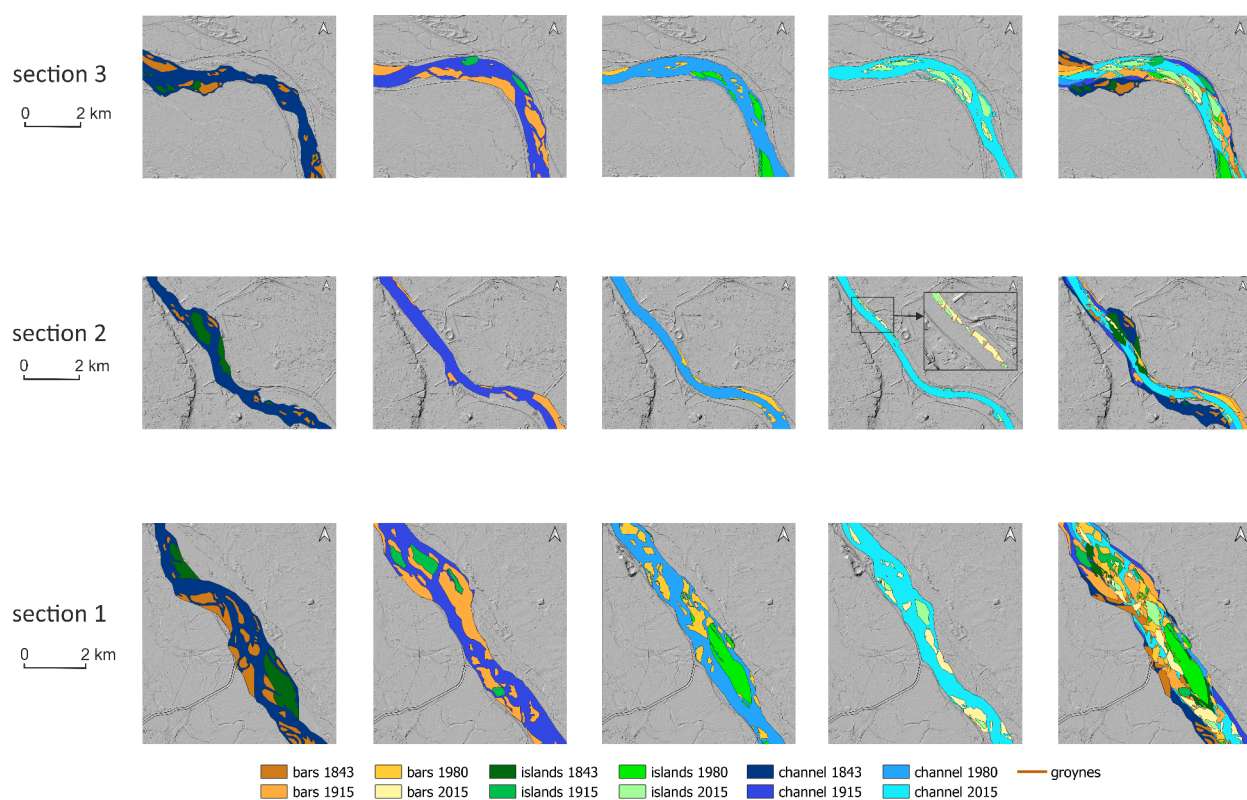


Figure 3. Changes in channel morphology and channel mesoforms of the Vistula River
Source: own elaboration

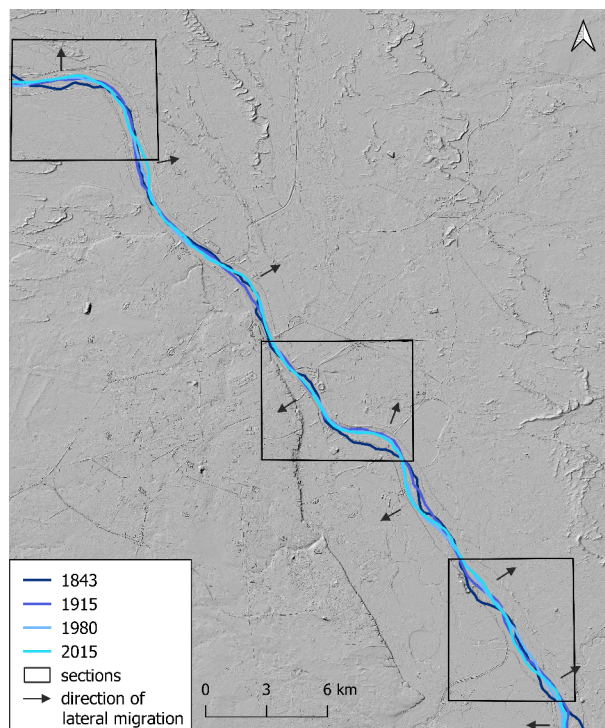


Figure 4. Vistula channel centerline changes over time
Source: own elaboration

7 side bars were present in the southern part, mainly between groynes (Fig. 3). The analysis of the centerline position revealed that the greatest changes occurred between 1843 and 1915 when the channel shifted southwestward (Fig. 4). After 1915, the centerline position did not change. The Vistula narrowed in this section between 1843 and 1915 (Fig. 6), but it widened between 1915 and 1980, and then narrowed again in 2015. The greatest transformations can be seen in figure 5 cross-sections A and C, which were drawn at the former mouth of the Siekierowski Canal that once surrounded the so-called Wilanowska Island. The width of the channel decreased from 1,077 m (A) to 781 m (C), and then to 327 m and 232 m over the four years studied (Fig. 6). In cross-section B, the width of the channel was 363 m in 1980 and measures 261 m today.

Section 3 (km 529–538 of the river)

The northern portion of the studied Vistula riverbed (section 3) is characterized by a wide (700–900 m) natural riverbed with numerous sandbars and islands (Fig. 3). The zone between the embankments ranges from 900 to 1,300 m (Fig. 7). The number of channel bars remains consistent at 18–21, while the number of stabilized islands increases significantly from 6 to 19 (Fig. 3, Table. 2). The lateral migration of the riverbed primarily occurs toward the northeast and north, as evidenced by the changes in the centerline position (Fig. 4). The channel width also fluctuates over the study period (Fig. 4). In profiles A and C in 1843 (Fig. 7), the width of the channel was 1,292 m and 573 m, respectively, but by 2015, it had decreased almost threefold due to the connection of islands with the riverbanks (Fig. 7).

In profile B (Fig. 7), we observe the opposite process – the widening of the channel. The width increased from 225 to 681 m in the 19th century. It is important to note that cross-section

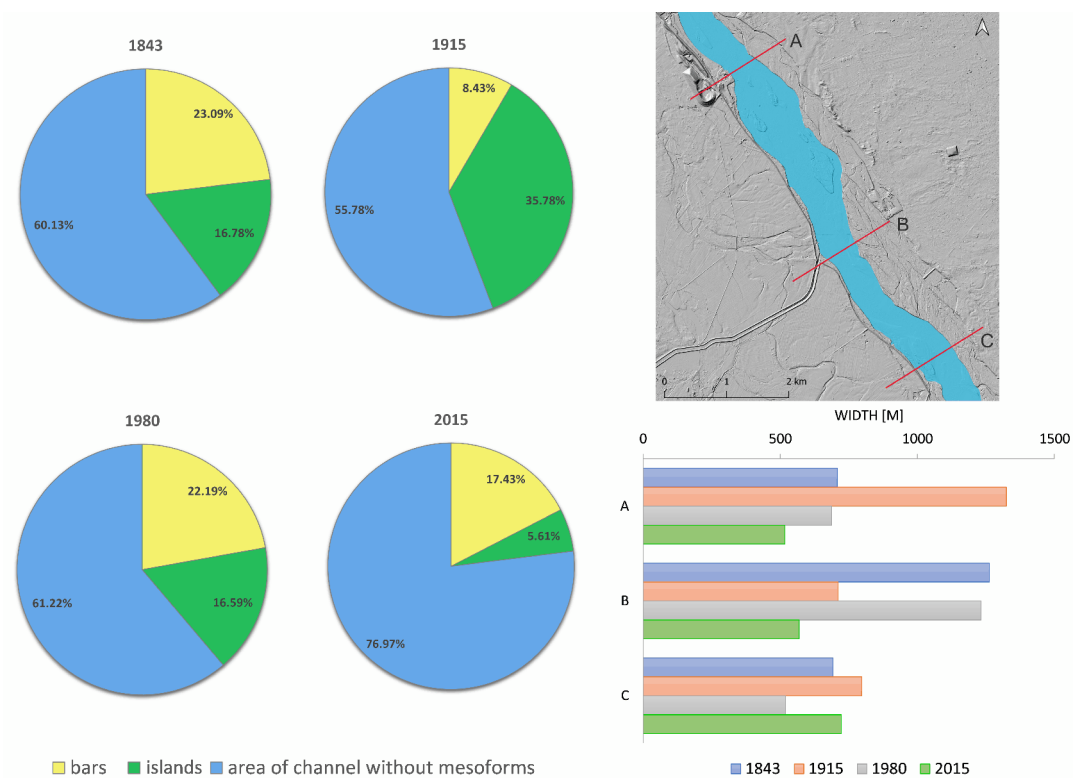


Figure 5. Estimated changes in riverbed width, channel-bar area, and vegetated island in section 1, upstream of Warsaw
Source: own elaboration

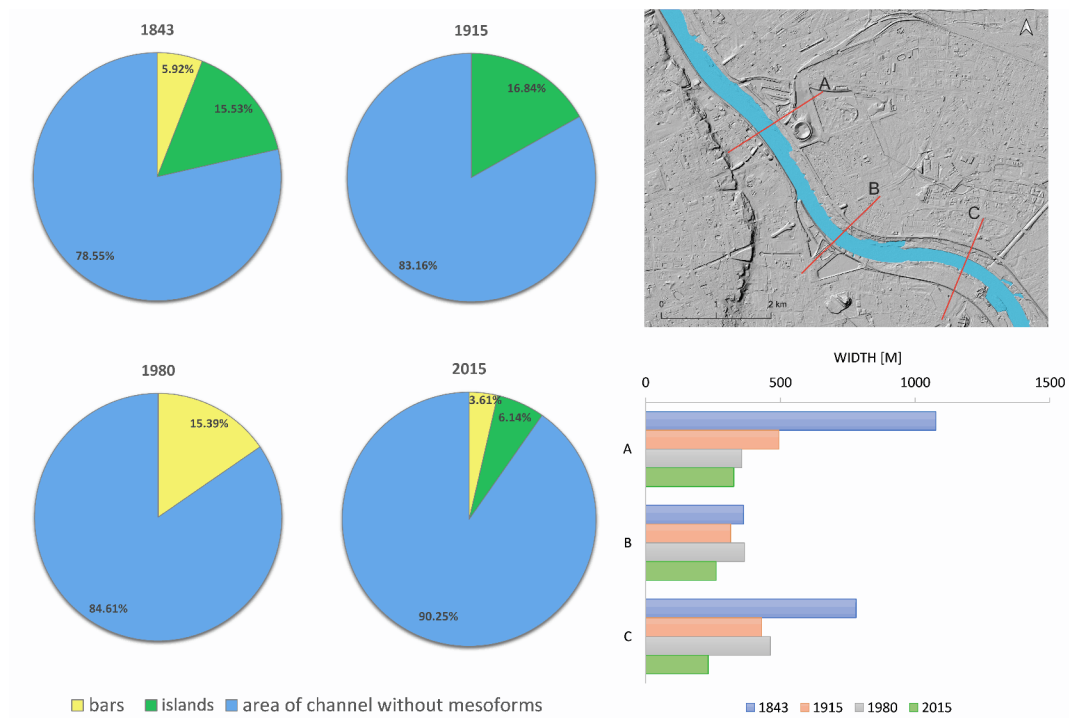


Figure 6. Estimated changes in riverbed width, channel-bar area, and vegetated island in section 2, downtown Warsaw
Source: own elaboration

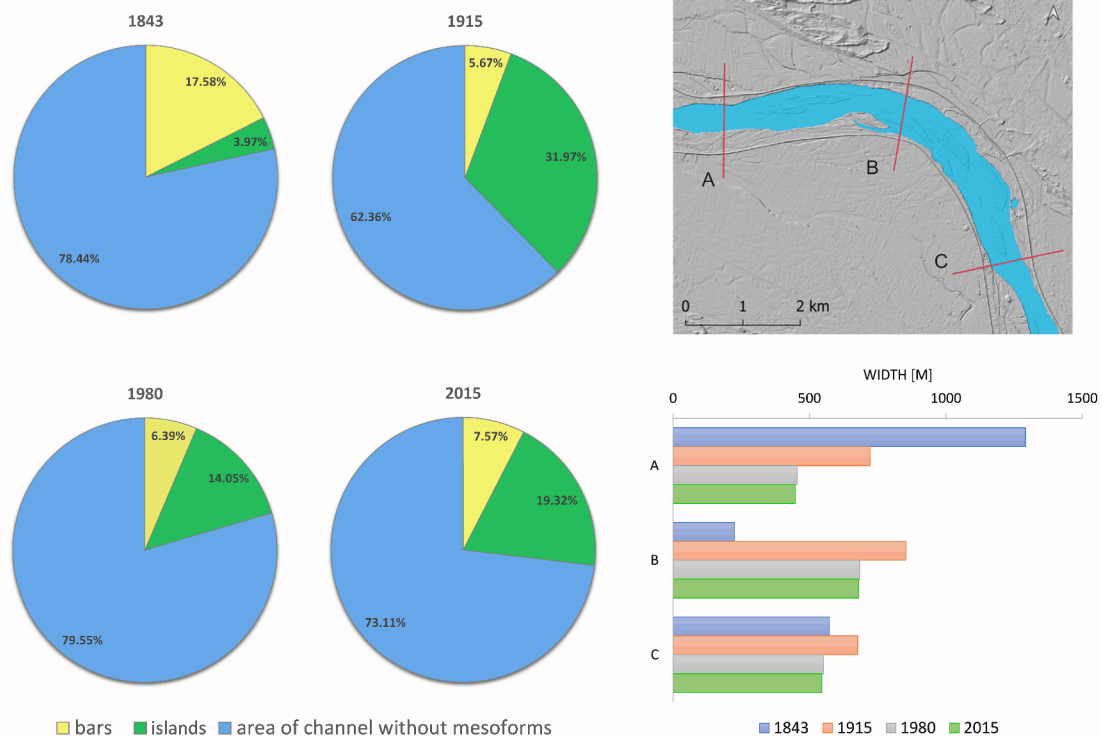


Figure 7. Estimated changes in riverbed width, channel-bar area, and vegetated island in section 3, downstream of Warsaw
Source: own elaboration

B (Fig. 7) is located almost on the axis of the bend, which likely contributes to more effective lateral erosion and subsequent riverbed widening.

Discussion

The development of river channels is significantly influenced by several morphometric parameters, including width, depth, and slope, as well as the magnitude and frequency of flow discharge, particularly at the bankfull stage. This study focused solely on cartographic materials. Unfortunately, this method did not enable the alteration in the hydraulic conditions of the riverbed to be assessed over the examined period. Nevertheless, the extensive modifications observed in river channel location and dimensions allow significant trends in its evolution to be identified.

The section of the Vistula Valley and riverbed in Warsaw is characterized by its "gorge" type, which is influenced by its geological structure (Biernacki 1975; Falkowski 1990). In this section, the valley bottom (floodplain) is relatively narrow and has erosion-resistant sediments in its alluvial base, resulting in a straight and narrow Vistula riverbed. This has been the focus of numerous geomorphological, hydrological, and hydrotechnical studies (e.g., Jacewicz & Kuźniar 2000; Magnuszewski & Gutry-Korycka 2009; Falkowski 2015). The importance of the shallow location of formations in stabilizing the riverbed has also been highlighted (Falkowski 2015). The shallow location of these sediments is crucial in stabilizing the riverbed. Upstream and downstream of this narrow section, the bed is wider, and there are sandbars and islands present within the river channel. This condition is evident on a map from 1843, which depicts the natural state of the riverbed before direct human intervention (Jacewicz & Kuźniar 2000). There were several small sandbars in the narrow riverbed; the riverbed mainly had

a transitional function. Accumulation was the dominant process, both upstream and downstream.

Morphological changes in the Vistula River channel from 1843 to 2015 were significant. The channel narrowed, particularly in the Warsaw section, and straightened. In the study area, covering approximately 50 km, the channel length was reduced by one kilometer, representing a reduction of 2%, and its area decreased by almost one-third.

The changes observed during the study period pertain to the width and position of the riverbed, and the number of channel bars and islands. In 1843, there were 40% more sand and gravel channel bars than currently, while the number of islands was almost five times fewer. Over the past 150 years, the area of sandbars has decreased by more than 7 km² and that of stable islands by approximately 2 km². The section of the river that has undergone the most significant changes is the central, regulated section, particularly its southern part below the geomorphological corset.

According to Ingarden (1921) and Jacewicz and Kuźniar (2000), the floods of 1867 and 1884 led to significant modifications in the river channel, but the primary changes were the result of engineering works that were carried out in stages. In section 2, parallel dams and revetments were used to stabilize the bank, and 16 groynes were constructed, mostly on the right bank. The change in channel width and the shift in the channel axis toward the west between 1843 and 1915, as shown in figure 3 (section 2), confirm these modifications. As per Ingarden (1921) and Matuszkiewicz and Roo-Zielińska (2000), lateral erosion increased between sections 2 and 3, causing a shift in the channel axis toward the NE and N in section 3. After the 1924 flood, further regulation was implemented, and the left bank of the river stabilized. Additionally, 9 new groynes were constructed on

the opposite side. In 1926–28, 12 groynes were built between sections 1 and 2. Channel dredging was performed in the early 20th century. Alluvial deposits were manually removed from the channel, but by the end of the 1920s, mechanical dredgers were used to extract the deposits. Although the depth of the channel was not analyzed in this study, the almost complete reduction of mid-channel bars in section 2 can be observed, according to studies by Wyżga 2003, Arróspide 2018, and Brenna et al. 2021. More hydraulic engineering structures were built in 1962, and at that time, the width of the channel in the downtown area (section 2) was limited to 225 m, creating the Warsaw Girdle (Warsaw corset). Based on the examination of historical maps, it is evident that in 1980, there were 15 groynes in section 1, 38 in section 2, and only four in section 3. However, it should be noted that not all structures may have been documented on the maps used for this analysis. According to Jacewicz and Kuźniar (2000), during the 1960s and 1970s, only local regulatory work was carried out outside the city limits. The construction of groynes narrowed the main riverbed, increasing river current velocity and bedload transport intensity. Between groynes, water flows more slowly, and channel deposits accumulate (Babiński 1992; Magnuszewski & Kowalski 2020; Warowna 2007; Vercruysse & Grabowski 2021). The material accumulated in the zone between the groynes is one of the primary accumulation forms in section 2. Mid-channel bars declined, and lateral bars appeared, eventually becoming part of the floodplain. The riverbed width was reduced by more than half, even up to 200 m (Fig. 5). The stability and erosion-transitional function of this section are due to natural factors (geomorphological corset), strongly reinforced by the regulation of the riverbed and the exploitation of sand from the riverbed (Warsaw corset) (Jackowski & Kuźniar 2000; Falkowski 2015; Falkowski et al. 2017; Ostrowski et al. 2021). Similar situations are known for other rivers (e.g., Piégay et al. 2005; Fryis & Brierley 2010).

The other two segments of the study display characteristics of accumulation zones. Here, the channel has narrowed somewhat, the sandbars have diminished in number, and there are more islands. The sandbars and islands in these areas became smaller as the channel deepened, transforming them into new islands. Sandbars were incorporated into the floodplain, resulting in a decrease in the channel area. According to Kalmykow-Piwińska and Falkowski (2012), the channel segment upstream of Warsaw (Kępy Zawadowskie) exhibits significant dynamics. Between 1898 and 2007, the sandbars and islands in this region underwent frequent changes. As a result, the cross-sectional area of the channel was significantly reduced, which could increase flood risk along the river section upstream and downstream of the city. These changes can be regarded as a dynamic equilibrium, but they

may also be influenced by the exploitation of Vistula alluvium and climate conditions (Piégay et al. 2005; Gregory 2006; among others).

The study of cartographic archival materials revealed the spatial variability of the Vistula riverbed and mesoforms but did not allow for an evaluation of the type of riverbeds and their migration rates due to variability in scales and levels of generalization. However, the GIS method makes it possible to trace changes in the accumulation and erosion zones and assess the impact of regulation on the riverbed.

Conclusions

This study identified changes in the morphometric parameters of the Vistula River and channel bars over the past 150 years, with a particular focus on the regulated section. Due to the geological structure known as the geomorphological corset, channel processes such as erosion and transportation occurred. Following regulation work, the length of the Warsaw corset increased by 14 km, resulting in a decrease in river width by more than half, and an area reduction of 51.5%. Presently, there is an erosion-transport zone that is approximately 17 km long. This process is also impacted by sand extraction in the Vistula channel bed in this area. Accumulation zones exist both upstream and downstream of the regulated section, with the accumulation process continuing after regulation. However, the tendency to reduce channel width and surface area has been noticeable for over 150 years. The number of sandbars decreased, whereas the number of islands increased. Before the regulation and embankment of the Vistula, sandbars occupied 21.5% of the channel area; afterwards, the figure was only 9.8%. As the channel narrows in both the northern and southern sections, sandbars are significantly reduced. This reduction can be attributed to various factors, including the expansion of the corset beyond its natural section, overexploitation of sand and the lowering of the Vistula bed, and changes in the balance of sand transport across the Vistula above the corset. Further examination of the sections above the Warsaw corset, particularly the channel sections located north and south of the analyzed section, is necessary.

The present investigation did not take hydraulic and hydrological factors into account, which are critical aspects that require further research to comprehend the modifications in the Vistula riverbed.

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