Spatiotemporal dynamics of floodplain patterns during the last 400 years south of Leipzig - A regional scale analysis

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Abstract. The Elster-Pleiße floodplain south of Leipzig has undergone significant hydromorphological changes over the past centuries, influenced by both natural processes and anthropogenic interventions. This study employs high-resolution LiDAR-based fluvial-geomorphological mapping (1x1 m resolution) and old maps analyses to reconstruct past river dynamics and identify shifts in channel morphology. Geomorphological mapping reveals an earlier, more dynamic floodplain characterized by meandering and anabranching channels, which transitioned into a system of stabilized, largely immobile watercourses. Comparative analyses of old maps spanning from the 16th to the 20th century indicate a gradual reduction in river sinuosity and lateral migration, coinciding with increasing human modifications such as mill races, timber rafting canals, and flood protection measures. Key transformations include the straightening of channels, floodplain aggradation, and the impact of open-cast lignite mining in recent centuries. The study highlights the complex interplay of climatic fluctuations, sedimentary processes, and anthropogenic activities in shaping the floodplain's evolution. Understanding these long-term dynamics provides crucial insights for contemporary river restoration and flood management strategies.

1 Introduction

Floodplains and riverine areas are crucial to ecological sustainability in Europe (European Parliament and Council of the European Union, 2000). However, the anthropogenic restructuring of rivers and floodplain landscapes in Central Europe is evident (Tockner et al., 2022). Pristine riverine systems are now rare. In Germany, the floodplain status report highlights the urgent need for revitalization (Koenzen et al., 2021). In accordance with the guidelines for the revitalization of floodplains, reference models are indispensable. To evaluate a potentially natural condition, the historical development of the river should be examined (Koenzen, 2005; Maaß et al., 2021). In addition to their natural characteristics and functions, floodplains and riverine areas are closely related to the history of the cultural landscape of Central Europe (Hein, 2020; Brown et al., 2018), and the remnants of these areas are considered valuable for protection (Council of the European Union, 1992).

Knowledge about historical river changes provides critical information for contemporary river management and restoration efforts (Leopoldina, 2024). By understanding past river dynamics, sedimentation patterns, and floodplain evolution, the development of strategies can improve ecological resilience (Brown et al., 2018; Hein et al., 2016; Maaß et al., 2018). These historical perspectives are essential for the implementation of adaptive management practices in the face of climate change and anthropogenic pressures (Heyden and Natho, 2022; Serra-Llobet et al., 2022). Typically, changes in river pattern and fluvial dynamics are often influenced by hydroclimatic factors (Macklin and Lewin, 2019; Notebaert and Verstraeten, 2010). Variations in precipitation levels and changes in vegetation cover can lead to alterations in river discharge and sediment supply, which in turn affect the morphology and course of rivers (Macklin et al., 2006; Benito et al., 2008). In general, these climatic changes can result in the reshaping of river landscapes over time, impacting ecosystems (Broothaerts et al., 2013; Sendek et al., 2021) and human activities (Brandolini and Carrer, 2021; Winiwarter et al., 2013). In particular, in urban settings, the interactions between humans and floodplains are complex and interconnected (Haase, 2003; Nießen, 2020; Hohensinner et al., 2013a). However, on a Holocene scale, a potential equilibrium state of river morphodynamics is under debate and responses of external drivers are discussed to be nonlinear (Elznicová et al., 2023).

Changes in floodplain dynamics during the Holocene, especially late Holocene climatic variations, have left terrain landforms and river channel patterns that are still preserved today (Schirmer et al., 2005; Schielein et al., 2011). The Little Ice Age (LIA; 1250-1860 AD), a period of relatively cooler and wetter climate in Central Europe (Wanner et al., 2022; Büntgen et al., 2011b) from the late Middle Ages to the nineteenth century, significantly influenced fluvial processes, driving increased fluvial erosion, lateral reworking, and aggradation in riverine systems (Macklin and Lewin, 2008; von Suchodoletz et al., 2022, 2024). However, the response of fluvial systems to climatic changes during the LIA seems to be variable both spatially and temporally (Rumsby and Macklin, 1996; Elznicová et al., 2023).

Apart from climatic variations, catchment-scale variability in land use, terrain openness, and geomorphological connectivity drive the fluvial system due to varying sediment supply and discharge peaks in frequency and magnitude, and therefore human-environment interactions are decisively modifying fluvial dynamics (Brown et al., 2009; von Suchodoletz et al., 2024; Dotterweich, 2008; Dreibrodt et al., 2023; Hoffmann et al., 2010; Ballasus et al., 2022; David et al., 2024). Since at least the Middle Ages, most rivers in Central Europe have been subject to anthropogenic alteration (Hoffmann, 2010). The construction of mill races transformed tributaries and branches and brought them under anthropogenic control, or entirely new channels were created to harness hydropower. Hydropower facilities incorporating water wheels, ponds, diversion channels, and dams greatly influenced sediment transport and flow velocity (Walter and Merritts, 2008; Werther et al., 2021a). Even after the abandonment of active mills or weirs, geomorphological adaptation processes can still be observed (Vetter, 2011; Buchty-Lemke and Lehmkuhl, 2018). Rivers also played an important role as transportation routes, and timber rafting strongly influenced river morphology by removing obstacles and straightening river courses. Consequently, it is difficult to discern the individual impacts of human actions, climate variations, and inherent landscape system factors as forces of change (Knox, 2006; Brown et al., 2021; Candel et al., 2018; Macklin and Lewin, 2008; Notebaert et al., 2018).

In the past, Leipzig's waterways were of interest to many scientists in both archaeology and history, not least because it was difficult to understand their formation (Arnhold, 1964; Grebenstein, 1959; Küas, 1976). Early research in Leipzig began with the *Dähne* family, who managed the city's waterworks in the 18th century. Their interest in the watercourses was already directed towards the city's water quality. At the beginning of the twentieth century, the town historian Ernst Müller collected many sources on the city's water supply. In particular, he answered questions of water usage rights on the Pleiße mill race arising from mediaeval contracts (*Stadtarchiv Leipzig, 0501, NL, Ernst Müller, Nr. 69*). Later, the archaeologist Herbert Küas and the hydraulic engineer Georg Grebenstein used his collection to work on the question of the *original* courses of the rivers. The water network of the Leipzig basin was characterized by a multitude of meandering and anastomosing rivers (Makaske, 2001), which were used, transformed, and realigned, which makes reconstruction more challenging. Both attempted to create a map as a reconstruction of the medieval city, which included watercourses as a vital part of the city's economy; e.g. mill races were dug to provide sufficient hydropower to operate mills and provide potable water (Grebenstein, 1959; Küas, 1976). In recent historical research, the earliest churches and burgwards of the region were linked with the early medieval settlement pattern that is centered along the river courses between Merseburg and Taucha (West-East), as well as Schkeuditz and Pegau (North-South) (Cottin, 2015b). The activities of Leipzig's monasteries and university in urban and suburban areas imply an early use of the watercourses by these organizations (Bünz and John, 2015; Gornig, 2023; Sembdner, 2010). However, more emphasis needs to be placed on the impact of these institutions on the rivers. Previous research on the water courses has thus shifted from questions of water quality to usage rights and to increasingly urgent questions of the origins of the city's layouts and urban-rural interdependencies (Cottin, 2015a, b). The main findings are that the rivers were altered and modified in the Middle Ages, which caused issues with floods and droughts in the early modern period. The primary objectives of managing the water were to operate the water mills, which played a crucial role in providing food for the urban residents (Hardt and Lohse, 2025). In consequence, the question that arises is when and whether these human activities have caused a change in river dynamics, even in a floodplain with a complex system of *natural* water courses such as in Leipzig. By the end of the 15th century, a complex system of ditches, weirs, and millraces had been created which was looked after, adapted and expanded over centuries, for instance through the establishment of a piping system begun in 1496, or by building a canal for timber rafting branching off from the Weiße Elster river near Pegau restructuring the Batschke river from 1608-1610 (Andronov et al., 2005). Today we observe a stable river water network with fixed courses.

In this study, we aim to address the following research questions:

(i) How active and dynamic was the Elster-Pleiße floodplain south of Leipzig in the past, as determined through systematic LiDAR-based geomorphological mapping?

(ii) When did the transition from a highly mobile river system to a more stabilized channel network occur, based on quantitative historical map analyses?

(iii) What were the primary drivers that influenced the stabilization and transformation of the floodplain?

2 Study area

The study area (Fig. 1B) encompasses the floodplain in the southern region of Leipzig (c. 20 km^2). The floodplain situated in the southern part of Leipzig extends up to 4 kilometers in width and comprises the inundation zones of the Weiße Elster, Pleiße, along with the Paußnitz and Batschke rivers. The Weiße Elster and the Pleiße rivers flow through this area, forming a watercourse junction that is accompanied by the Elster-Pleiße floodplain forest. We restricted our study area to the Holocene floodplain, as identified and delimited from the the geological map, the lithofacies map and the present topography (Haase and Gläser, 2009). To the north, the *Palmgartenwehr*, which marks the transition of the Elster flooding canal (*Elsterflutbett*) into the Weiße Elster river, defines the boundary. The southern boundary is marked by the post-mining lakes Cospudener See and Markkleeberger See, beyond which lies a landscape heavily influenced by open-cast lignite mining (Haase et al., 2002; Berkner, 2019). Positioned in the rain shadow of the Harz Mountains (Fig. 1A), Leipzig receives an annual rainfall of approximately 500-550 mm, with a slight maximum during the summer months. Recent years have witnessed a trend of increasing temperatures and occasional episodes of intense drought, influencing tree-ring growth patterns (Schnabel et al., 2021). In the headwater regions of the Weiße Elster and Pleiße rivers, annual precipitation reaches about 900 mm, with a pronounced peak in the summer. The Weiße Elster river, stretching roughly 250 km and draining an area of about 2900 km^2, is the main stream traversing the Leipzig Basin (MQ around 17 m^3/s). Originating in the Czech Elster Mountains and discharging into the Saale river near Halle, this river is a third-order branch in the Elbe river network (von Suchodoletz et al., 2022). Around Leipzig, the Weiße Elster river merges with the Pleiße river (MQ around 2 m^3/s), a lowland river currently measuring about 90 km in length, although it extended about 115 km before 20th-century coal mining (Haikal, 2001; Tinapp et al., 2020). Its valley is notably narrower, about half the width of the Weiße Elster river's, south of Leipzig. Leipzig is located in the Leipzig Basin and belongs to the North German Lowlands, which received their main geomorphological features through glacial and periglacial overprinting in the Quaternary period (Eissmann, 2002; Denzer et al., 2015). The morphology of the wide valley is characterized by gravel terraces from the Saalian glaciation and partly also from the Weichselian glaciation. Older fluvial deposits underlie the younger sediments and are not visible at the surface (Eissmann, 2002). Outside, the valleys, the terrain surface in the larger area exhibits localized remnants of Saalian terminal moraines manifesting as ridges and hills (Eissmann, 2002). The ground moraine plains are predominantly overlain by sandy loess (Lehmkuhl et al., 2021; Haase et al., 2007). Characteristic soil types in those areas are Cambisols, (Albe-) Luvisols and Stagnosols (Landesamt für Umwelt, Landwirtschaft und Geologie, 2020). Since the latter part of the 20th century, numerous researchers have concentrated on understanding the development of the Holocene floodplains associated with rivers near Leipzig (Neumeister, 1964; Händel, 1967; Tinapp, 2002; Fuhrmann, 2005; Tinapp et al., 2019; von Suchodoletz et al., 2022). Their studies generally focused on insight into significant changes in floodplain sedimentation, climatic changes, and the dynamics of human settlements during the entire Holocene. However, Ballasus et al. (2022) highlighted ongoing discussions regarding the spatio-temporal dependencies of human influence within terrestrial watersheds and the subsequent floodplain aggradation. Unlike the Weiße Elster river floodplain (Mol, 1995; Tinapp, 2002; von Suchodoletz et al., 2022, 2024), which has been investigated more thoroughly, the sedimentary structure of the Pleiße river floodplain remains inadequately explored (Tinapp et al., 2019). Regarding the Pleiße river, flood loam deposits of approximately 2.5 m were identified, with only about 1 m accumulated since the Slavic era (Neumeister, 1964; Tinapp et al., 2019). Also, Tinapp (2002) noted increased flood loam accumulation starting around the beginning of the 9th century in the Weiße Elster floodplain. Regarding a standard Holocene floodplain sediment stratigraphy, the oldest Holocene sediments in the lower Pleiße valley are peat deposits that developed in small depressions of the Weichselian valley floor during the Preboreal period (Neumeister, 1964; Händel, 1967; Tinapp et al., 2019). Organic sediments in the same stratigraphic position are also known from the lower Weiße Elster river valley (Hiller et al., 1991; Mol, 1995; Tinapp, 2002), and organic deposition since that period is also known from other catchments in Central Germany (Kirchner et al., 2022; Litt, 1992). Probably wetter conditions and higher groundwater levels in the valleys during the Preboreal resulted in the formation of many small peat layers on the Weichselian fluvial sediment base. On top of these, several layers of alluvial overbank fines exist, featuring intervals of diminished sediment accumulation or increased soil development. Typical soil types in the floodplains are Gleysols and Fluvisols with varying properties (e.g. mollic, cambic), (Haase et al., 2000; Landesamt für Umwelt, Landwirtschaft und Geologie, 2020). Fluvial geomorphological processes are a crucial key for analyzing changes in land surface and land use patterns over time. For example, subsurface information were used in a quantitative modeling to depict the paleorelief of Leipzig's city center (Grimm and Heinrich, 2019). Fluvial processes also created landscape segments with select value for nature conservation today. Currently, 13% of the urban area of Leipzig is designated as a landscape protection area, with about half of these areas belonging to the SAC area (Special area of conservation; *FFH - Flora-Fauna-Habitat*) *Leipziger Auensystem* (Scholz et al., 2022). As a result, a significant portion of the areas within the floodplain is subject to special protection status and under a riperian forest cover, which helps to preserve surface structures. The southern floodplain forest (also known as *Leipziger Ratsholz*) has belonged to the city of Leipzig since 1543 AD. Previously, it had been expanded and maintained by the Augustinian monastery of St. Thomas for over three centuries (Lange, 1959; Rehm, 1996). The forest history of the 19th and 20th centuries shows the spatial consistency of forest distribution. Only the change in management from the former coppice-with-standard to high forest management in the second half of the 19th century influenced the tree species composition (Gläser, 2005; Haase and Gläser, 2009). The long-term continuity of the forest stand, diversity of tree species, and the history of land use establish the Leipzig floodplain forest as a hotspot of biodiversity with national significance (Wirth et al., 2021).

3 Material and Methods

3.1 Data

3.1.1 Digital Geodata

Digital Terrain Model (DTM)

High-resolution airborne laser scanning data were provided by the State Office for Geoinformation and Surveying Saxony (GeoSN, 2018). We used the derived 1 × 1 m spatial resolved DTM, which was recorded on February 13th and 14th, 2018 (Tab. 1). It has a height accuracy of ± 0.2 m and is suitable for the mapping of fluvial geomorphological structures (Kokalj and Hesse, 2017).

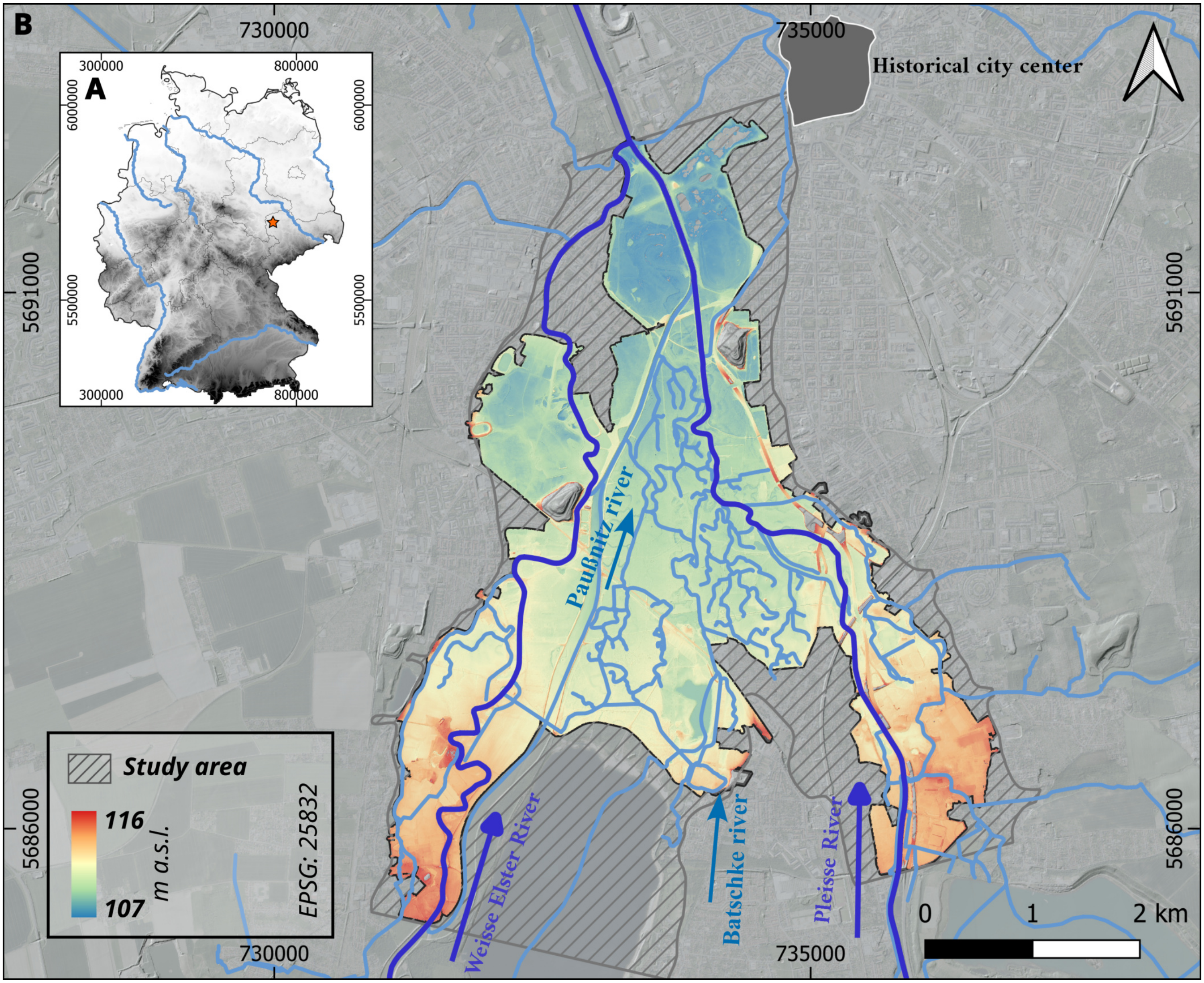

Figure 1. Geographical context of the study area. A) Location of Leipzig within Germany marked by red star. 20x20 m DTM data from Sonny (2021). B) Local Context of the Weisse Elster-Pleiße floodplain south of Leipzig. Dark blue lines indicate major rivers, bright blue line indicate tributaries and anthropogenic channels. (1x1 m LiDAR DTM by GeoSN (2018)). EPSG:25832

Digital Orthophoto (DOP)

A high-resolution aerial image (0.2 x 0.2 m spatial resolution) was provided by the State Office for Geoinformation and Surveying Saxony (GeoSN, 2021). The DOP is also available in 2x2 km grid cells, and the recordings from the study area cover the period between April 21st and April 27th, 2021 (Tab. 1). We used the DOP for the manual verification of mapped structures, for example, to identify current waterbodies.

Open Street Map (OSM)

The Open Street Map layer was used to manually verify that mapped structures were not incorrectly assigned to anthropogenic tracks and paths. For this purpose, an *XYZ-tile* integration (Table 1) of OSM with continuously updated data was used (OSM, 2021).

3.1.2 Old Maps

The purposes of the variety of old maps, that show Leipzig and its surroundings differ considerably over the course of time (Ebeling, 1999; Schneider, 2006; Renes, 2016). Starting with first land surveys in the 16th century, which were financed by the Saxon rulers to measure their territories, the maps of the 17th and 18th century contain detailed views of the city, which usually include the rivers, but lack detailed sketches of the mills, or plans of the entire catchment of the rivers. However, most of them are not drawn geometrically. With the help of modern geometrical measurements, the first precise maps in a geographical sense emerged, in the 19th century. This way, maps were created either for detailed views on river structures or for overviews of whole countries (Witschas, 2002; Meyer, 2007). For this study, we have chosen the maps that offer the most comprehensive overview of the rivers in the floodplain and are the most accurate in geodetic terms. The *Öder-Zimmermann* map of Leipzig is a colored, hand-painted map. The basis for this map that was created was a land survey of the Saxon elector August I. As the elector had a penchant for cartography, his cartographs were equipped with the techniques and knowledge of the time. In 1585, his successor Christian I. ordered Matthias Öder to create the map discussed. In 1595, Öder hired his cousin Balthasar Zimmermann for support. After Öder's passing, Zimmermann continued working on the map until his death in 1633 or 1634. Hence, the name *Oeder-Zimmermann* (Wiegand, 2014). This is why the *Öder-Zimmermann* map is geometrically accurate and remained unrivalled in its precision until the late 18th century (Blaschke, 2002). The *Öder-Zimmermann* was drawn in 1:53,333. The next selected maps are the *mileage sheets* (*Sächsische Meilenblätter*) of Saxony, which were produced for the Saxon electors between 1780 and 1806. The maps (map sheets 18, 19, 27) showing the study area are from 1802 to 1806 and were drawn with a spatial scale of 1:12,000. This hand-printed map is digitally accessible and importable into GIS. For easy reproducibility, we have chosen the georeferenced wms-version (*WebMapService*) (Historischer Dienst Sachsen, 01.05.2007). The Ordnance Survey Maps (*Messtischblätter*; 1:25,000) were created between 1887 and 1928 for a land survey by the Royal Saxon General Staff (until 1918) and German Reich Office for Land Survey Saxony (after 1918)(GeoSN, 2025). The maps covering Leipzig (sheets 4639 and 4640), originate from the renewal series of the 1930s (sheets that cover Leipzig were first drawn in 1907/1908 and updated in 1939/1941), after the *Elsterflutbett* and *Elsterflutbecken* (both artificial water retention basins) had been built. As an additional old map for discussing the aim of the study, we refer to the map called the nun's miller survey (*Nonnenmüllerplan*, Tab. 1), which was created in 1682 by the miller of Leipzig's *Nonnenmühle*, a mill that once belonged to the nunnery of St. George. This old map is not suitable for georeferencing and will therefore not be further quantitatively evaluated, but it does show the entire study area. This old map has not yet been included in any historical study, apart from a visualization in a work on the floodplain depicting the rafting site south of the city (Liebmann, 2023). The map has an imprint claiming that it shows the Pleiße and Weisse Elster rivers with their mills, weirs, meadows and forests between the city of Leipzig, Connewitz, Großzschocher and the Rosental (Tab. 1). The most important features of this map are the colored depictions of the forests, meadows and the rivers surrounded by rows of tree to explore the early modern landscape.

Table 1. Metadata of basic data. Acquisition and quality. Extended metadata for old maps in Tab. S1

Nr.	ID	Name	Publisher/Illustrator/Client	Dating	Comment Dating	Scale	URL/Reference
1	LE617	Ordnance Survey Maps (Sheet 4639) - Leipzig (West)	*Deutsches Reich / Reichsamt für Landesaufnahme / Zweigstelle Landesaufnahme Sachsen*	1939	Recorded 1904, published 1907, corrected 1922, last supplements 1939, edition 1942	1:25,000	(MB25, 1939a)
2	LE615	Ordnance Survey Maps (Sheet 4640) - Leipzig (Ost)	*Deutsches Reich / Reichsamt für Landesaufnahme / Zweigstelle Landesaufnahme Sachsen*	1941	Recorded 1905, published 1908, corrected 1941, edition 1944, unmodified reprint 1993	1:25,000	(MB25, 1941)
3	LE631	Ordnance Survey Maps (Sheet 4739) - Zwenkau	*Deutsches Reich / Reichsamt für Landesaufnahme / Zweigstelle Landesaufnahme Sachsen*	1939	Recorded 1904, published 1906, corrected 1921, last supplements 1939, unmodified reprint 1993	1:25,000	(MB25, 1939b)
4	LE637	Ordnance Survey Maps (Sheet 4740) - Markkleeberg	*Deutsches Reich / Reichsamt für Landesaufnahme / Zweigstelle Landesaufnahme Sachsen*	1940	Recorded 1905, published 1907, corrected 1940, edition 1944, unmodified reprint 1996	1:25,000	(MB25, 1940)
5	LE642	Mileage sheets (Berlin copy) 19 : Leipzig	Friedrich Ludwig Aster	1802	-	1:12,000	(Aster, 1802a)
6	LE643	Mileage sheets (Berlin copy) 18 : Plagwitz, Leipzig-Schönau, Leipzig-Lindenau	Friedrich Ludwig Aster	1806	-	1:12,000	(Aster, 1806)
7	LE644	Mileage sheets (Berlin copy) 27 : Markkleeberg, Großdeuben, Gaschwitz	Friedrich Ludwig Aster	1802	-	1:12,000	(Aster, 1802b)
8	LE392	*Nonnenmüller Plan: Abriss der Wasser Pleiße und Elster*	Hans Bernhardt Kärtzer	1682	-	-	(Kärtzer, 1682)
9	LE395	*Öder-Zimmermann*	Matthias Öder, Balthasar Zimmermann	1586-1633	1586 Matthias Öder received the task of saxons elector to measure his lands; 1595 his cousin Balthasar Zimmermann worked with him; 1614 Öder passed away and Zimmermann carried the works on; 1633 or 1634 Zimmermann passed away, by then most maps were finished.	1:53,333	(Öder and Zimmermann, 1586-1633)
10	-	Digital Terrain Model	GeoSN	2018	-	1x1m resolution	(GeoSN, 2018)

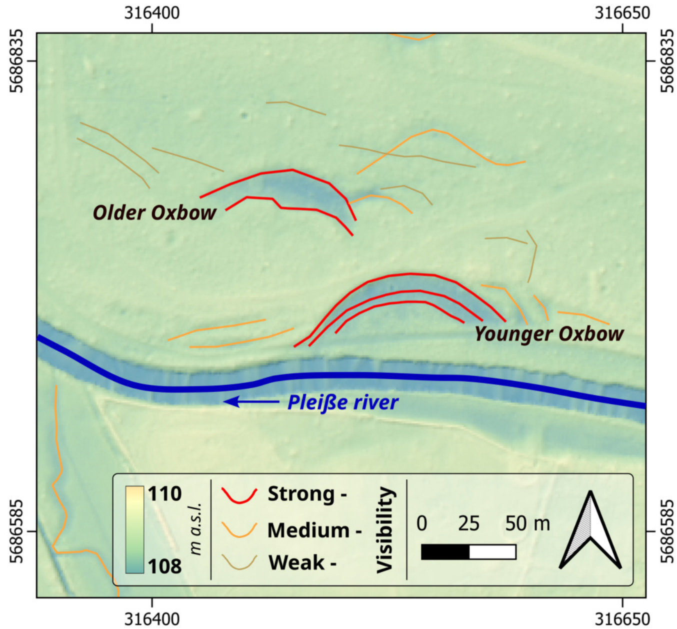

Figure 2. Section of the study area (Pleiße floodplain) with examples for visibility classes. Location of the section is shown in Fig. 4A as panel E. Background layer: DTM 1x1m (GeoSN, 2018). EPSG:25833

3.2 Methods

3.2.1 Geomorphological Mapping

Digital Terrain Models (DTMs) are used not only in geography and geomorphology, but also, for example, in archaeology, hydrology, forestry, and disaster risk management (Hesse, 2010; Ninfo et al., 2016; Teofilo et al., 2019; van der Meulen et al., 2020). Geomorphological structures were visualized using a hillshade of the DTM with contrast enhancement by two-fold exaggeration (Kokalj and Hesse, 2017). Furthermore, we used the *local cumulative cut stretch* to flexibly map different topographic areas. Smaller paths and trails can have a strong similarity to river channels in the DTM and hillshade. To distinguish them from each other, we used the OSM, where official roads and (sometimes unofficial) paths are marked. In addition, we included indications of unofficial trails or paths from the DOP. Relics of buildings or other construction structures were also excluded in this way (Schmidt et al., 2018). The mapping was carried out with three mapped classes based on the size and subjective distinctness of the structure (classes: strong, medium, weak visibility; see example in Fig. 2). We focused on the structural diversity that is directly related to fluvial dynamics: natural levees, crevasse channels and splays, meanders and oxbows and backflow channels (Beckenbach, 2016; Kirchner et al., 2018; Schirmer et al., 2005; Wierzbicki et al., 2013, 2020).

3.2.2 Georeferencing and Vectorization of Old Maps

The 20th century ordnance survey maps and the early 19th mileage sheets were digitally available as georeferenced raster layers (Fig. 3). We verified the accuracy and precision against additional geo data (DEM, OpenStreetMap, etc.). Only the early 17th century *Öder-Zimmermann* map had to be processed. We georeferenced this old map using the regressive-iterative GIS-reconstruction method (Hohensinner et al., 2013b) by using riverine structures (rivers and mill races), hydraulic constructions (weirs and mills) and infrastructure (roads and bridges) to project the maps onto a coordinate system in a Geoinformation system (QGIS) (see Tab. 1). The georeferencing procedure follows the standardized guideline incl. metadata storage (Schmidt et al., 2024). Following the principle "two steps back, one step forward" (Hohensinner et al., 2013b), both the ordnance survey and mileage sheets helped to determine the locations of these fixed points on the *Öder-Zimmermann* map for georeferencing. In this approach, one moves step-by-step back in time, in order to be able to validly use the fixed points and their location from younger maps to older maps. At the same time, the mapped features get revised from old to young. The vectorization of the rivers on the old maps was likewise carried out in a standardized form (Schmidt et al., 2024). For reasons of comparability, the rivers were drawn as lines (Tab. 2). As a result, we obtained several layers depicting the rivers at a certain point in time (for each old map one layer).

Table 2. Metadata structure of vectorized map elements. Table structure based on the template from (Schmidt et al., 2024)

Structure Type	Structure Type Reliability	Structure location Reliability	Dating	Dating Reliability	Realized or Planned	Description	Editor	Modification Date	Source ID	Scale
Rivers and mill races	certain, clear signature	certain	1939, 1941	terminus ante quem	realized	all flowing and standing waters	Sophie Lindemann	2024-07-30	LE614, LE615, LE631, LE637	1:25,000
Rivers and mill races	certain, clear signature	small uncertainty, due to georeferencing offset	1802-1806	terminus ante quem	realized	all flowing and standing waters	Sophie Lindemann	2024-07-18	LE642, LE643, LE644	1:12,000
Rivers and mill races	certain, clear signature	medium uncertainty, due to georeferencing offset	1586-1633	terminus ante quem	realized	all flowing and standing waters	Sophie Lindemann	2024-07-14	LE395	1:53,333

4 Results

4.1 Fluvial Geomorphology

In total, 1,306 geomorphological structures with an overall length of 116 km were mapped in the study area (Fig. 4A and 8). In particular, the central area between the Weiße Elster and Pleiße rivers shows a high density of structures. In contrast, the peripheral areas of the floodplain are more heavily modified due to anthropogenic use (park, recreational areas, building areas, infrastructure, etc.), so that *natural* fluvial structures often become blurry for recording purposes. The majority of all structures were found along the Paußnitz and the Pleiße rivers (Fig. 7). The percentage of structures with medium to weak visibility is the highest, whereas the relative amount of strong visibility structures is rather low (Fig. 6). The floodplain areas surrounding the Weiße Elster and Pleiße rivers are slightly elevated by 0.5 m compared to the central section of the Elster-Pleiße floodplain (Fig. 5). The central section is traversed by the Paußnitz and Batschke rivers.

4.1.1 Weisse Elster river

Although the floodplain area along the Weiße Elster river has a strong anthropogenic overprint, so that relatively few structures can be found (Fig. 4A), two sections stand out. At one location, the recent Weiße Elster river is enclosed by the Zickmantel Mill Canal (*Zickmantelscher Mühlgraben*) and the *Stille Wasser*, which occupy a former meander loop of the Weiße Elster river (Fig. 4B). Both have a distinct curved shape of an old river channel. The western part was part of the water supply for the Knauthain mill race. The canal begins west of the Weiße Elster river and flows northwest into the Knauthain Mill Canal, with a generally straight path. Between the canal and the Weiße Elster river, further meandering structures are visible, while upstream the Weiße Elster river follows a straight course, intersecting older channel features, mostly in forest-covered areas, with some in allotment gardens. Another interesting feature can be observed further south near Leipzig's *Windorf* district. Here, a loop structure touches the Weiße Elster river and is intersected by a small channel, suggesting this section as part of an older meander generation (Fig. 4B). The mapped structures along the Weiße Elster river are of strong visibility and are likely its former meanders. Most of these oxbows are filled with water today (oxbow lakes). Using GIS, the widths of the structures were assessed, ranging between 20 and 25 meters. The old oxbows exhibit typical meandering shapes, featuring steep cut banks and smooth point bars, showcasing natural riverine processes. Along the old meanders, natural levees can be found, indicating relatively low lateral dynamics. Additionally, at one location, remnants of a crevasse splay can also be found. The weak and medium visibility structures indicate rather small backflow channels. Though, the preservation due to anthropogenic alteration is rather poor.

4.1.2 Paußnitz river

Almost the entire Paußnitz floodplain area is forest-covered today. Due to its conservation-effect, the diversity and number of fluvial-geomorphological structures are therefore very high in the area (Fig. 7). Multiple former channel structures are visible. These structures connect to the current course, indicating an alignment over time (Fig. 3D). In the southern region, old meander

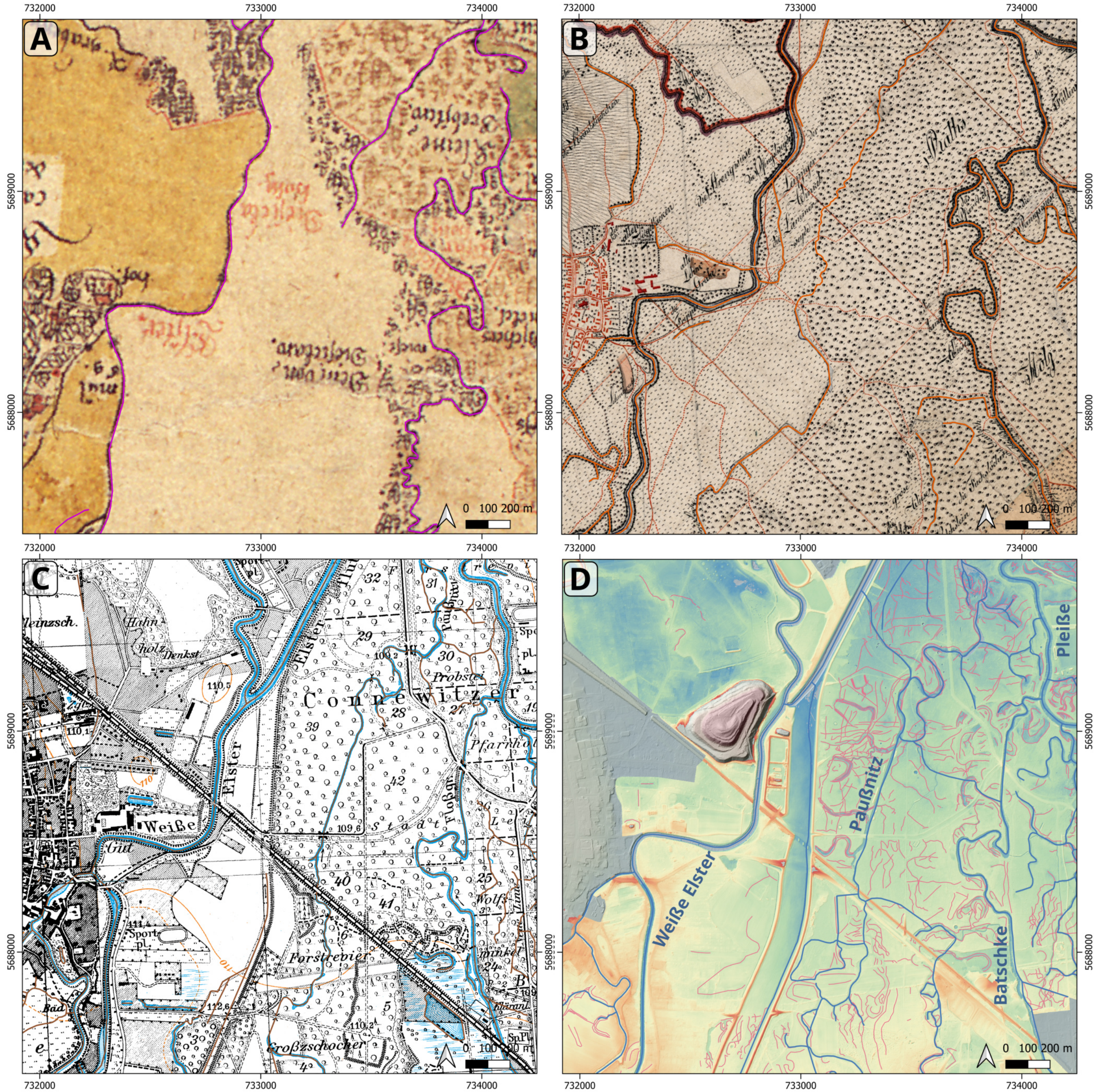

Figure 3. Sections of the study area with georeferenced old maps and the LiDAR DEM (Tab. 1 with vectorized rivers and channels (Tab. 2. A) *Öder-Zimmermann* (1585-1633 AD); B) *Meilenblätter von Sachsen, Berliner Exemplar* (1802 AD); C) *Messtischblätter* (1930 AD); LiDAR DEM with mapped fluvial geomorphologic structures. EPSG:25832

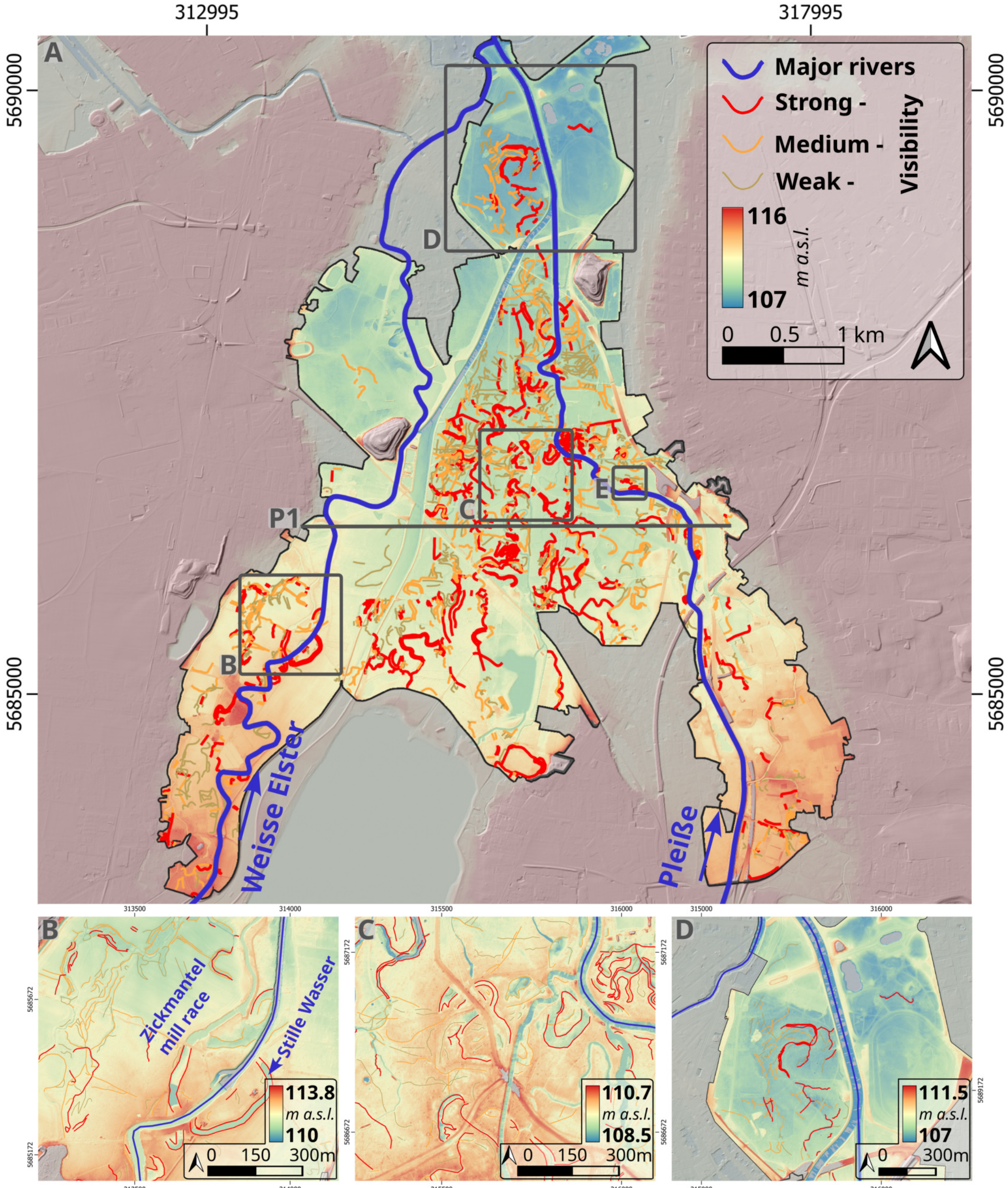

Figure 4. Classified vectors of geomorphological mapping based on the LiDAR DTM. A) Total study area with main tributaries. Positions of the enlarged sections are indicated with gray boxes. Location of topographic cross-section of P1 is shown in panel A. B) Enlarged section of the Weisse Elster river zone with remnants of palaeomeanders. C) Enlarged section of the Batschke zone with natural levees and oxbows. D) Enlarged section of the Pleiße river zone (post confluence with Batschke river) with remnants of palaeomeanders. The legend for vectors from panel A is valid to panel A-D. Location of panel E refers to Fig. 2. DEM in A-D by (GeoSN, 2018). EPSG:25833

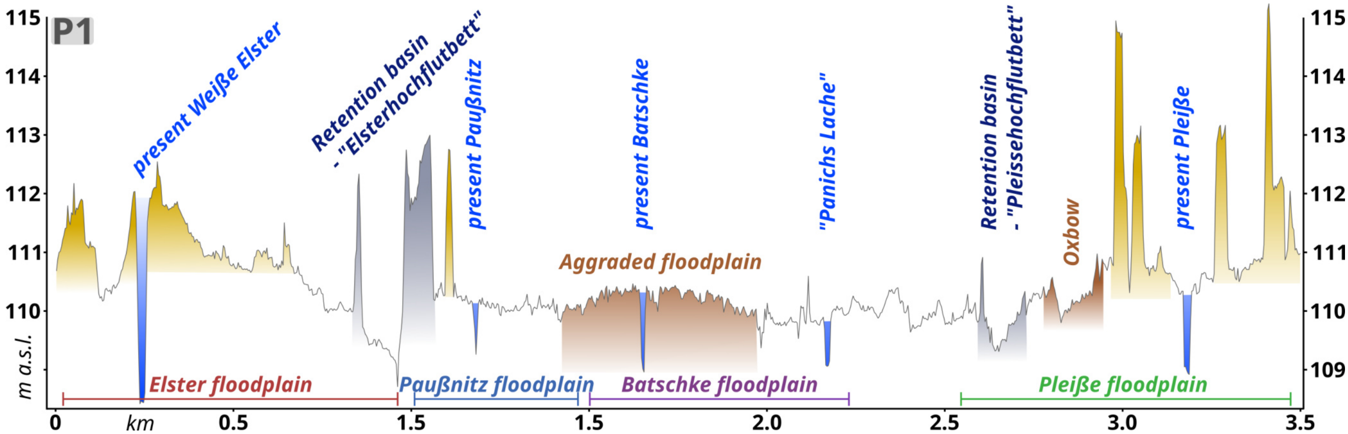

Figure 5. Topographic profile of the cross-section before the confluence of the tributaries based on the 1x1 m LiDAR DTM (GeoSN, 2018). The yellow color indicates modern infrastructure that alter the topography. The brown color highlights notable geomorphic features mentioned in the text. The location of the cross-section P1 is shown in Fig. 4A.

structures of the Paußnitz river are noted after branching from the *Lauerscher Grenzgraben* (20th century, artificial channel), indicating a complex historical trajectory. The general appearance of the Paußnitz is characterized by old meander structures, which also exhibit a point-bar morphology in many places. Large bends of the oxbows reveal steep cut banks and gentle point bars, with bed widths c. 21-22 m similar to the modern Paußnitz. A fan-shaped structure along the Paußnitz likely formed from a natural levee breach (crevasse splay). Natural levees can be found along all former meander structures, indicating relatively low lateral dynamics. At the same time, the point bar positions of the former meanders are characterized by a ridge-and-swale-structured relief, indicating active lateral dynamics before the formation of the levees. Historical interventions in the 20th century, influenced by mining and conservation efforts, shaped the current pathways, altering the river's natural flow and morphology. The Paußnitz originally drained into the Batschke river, which in turn drained into the Weiße Elster river, rather than its current path into the *Elsterhochflutbett*. In the 1970s, the Paußnitz's river course was modified due to lignite mining around what is now Lake Cospuden, leading to the destruction of its former course. Groundwater from the mine was directed into the Paußnitz's remaining northern section. Today, the *Lauerscher Grenzgraben* receives water from the Weiße Elster river and passes it through into the Paußnitz river.

4.1.3 Batschke river

Today, the Batschke river begins in the far south near the northern shore of Lake Cospuden, fed by the *Lauerscher Grenzgraben*. From there, it flows relatively straight northward, passing through the southern floodplain forest near Lake Lauer and connecting with it. Afterwards, it has some meander structures before flowing straight through the *Pfarrholz* forest and finally flows in a meandering pattern into the Pleiße river. The area between the Batschke and the Pleiße rivers is defined by the southern floodplain forest and an extensive network of unnamed ditches connecting the Batschke river to the Pleiße river, reaching

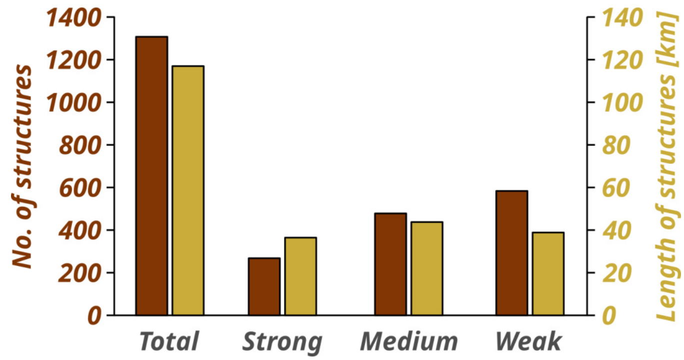

Figure 6. Stacked barplot with number and length of mapped fluvial-geomorphological structures according to their visibility class.

as far as the *Pfarrholz* forest near the Batschke's mouth. North of this confluence, further ditch systems are active and link to the Paußnitz river, which later drains into the Weisse Elster river. At the Batschke's confluence with the Pleiße river, a broad complex of channels with prominent meanders is visible (Fig. 4C). Furthermore, older structures appear intertwined, crossing paths with one another and also with the current Batschke river course, making it difficult to trace their connections. The most distinct feature is a loop structure directly south of the confluence. The main course of the Batschke river was modified into a timber-rafting canal in the early 17th century, with timber rafting ceasing in 1864. Since then, the Batschke river's remaining course has been a stable, straight channel. While meander-like bends are highly visible in the area, detailed ridge-and-swale structures are slightly lesser pronounced, likely due to the interference from very dense vegetation and thus a poorer digital terrain model. The subtle asymmetry of the cross-section and indistinct cut bank and point bars might indicate that this channel has undergone significant sedimentation after the meander structures were abandoned. Natural levees are clearly visible along almost all former courses of the Batschke river. Moreover, several crevasse splays and crevasse channels are recognizable, and overall, the entire area of the Batschke floodplain is vertically aggraded by up to 0.5m (Fig. 5). Besides the main course of the Batschke river, several smaller channel structures are visible. These structures vary in width, especially between the broader channels west of the Pleiße river and the narrower ones to the east, suggesting these may have been separate rivers that merged over time. This branching pattern resembles an anastomosing river system.

4.1.4 Pleiße river

In the southeastern study area, between Markkleeberg and the Leipzig district of Dölitz-Dösen along the Pleiße river, fewer structures were found. The Pleiße floodplain area is heavily influenced by human activity. Large areas are built up with buildings and infrastructure and are unsuitable for DTM analysis. As a result, hardly any structures are preserved, especially in the southern part of the investigation area. Only small backflow channels can be identified. An important hydrological influence is the branch of the southern Pleiße mill race (*Mühlpleiße*) from the Pleiße river to supply the Dölitzer mill with water. In the area where the Pleiße river enters the wide floodplain between the Weiße Elster and Pleiße rivers, smaller and larger former courses can be recognized. In the area of the present Pleiße river retention basin (*Pleißehochflutbett*), a large-scale meander loop with a

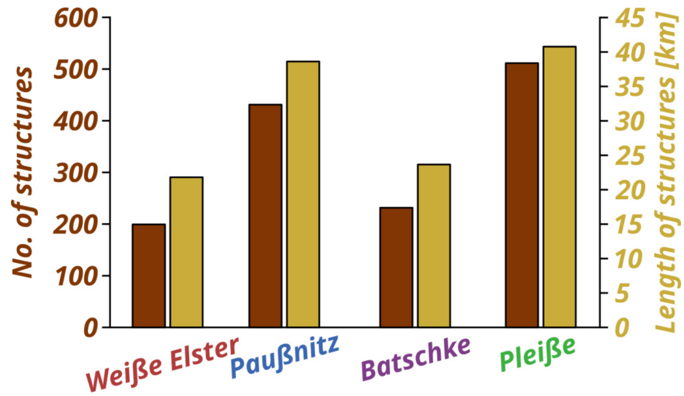

Figure 7. Stacked barplot with number and length of mapped fluvial-geomorphological structures according to their local drainage basin/tributary.

pronounced cut bank is preserved (diameter over 300 meters; Fig. 5). Smaller remnants of meander loops appear with varying intensity (Fig. 2). The area around the Batschke river confluence is outstanding for its dense network of structures that can also be seen on the eastern side of the Pleiße river. It indicates an additional inflow from a Pleiße branch or another river (Fig. 4C, northeastern part). Subsequently, the larger structures decrease to the north, and only smaller backflow channels can be seen. Generally, natural levees are not visible along the Pleiße river, and thus no crevasse splays.

4.2 Old Maps

It is easy to see in the ordnance survey maps from the 20th century that some river courses have been straightened (Fig. 3C). Those channels that have not been straightened show exactly the same meandering structures as the mileage survey (1802-1806) and the *Öder-Zimmermann* map (1585-1633). Hence, it was surprising to find that the 20th, early 19th and early 17th century maps show only slight movement differences instead of the expected river channel movements. Especially, position and shape of the meander bends are nearly the same on all maps. Minor offsets in the representation of the Weiße Elster and the Pleiße rivers are only evident at a few locations. They can be found in the southern part of the Weiße Elster and Pleiße rivers in the study area. Two meander bends seem to be more curvy in the mileage sheets, compared to the *Öder-Zimmermann*. Most of the recognizable differences can be traced back to historical anthropogenic influences. For instance, the *Elsterflutbett* is a newly added structure from the year 1928 on the ordnance survey map. This artifical retention basin is derived from the Weiße Elster river and led to the middle of the floodplain, where it meets another channel that is diverted from the Pleiße river. The Batschke river was converted into a raft ditch in early 17th century. On the *Öder-Zimmermann* map, the river has rather large meandering bends. The early 19th century mileage survey, however, reveals a redirection and straightening in parts of this stream for the purpose of timber rafting, whereby the older river course was abandoned. The Paußnitz river is depicted as a very short stream on the *Öder-Zimmermann* and is not drawn in the entire study area. In the mileage survey and the ordnance survey maps, this river is completely drawn. In the 19th century, the Paußnitz river was depicted as a slightly meandering

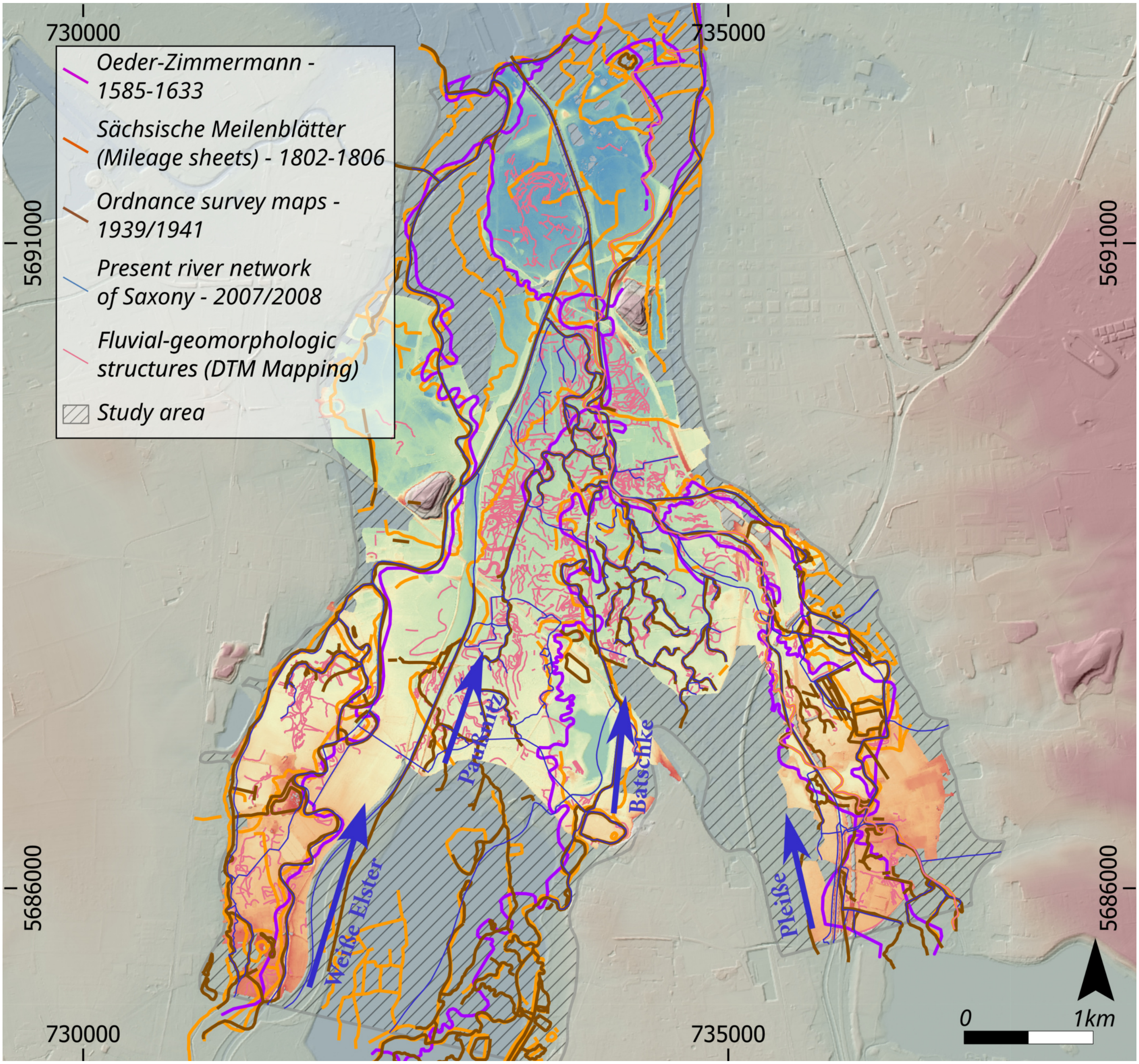

Figure 8. Study area with vectorized rivers and channels from the old map collection (Tab. 2). The geomorphological mapping based on the LiDAR DTM (see Fig. 3). EPSG:25832

river, whereas in the 20th century a straightened course is already recognizable. The quantitative analysis of river networks of all vectorized old maps shows a general decrease in the sinuosity of the main rivers (Weiße Elster, Pleiße, Batschke, and Paußnitz rivers) over time (see Table 3). The Batschke river has the highest sinuosities compared to the other main rivers (Fig. 9A). In general, the representation of smaller tributaries on the *Öder-Zimmermann map* is relatively sparse. The level of detail concerning the depiction of small side branches and tributaries increases over time, observed by decreasing values of the shares of main courses in the total river network.

Table 3. Sinuosities and river metrics based on the vectorized old maps.

Layer	Age	Sinuosity				River Section Lenghts [m]				Downstream linear distance [m]				Total river length [m]	Tributary river length [m]	Share of main watercourses in total network [%]
		Weiße Elster	Paußnitz	Batschke	Pleiße	Weiße Elster	Paußnitz	Batschke	Pleiße	Weiße Elster	Paußnitz	Batschke	Pleiße			
Öder-Zimmermann	1585-1633	1.49	NA	2.03	1.39	10547.85	NA	9625.10	9748.67	7068.16	NA	4745.89	7003.38	48301.03	18379.41	61.95
Mileage sheets	1802/1806	1.52	1.36	1.85	1.40	12234.02	4101.31	4772.82	10882.13	8052.01	3005.84	2579.23	7758.02	112342.03	80351.75	28.48
Ordnance survey maps	1939/1941	1.34	1.40	1.43	1.19	10648.66	7916.23	7596.13	7004.18	7959.05	5646.00	5313.12	5910.06	101747.28	68582.08	32.60
Present river network of saxony	2007-2008	1.37	1.37	1.29	1.11	10176.00	4614.09	3450.23	6088.21	7440.22	3367.90	2673.62	5493.70	90875.33	66546.80	26.77

5 Discussion

5.1 Reliability of old maps

The rivers, vectorized from old maps, show minor variations from each other (Fig. 8). Although georeferencing precision is not perfect, the shape and general positions of the river courses are comparable (Tab. 1). In addition, Zielhofer et al. (2022) have already worked with georeferenced historical maps and, despite slight georeferencing deviation, were able to understand changes in the river system through quantitative analyses. The elements in the *Öder-Zimmermann* map were measured field-based and represented using contemporary methods (Wiegand, 2014). Although trigonometric precision is not to be assumed, the internal positional accuracy of the map seems evident. The mileage sheets were produced under the direction of Friedrich Ludwig Aster as part of the electoral Saxon topographical survey (Zimmermann, 2006). No older maps were redrawn; instead, all landscape elements were newly measured using geodetic triangulation with a theodolite (Brunner, 2007; Walz and Schumacher, 2011). The new surveying of topography, as well as cultural landscape elements at the end of the 19th century/beginning of the 20th century, is based on the Prussian original survey (*Urmesstischblätter*) and was likewise newly recorded using triangulation and resulted in the Ordnance survey maps (*Messtischblätter*) (Walz, 2002; Lorek and Medyńska-Gulij, 2020). The maps utilized have been independently surveyed, ensuring that the georeferenced and vectorized river courses are distinct and autonomous.

The use of old maps as a basis for quantitative landscape reconstruction is a well-proven approach. In recent years, their use for reconstructing water landscapes has increased (Hohensinner et al., 2013a; Zlinszky and Timár, 2013; Zielhofer et al., 2022). In addition, the spatial-temporal resolution allows a detailed approach to landscape development (Hohensinner et al., 2013b; Werther et al., 2021b). With our approach, combining old map analyses with geomorphological mapping (DTM analyses), we provide a comprehensive understanding of river network changes over time. Old maps offer historical context and details about past geographical features, while DTMs provide precise topographic information. This combined approach allows for a detailed examination of the relative chronology of changes and helps identify topographic legacies left by dynamic floodplain systems, enhancing our understanding of the evolution of these landscapes.

5.2 Meander migration through time

Despite the construction of mill races in the Middle Ages, the river sections in the study area largely follow stable, quasi-natural courses over time (Fig. 8). Several studies were already able to derive past river courses from old maps and discuss them in a spatio-temporal context (Schielein, 2010; Hohensinner et al., 2013a; Elznicová et al., 2021; Werther et al., 2021b; Zielhofer et al., 2022). The accompanying natural levees in the present study indicate positional river course stability, and the mapped fluvial geomorphological structures reveal older meandering river courses. The older, more active anastomosing river system with meandering branches predates the oldest map (*Öder-Zimmermann 1585-1633*). In the catchment areas of the Rhine and the Danube rivers, two Holocene river terraces are known, which fall into the last 500 years (Schellmann, 1994; Schirmer et al., 2005; Schielein et al., 2011). This shows that significant lateral dynamics have been expected within the investigation period. Interestingly, the diversity and distinctiveness of the mapped fluvial-geomorphological structures have been preserved, indicating no massive sedimentation has occurred since. Physically, the movement of meanders is initiated by impulses acting on the banks (van de Lageweg et al., 2014). The erosion effect is therefore dependent on the stream power during flood events, especially during bankfull discharge (Kleinhans and van den Berg, 2011). Beside analysis of specific decades in the early modern period (Hardt and Lohse, 2025), there are no comprehensive data on the long-term flood history of the region. A high-resolution chronicle of historical flood events would be a prerequisite for a better understanding of stream power variability over time. At the same time, other variables affect effective lateral erosion. Sediment cohesiveness and thickness as well as an emergence of a protecting vegetation cover strongly influence the bank erodibility (Candel et al., 2018; Kleinhans and van den Berg, 2011). Although the stratigraphic record in fluvial systems is fragmentary (Durkin et al., 2018), quantitative analyses of preservation percentages of sediment facies over time in a meandering system can nevertheless be demonstrated (Elznicová et al., 2023). Chronostratigraphic studies 80 km south of the study area, both at the Weiße Elster and at the Pleiße rivers, show lateral dynamics of the Weiße Elster river for the last 400 years (Tinapp et al., 2019; von Suchodoletz et al., 2022, 2024). An increased meandering has been observed in other rivers of Central Europe for the last millennium (Candel et al., 2018; Elznicová et al., 2021). The decline of active meanders, in turn, is associated with increasing direct anthropogenic influence in different catchments (Vayssière et al., 2020; Elznicová et al., 2021, 2023). Especially weirs and other structures of hydropower use are discussed to prevent the activation of the hydrodynamic system (Buchty-Lemke and Lehmkuhl, 2018; Vayssière et al., 2020). In our study area, rivers that did not have specific hydro power facilities (weirs, mills, etc.) were also affected by the decline of active meanders (Batschke and Paußnitz rivers). However, there is a potential for indirect influence via the connectivity with neighboring associated waters through the anastomosing river system. The aggradation of cohesive sediments is an important factor for the decline of an active meandering river in the study area. The sedimentary unit's (overbank fines) thickness significantly influences its cohesiveness and susceptibility to lateral erosion Grabowski et al. (2011). The study area typically has 2.5 m thick fine-grained floodplain deposits (Graubner and Schmidt, 2025), with the floodplains of the White Elster river and its tributaries Batschke and Paußnitz rivers characterized by thicker deposits than the Pleiße floodplain. A medieval colluvium, which lies in the convergence area with the floodplain of the White Elster riverand is subsequently covered by overbank fine sediments, provides an initial clue for the chronostratigraphy (Tinapp et al., 2008). In the last 1000 years, approximately 1 m of alluvial clay has been deposited. This means that for the beginning of the study period (400 years ago), an overbank fine sediment thickness of 1.5 to a maximum of 2 m must be accounted for. Another factor is the grain size distribution, notably the clay content (Grabowski et al., 2011). The overbank fine sediments in the Leipzig Basin are characterized by loamy clays, with clay contents up to 50% being common (Neumeister, 1964; Kirsten et al., 2022). The oldest floodplain deposits show a very clayey sediment but are covered by siltier sediments (Neumeister, 1964; Händel, 1967). Generally, the clay contents increase in the stratigraphies in the younger deposits. However, when the clay content exceeds 50%, an increase in erodibility is possible again (Grabowski et al., 2011). Consequently, the sediments within the study region exhibit good conditions regarding bank stability. Stabilization of river courses is possible through decreasing erodibility due to gradually increasing clay content and increasing thickness over time. The influence of sediment supply from the catchments plays a significant role for the delivery of overbank fine sediments over time (Houben et al., 2013; von Suchodoletz et al., 2024). The mid-mountain range of the Weiße Elster catchment is susceptible to soil erosion due to increasing deforestation

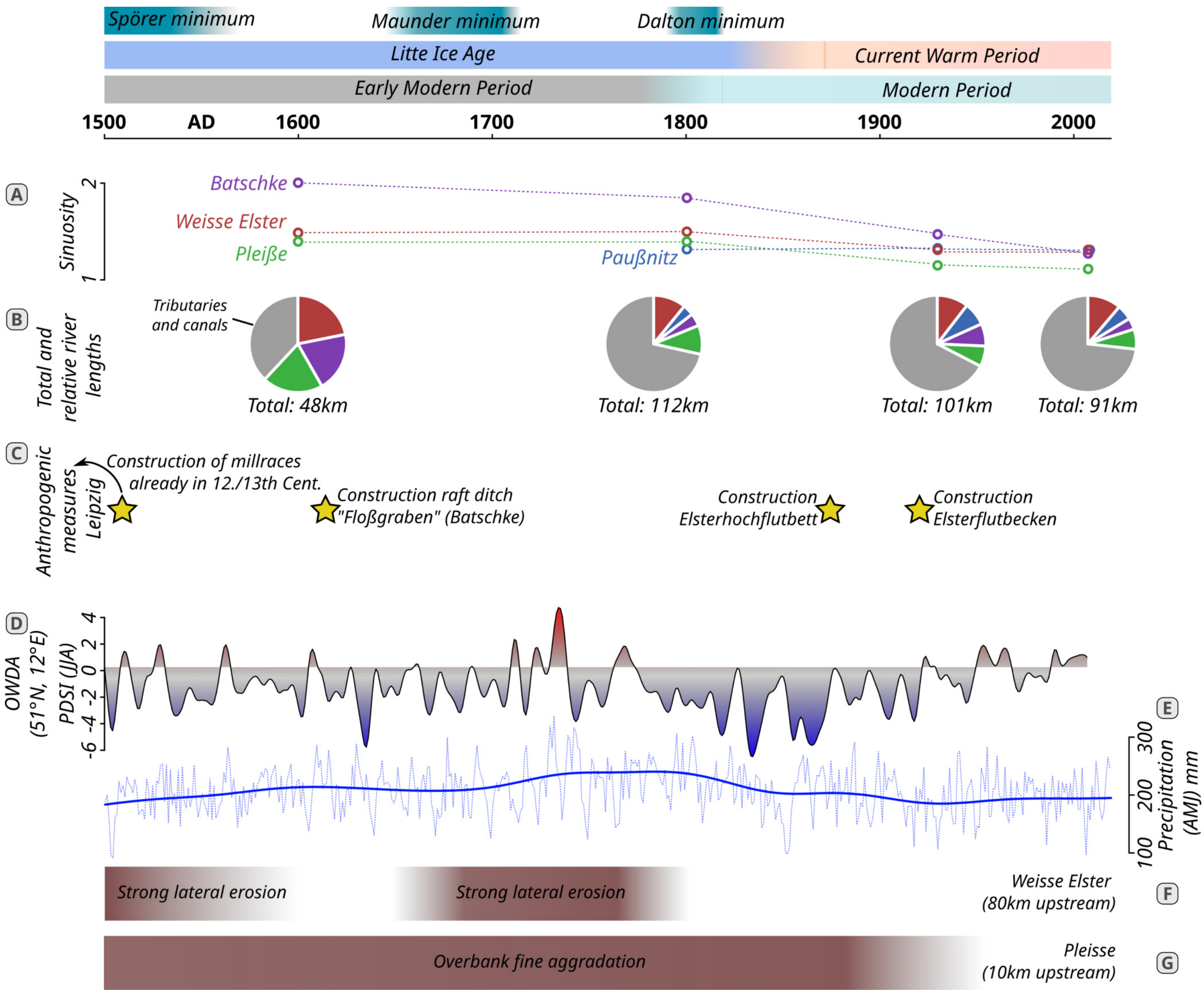

Figure 9. Timeline of quantitative river network changes in the study area and comparison with main anthropogenic alteration of the river network, palaeoclimatological data and fluvial geomorphological pattern. A) Sinuosity of the four studied rivers based on the old map mapping (Tab. 3), B) Total and relative river lengths and further small stream values (Tab. 3), C) Main anthropogenic hydro measures in the study area, D) Drought severity index from the Old World Drought Atlas (Cook et al., 2015), E) Spring precipitation reconstruction (Büntgen et al., 2011b), F) Fluvial geomorphological pattern of the Weisse Elster river (c. 80 km upstream of the study area) (von Suchodoletz et al., 2022, 2024), G) F) Fluvial geomorphological pattern of the Pleiße river (c. 10 km upstream of the study area) (Tinapp et al., 2019).

since the Middle Ages (Kaiser et al., 2023; Feeser et al., 2024). Colluvial deposits have formed since the 15th century and indicate sediment supply from the slope to the tributaries (Kaiser et al., 2021).

5.3 Hydro-climatic variability

Hydro-climatic variations significantly impact riverbank erosion, with factors such as stream power and the accents of precipitation or spring snowmelts playing critical roles. During the Medieval Warm Period (950–1250 CE), temperatures were about 1–1.5°C higher than today, whereas the "Little Ice Age" (LIA, 1500–1800 CE) was a period marked by colder and wetter conditions, followed by the "Modern Optimum" characterized by rising temperatures due to industrialization (Mann, 2002; Herrmann, 2016). Regional reconstructions based on tree-ring growth models provide insights into Central Europe's climate history (Büntgen et al., 2011a), but there are no specific hydro-climatic reconstructions for the Leipzig region over the last 500 years. For the Little Ice Age, studies indicate maximum summer precipitation, contrasting with the Old World Drought Atlas, which shows increased, rather short-term, summer droughts for the same period (Büntgen et al., 2011b; Cook et al., 2015). A regional speleothem record from southern Germany follows the precipitation reconstruction from tree ring analysis (Kluge et al., 2023). However, the climatic impacts of the LIA in Central Europe are discussed to be generally variable (Wanner et al., 2022). Floodplain sediment archives from Central Germany reveal both lateral erosion and overbank sedimentation phases during the Little Ice Age (Tinapp et al., 2019; von Suchodoletz et al., 2024) (Fig. 9). Moreover, a meta-study of several German river catchments shows relatively high river activities for the last centuries (Hoffmann et al., 2008). In a pan-European context, the sedimentological data show that the rivers do not behave uniformly; rather, the response to climatic changes of the Little Ice Age (LIA) is spatially highly variable (Rumsby and Macklin, 1996; Brown, 2002; Pears et al., 2023).

5.4 Chronology of river use

Different phases of floodplain and river use can be distinguished in Leipzig. Since the 10th century, the early urban agglomeration of Leipzig emerged as a stronghold on a ridge near the confluence of Pleiße, Weiße Elster and Parthe rivers. This castle secured the route over the rivers to the important Merseburg (Hardt, 2015; Hardt and Lohse, 2025). The floodplain served as a resource for both timber and food and water supply. Leipzig's monasteries were established before the 13th century (Bünz, 2015). It is likely that these monasteries developed the water engineering measures to build the mills with the help of weirs and mill races (Hardt and Lohse, 2025). The construction of the mill races for the water supply of the city mills dates between the 12th and 13th centuries (Grebenstein, 1959, 1995; Hardt and Lohse, 2025). The mills further south, which are connected to the Pleiße and Weiße Elster rivers via the *Mühlpleiße* and *Knauthainer Elstermühlgraben*, also date back to this period (Cottin, 2015b; Gornig, 2023). However, the construction of the nun mill (*Nonnenmühle*) by the nunnery of St. George is the only mentioned in Leipzig's sources in 1287 (CDS II 10, No. 23, p. 16). The alluvial forests further away from the city are mainly owned by the monasteries *Augustiner-Chorherren-Stift zu St. Thomas* and the nunnery of St. George (Gornig, 2023). Under these orders, these forests were likely to be more protected from over-exploitation. For example, St. Thomas obtains an injunction against the city council in the year 1373 regarding citizen's unlawful cutting of wood in their forests (CDS II, p. 109ff.). Major river transformations of the Weiße Elster and Pleiße are therefore likely to have been completed by the 13th century. The next phase of larger changes to the rivers was initiated in the 16th century, when the *Elsterfloßgraben* was developed. The use of the forests near the city exceeded the timber supply, which is why other sources further upstream were used to transport timber (Denzer et al., 2015). These developments resulted in the construction of the rafting ditch that reached Leipzig in the early 17th century, when the Batschke was converted into a straighter canal (since then called officially *Batschke-Floßgraben*) (Andronov et al., 2005).

The evolution of the Paußnitz is rather difficult to understand. This river is mentioned as a part of a forest and was therefore owned by monastry of St. Thomas (CDS II 9, No. 108, p. 86). On the nun miller survey of 1682 (by H.B. Kärtzer; Tab. 1), the Paußnitz is not shown as a river at all, but as a wetland in the *Probstei* forest (Fig. 10). On the *Öder-Zimmermann* map it is a rather short river, and not completely depicted. Therefore, it indicates that the Paußnitz river, compared to other water bodies, had a lesser significance as a discrete flowing water body. The specific fluvial structures from the geomorphological mapping show, however, that the Paußnitz was a dynamic watercourse in the past. The first written mention could have been in 1349 as *fluvius ... Pustenicz* (Greule, 2014; Eichler and Walther, 2010). The name is probably derived from the Slavic word *pusty* for *barren, wild* . On the *mileage sheets*, the toponyms *Schwarze Lache* and *Schwarze Lagge* (black puddle) can be found in the area of the Paußnitz river course, which indicates that the Paußnitz river did not constantly carry water every year, but rather reflects a wetland with oxbow lakes or backflow channels with still water characteristics. This corresponds to the representation in the nun miller suvey map, which shows rather a wetland than a discrete river course (Fig. 10). At the same time, there are strong indications from geomorphology of an active, dynamic course of the Paußnitz river before that shows an active meandering behaviour (Fig. 4). On the 19th century maps, it appears to be a canalized stream (Fig. 8). We assume that this river changed its dynamic over time and only had a fixed river channel in the 18th century. Overall, the significant phases of river modifications were before the 13th century regarding the hydro power and in the early 17th century regarding timber rafting (Fig. 9C). The use of the rivers to power the mills, and the floodplain forests to feeding cattle and supply wood were the drivers behind these major transformations. Regarding the river network, in the late 19th and early 20th century, significant influence was exerted as flood protection measures and straightening actions at a high technical level completely changed the water network structure (Haase and Nuissl, 2007; Berkner, 2018). This, among other things, resulted in a decrease in the total water body lengths (Fig. 9B).

5.5 River stabilization by anthropogenic measures

In addition to sedimentological constraints, anthropogenic measures on rivers can also play a role in the stabilization of rivers in the southern Leipzig area. The Leipzig floodplain has been used for a long time, and widespread human intervention is therefore to be suspected at least since the beginning of the Middle Ages, although there have been isolated finds in the floodplain since the Neolithic period (Liebmann, 2023). European-scale studies show the use of bio-engineered wooden structures for riverbank protection since the 19th century (Evette et al., 2009). However, eighteenth-century hydraulic engineers already discussed several measures of bank stabilisation, including the planting of river banks and the use of wooden structures (Silberschlag and von Hohenthal, 1756). Regarding pre-industrial riverbank protection, there is archaeological evidence from the Rhine, where large-scale protections using stone packings and wooden stakes were found as early as antiquity (Gerlach et al., 2016). Along the Main and further rivers in Southern Germany, there is already evidence of riverbank protection using wooden stakes since the High Middle Ages (Becker and Schirmer, 1977; Pfäffgen and Weski, 2024). However, both rivers are navigable and thus

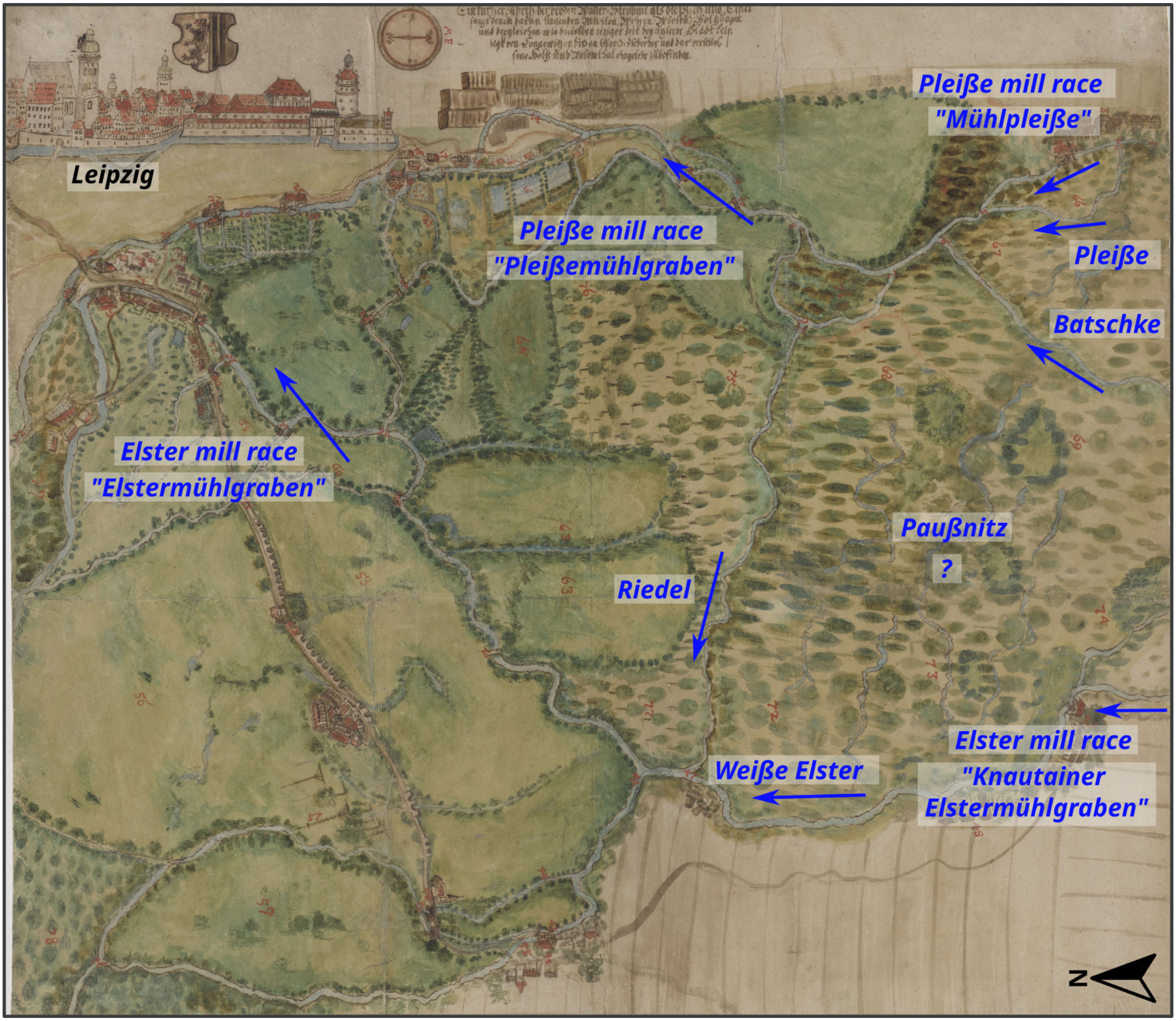

Figure 10. Map of the nun miller H. B. Kärtzer 1682 (see Tab. 1), modified.

subject to different economic significance. Furthermore, the construction of riverbank protection and its capacity is dependent on the economic and organizational strength of the owners (Gerlach, 1990). Monastic ownership is considered very likely for riverbank protection measures. Most of the lands in the study area belonged to the Leipzig monasteries until the Reformation, making specific riverbank protection measures probable (Gerlach, 1990). Technically, fascines (bushes and shrubs held together with willow wickerwork) are well known (Pfäffgen and Weski, 2024). Another example of river-related protective measures is the regulation of fish ponds along the city-close Pleiße. Measures of damming the Pleiße river close to the city and fishponds with willows can be seen in sources from around 1500 (CDS II 9, No. 366, p. 363; CDS II 8, No. 481, p. 402). In 1475, fishermen were granted the right to fish in the holes in the south-west of the city, which were left over after the removal of the brick earth and happened to carry water. This water was held permanently with the help of willows. In 1503, the monastery of St. Thomas argued against the city council of Leipzig that the willows planted in the *wild waters* (Pleiße) were washing away their meadows. Despite these findings, it is not clear to what extent riverbank protections have been installed along smaller rivers and outside the direct urban environment. Further research is needed here. On the old maps, since the 17th century, rows of trees can be seen along the river (Fig. 10). It is likely that these trees are willows, as this genus can grow well in moist locations and can cope with standing water for an extended period of time. These willows can be seen also on most of the land surveys (e.g. mileage sheets) and sketches of the time (Fig. 3). Willows along the rivers stabilize the banks through their roots and thereby protect the banks from lateral erosion (van Splunder et al., 1994; Makaske, 2001). Furthermore, the historical practice of planting willows along riverbanks, as observed in old maps, served as a noteworthy economic utilization of these areas, which were not suitable for other land uses due to the wetland conditions (Burggraaff, 2021). This strategy allowed for the harvest of willow wood, used for firewood and wickerworks.

6 Conclusions

This study demonstrates that the Elster-Pleiße floodplain has experienced a marked transformation from a naturally dynamic riverine system to a largely stabilized floodplain. While natural hydroclimatic variations influenced past meandering and sedimentation processes, human interventions have played a predominant role in constraining channel mobility. The introduction of mill races, artificial canals, and flood control infrastructure significantly altered the hydrological connectivity and sediment transport within the floodplain. Historical map analyses show that river stabilization began as early as the Middle Ages, with intensified modifications occurring during the 17th to 20th centuries. The transition from an anastomosing to a more rigid fluvial system coincided with increased clay deposition and vegetation stabilization along riverbanks, further reducing lateral erosion. Despite these alterations, remnants of older geomorphological features remain identifiable, offering valuable reference points for ecological restoration. Future management efforts should consider the historical floodplain configuration to inform sustainable conservation strategies and enhance flood resilience. By integrating historical cartographic evidence with modern geomorphological analysis, this study underscores the importance of historical perspectives in contemporary floodplain management and river restoration.

Code availability. Not applicable

Data availability. Data available on request from the corresponding author

Code and data availability. Not applicable

Sample availability. Not applicable

Video supplement. Not applicable

Appendix A

A1

Author contributions. JS (Conceptualization, Methodology, Funding acquisition, Software, Formal analysis, Data curation, Investigation, Visualization, Writing - original draft, Writing - Review and editing), SL (Conceptualization, Methodology, Software, Formal analysis, Data curation, Investigation, Writing - original draft, Writing - Review and editing), FG (Data curation, Investigation), MHe (Investigation, Writing - Review and editing), NL (Data curation, Writing - Review and editing), JSF (Funding acquisition, Writing - Review and editing), MH (Funding acquisition, Writing - Review and editing).

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Disclaimer. Not applicable

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