Ecohydrological changes and potential Salmon habitat suitability since pre-industrial times at the Mulde River (Germany)

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Abstract. Channel patterns and river connectivity are widely recognized to be an integral descriptive parameter for the geomorphic behaviour and ecohydrological properties of rivers. They are sensitively affected by climate and land-use changes and, in turn, can indicate the habitat suitability for the aquatic fauna, i.a. expressed by the diversity of channel width, flow velocity and depositional regimes. Both, habitat potential and the overall river connectivity are additionally influenced by barriers such as weirs and dams, at least since Medieval times. Here we present the results of a multi-temporal study investigating river morphology, river connectivity and floodplain land use in the Mulde River system. The study is motivated by the local extinction of the Atlantic Salmon *(Salmo salar)* within the last two centuries and low-success reintroduction endeavours. In order to test for a relation to water body structures, we make use of old maps ('Sächsische Meilenblätter', 1780-1821; 'Von Deckersche Quadratmeilenblätter', 1816-1821) to pinpoint (i) historical barriers and (ii) historical floodplain land use as a pollution proxy that may have affected migratory fish populations. Furthermore, we (iii) evaluate anthropogenic changes in channel patterns assuming that these also influence salmon habitat suitability. Preliminary results point to a negative relation between an increasing number of cumulative barriers, increased floodplain land use and the occurrence of salmon populations during the past. Sinuous and meandering channel patterns correspond with higher probabilities of salmon occurrence.

1 Introduction

1.1 Ecohydrological downturn in rivers

Rivers are hit particularly hard by the global biodiversity crisis. Hereby, migratory fish populations are among the species most affected by a decline in biodiversity worldwide (He et al., 2019; Sayer et al., 2025). Even before the major river regulations of modern times, people intervened in river structure and floodplains and tried to adapt them to their needs. For the benefit of transport, hydropower, food and water supply, artificial features were implemented, for example in the form of bridges, weirs and locks, as well as hydraulic engineering measures such as bank reinforcements or dikes (Holbach and Selzer, 2020; Mauch and Zeller, 2008). The hydraulic connectivity of the rivers was increasingly reduced, and pollution and overfishing often led to a significant decline in migratory fish populations (Bartosiewicz et al., 2008; Galik et al., 2015; Haidvogl et al., 2015). Regarding the Elbe River as a first order river system in Central Europe, the mid-20th century saw the extinction of the Elbe salmon (*Salmo salar*), following a long-lasting abundance decline in previous times (Andreska and Hanel, 2015; Bauch, 1958; Wolter, 2015). After decades of complete absence, the Saxonian state fishing authorities launched a still ongoing reintroduction programme starting in the 1990s (Füllner et al., 2004b).

1.2 Salmon habitat suitability and water body structure

Salmon populations are affected by river connectivity and habitat suitability. Depending on its life stage, the salmon has different habitat requirements (Füllner et al., 2004a): Salmon requires a gravel bed for spawning (Geist and Dauble, 1998). Its eggs have a long development period of approx. 180 days and during this time are sensitive to changes in bed shear stress or shear forces that can be caused by floods (MUNLV, 2006). This effect can be intensified by anthropogenic river straightening or by severe incision (Aruga et al., 2023). Straightening in particular prevents the self-regulation of the watercourse during floods (Newson and Newson, 2000). Young salmon prefer waters with a low proportion of fine sediment. An excess of fine-grained sediments may clog the spaces between pebbles and boulders, thus reducing the availability of hiding places in their nursery habitats (Armstrong et al., 2003). Increased sediment mobilisation, e.g. through increased flow velocities, is unfavourable at this stage. The yolk sac larvae of the salmon require riffles for their development. These are shallow sections with turbulent currents. Even at high water, young salmon like to move into shallow water at the edge of rivers. If these areas are missing, e.g. in deeply incised rivers or areas that have been anthropogenically straightened or dammed, this is also unfavourable for the establishment of salmon. From the final freshwater (parr) stage onwards, salmon prefer deeper, stronger flowing areas. When the adult salmons are later ascending upstream again to spawn, they wait in deep pools for the onset of spawning maturity. It is important that a river has all these diverse areas downstream (Armstrong et al., 2003), but the distance between the individual areas must not be too high so that the larvae can still reach them (MUNLV, 2006).

Narrowing of the river cross-section or abrupt changes in gradient lead to abrupt changes in flow conditions (laminar/turbulent) and increased erosion capacity. However, subsequently installed barriers such as weirs can also have this effect (Downward and Skinner, 2005; Fehér et al., 2014; He et al., 2024; Meybeck and Vörösmarty, 2005). In natural river systems, the interplay of river bed characteristics, cross-sectional profile, ground plan pattern and bed gradient leads to self-regulation; artificial changes unbalance this.

The longitudinal richness and heterogeneity of river structure therefore has a direct impact on migratory fish populations. It i.a. regulates flow velocities, riffle-pool distributions, riverbed substrates and the access to thermal refuges, the latter preventing heat stress (Dugdale et al., 2015; Ebersole et al., 2003). However, the overall riverine structural diversity has suffered from the construction of barriers and river embankments as well as from the homogenization of the discharge (Clavero and Hermoso, 2015; He et al., 2024). To mitigate this development, the EU installed the European Water Framework Directive as a political instrument facilitating both the documentation and improvement of the habitat suitability and river connectivity. In general, it aims to restore and maintain a good physico-chemical condition of all EU-wide ground- and surface water bodies (Hering et al., 2010). The operational analysis method for this is the assessment of water body structure based on on-site surveys and map evaluation (Zumbroich and Müller, 1999).

1.3 River pollution and effects on salmon populations

Apart from their specific structural habitat requirements, salmons react most sensitively to the chemical water quality, as well. Juvenile salmons imprint on the chemical and olfactory signature in their natal river thus providing the adult fish with an orientation cue during their upstream migration for spawning (Bett et al., 2016). Changes in the chemical composition of the river water might lead to a confusion of this homing mechanism and an avoidance of the natal river (Saunders and Sprague, 1967). Furthermore, exposure to river pollutants such as heavy metals (e.g. from mining activity) and organic contaminants (e.g. from agricultural practices, municipal and industrial effluents) even in fairly low, i.e. sublethal concentrations pose a threat to the livelihood of salmons in multiple ways: Among them are growth impairment, disruption of the sensory system, as well as reduced predator avoidance and reproduction rates (Cobelo-García et al., 2017; Dubé et al., 2005; Hecht et al., 2007; Morán et al., 2018; Ross et al., 2013; Sauliutė and Svecevičius, 2017). In addition, organic pollutants and nutrient inputs may cause the depletion of oxygen in the water, another parameter salmons have particular requirements for (Armstrong et al., 2003; Manitcharoen et al., 2020; Sánchez et al., 2007).

1.4 Historical perspective of the ecohydrological downturn of rivers

The impact pattern of migratory fish populations, habitat suitability, and pollution can be understood from an actualistic perspective. However, not much is yet known about how intensively human influence affected habitat suitability and pollution and therefore also migratory fish populations in the past. Indeed, this knowledge is important in order to better understand the current reintroduction projects and possible setbacks. What is the baseline of the natural river habitat and how have disturbances developed over time in river systems on the way to the fluvial anthroposphere (Werther et al., 2021)?

In order to identify the natural baseline of the water body structure, it is advisable to reconstruct the **historical channel pattern of preindustrial rivers** using old maps, often being the sole source of exploitable information for that time (Hohensinner et al. 2021; Witkowski, 2021).

In order to assess the potential for historical river pollution in floodplains, the reconstruction of **historical floodplain land use** is an initial proxy parameter. Agronomic and other intensive forms of land use in floodplains have direct consequences on nutrient inputs into rivers (Krause et al., 2008) and they also act as a source of suspended river sediment (Yu and Rhoads, 2018) that have adverse effects on the spawning success and juvenile vitality of salmons (Armstrong et al., 2003). Urban and industrial development, crafts and manufacturing in the floodplain correspond to the discharge of residential and commercial wastewater (Derx et al., 2016; Español et al., 2017; Lyubimova et al., 2016). Historical mining activities have a significant influence on pollutant input into rivers, especially in low mountain river catchments (Mills et al., 2014; Resongles et al., 2014). While the mines themselves are usually located outside the floodplain, secondary structures for ore processing, as well as spoil tips or mining settlements are often positioned directly within the floodplain or at its margins (Cembrzyński, 2019; Derner et al., 2024; Knittel et al., 2005). Furthermore, flooded adits and shafts in former mining districts often have a direct connection to ground- and/or surface waters in the floodplain (Bozau et al., 2017; Greif et al., 2008).

Fish population in the past, especially migratory fish, can be reconstructed in various ways, e.g. based on zoological remains (Schaal et al., 2020), written sources (Andreska and Hanel, 2015) or biomolecular approaches such as sedimentary DNA (Brown et al., 2018). For the Elbe River catchment, only written sources do currently allow for a large-scale analysis. Because of their fishing rights reserved for the nobility and their associated cultural significance, migratory fish such as the Atlantic Salmon are often named in archival records, early writings of modern natural history (Kentmann, 1549) but also in more recent fishing reports (Füllner et al., 2004b; Wolter, 2015). Historical data on migratory fish can therefore be used as a proxy parameter for historical aquatic biodiversity (Haidvogl, 2013; Haidvogl et al., 2015).

1.5 Aim of the study

A) In order to develop a basic understanding of historical river connectivity and habitat suitability, this study aims to initially compile a systematic, quantitative data set covering the spatial and temporal development of channel patterns, floodplain land use, and barriers for the Mulde River system since the onset of the 19th century. The Mulde River system is part of the Elbe River system and was selected for this pilot study due to its high diversity in natural channel patterns. Floodplain land use serves as a proxy parameter for human impact and the corresponding potential for floodplain pollution. When it comes to the parameters, we would like to focus in particular on the methodological development and thus also show the resulting perspectives and limitations.

B) According to the historical Atlantic Salmon presence in the second order Mulde River system and first order Elbe River system, this study builds up an initial open access data base on modern and historical salmon catches. The data acquired using secondary historical sources are spatialized for the Mulde and Elbe River systems applying a semi-quantitative grid approach (Clavero and Hermoso, 2015; Zielhofer et al., 2022) and are compared with the historical water body structure parameters.

C) Finally, our goal is to carry out a critical assessment of the previous results and to highlight research perspectives for further development.

2 Study Area

2.1. Catchment hydrology of the Mulde River

The Mulde River (‘Vereinigte Mulde’), situated in Eastern Germany, is among the largest tributaries within the Elbe River system (Fig. 1). It forms at the confluence of its branches Zwickauer and the Freiberger Mulde. Both of the latter and their major subordinate tributaries (e.g. Chemnitz, Zschopau) originate in the Ore Mountains (‘Erzgebirge’). The Mulde River flows through the Leipzig lowland basin (Decker, 2014) and at Dessau-Roßlau joins the Elbe River (Fig. 1). It has an overall catchment area of 7345 km^2 and a length of 147 km (plus a length of 167 km and 124 km for the Zwickauer and Freiberger Mulde before their confluence, respectively). From headwaters to the mouth of the Mulde River, stream gradients range from ca. 14 to 0.3 ‰ (Otto and Mleinek, 1997). Its flow regime is dominated by snowmelts in the Ore Mountains so that discharge maxima usually occur in March/April and minima in autumn. In deviation from this pattern, extreme flooding more likely happens in the summer season, when the mean discharge values of ca. 70 $m^3\ s^{-1}$ can be exceeded many times over (approx. 2500 $m^3\ s^{-1}$ in August 2002) (Vetter, 2011b).

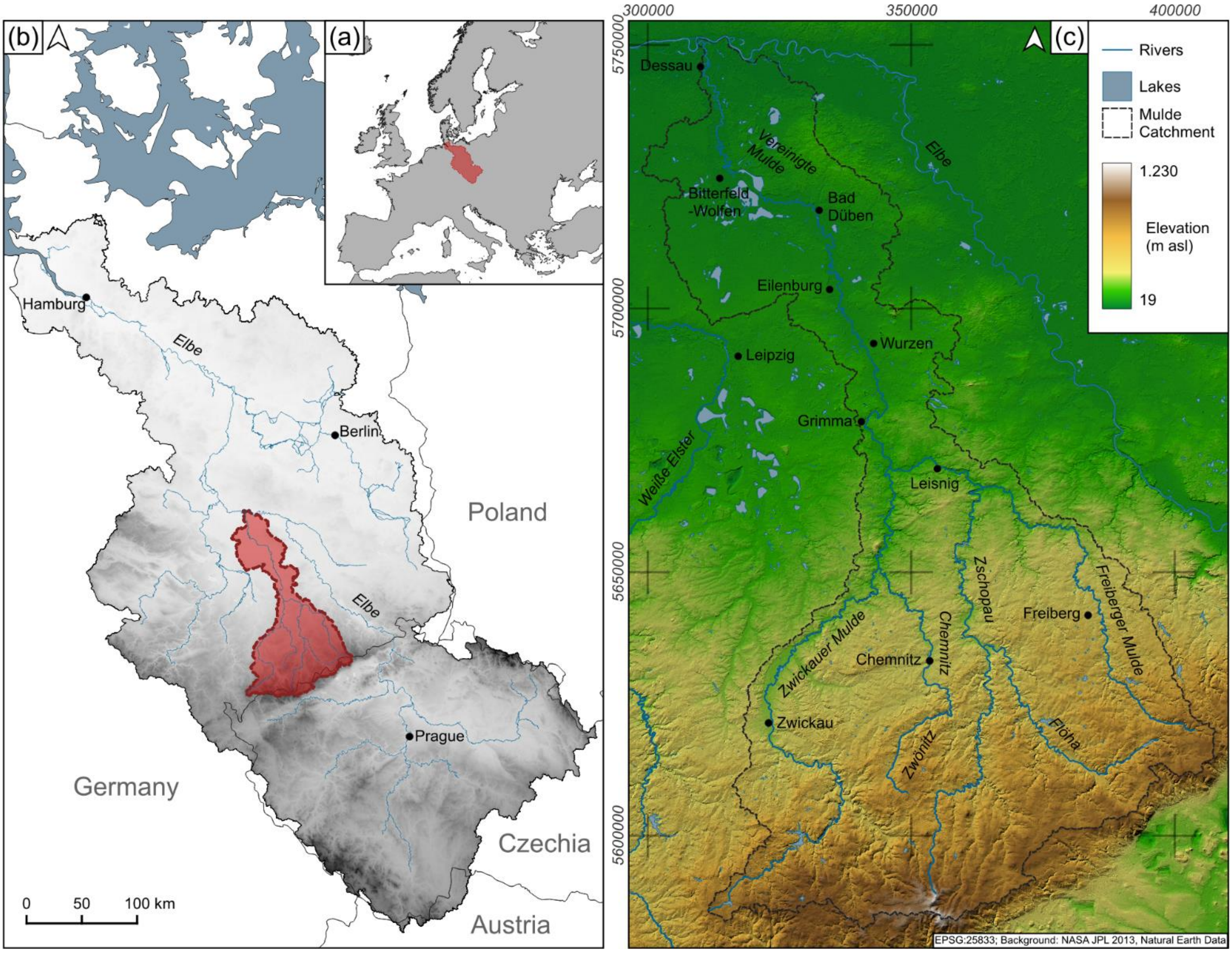


Fig. 1. Mulde River system (study area) as part of the Elbe River system (a) Elbe River catchment within Central Europe. (b) Elbe River system with major (Strahler ≥ 5) tributaries and the Mulde River study area (red). (c) Mulde River study area with major tributaries and places mentioned in the text.

2.2 Geology

The headwaters of the Mulde River system are located in the ridge area of the Ore Mountains (highest elevation: Klínovec, 1244 m asl). They were formed during the Variscan orogeny and mainly consist of Palaeozoic, highly metamorphic and magmatic rocks (Ulrich, 2013). Structurally, the Molasse Basin (‘Erzgebirgsbecken’), the Granulite Mountains and the Saxonian Volcanite Complex are also a product of the Variscan orogeny or its direct aftereffects and are dominated by conglomerates, granulite and rhyolite, respectively (Fig. 2). After an applanation in the Permian, Tertiary intra-plate tectonics affected the aforementioned units and created a fault-block that was uplifted and tilted to the northwest. This resulted in a gently-inclined low mountain area with rather uniform relief features apart from the varyingly-deep incised river valleys (Wagenbreth and Steiner, 1990).

In the lower course north of Wurzen, the landscape is characterized by unconsolidated sediments from the Tertiary (marine and fluvial deposits, lignites) and Quaternary (mainly glaciofluvial sands and glacial tills from the Elsterian and Saalian) (Eissmann, 2002a, b).

The Holocene floodplain of the Mulde River features gravel beds and fine-grained overbank deposits in the lower and middle course. These overbank deposits have been largely supplied by historical and pre-historical land use-driven soil erosion in the ore mountains and corresponding forelands (Vetter, 2011b; Tinapp et al., 2008; 2019; Ballasus et al., 2022; Derner et al., 2024).

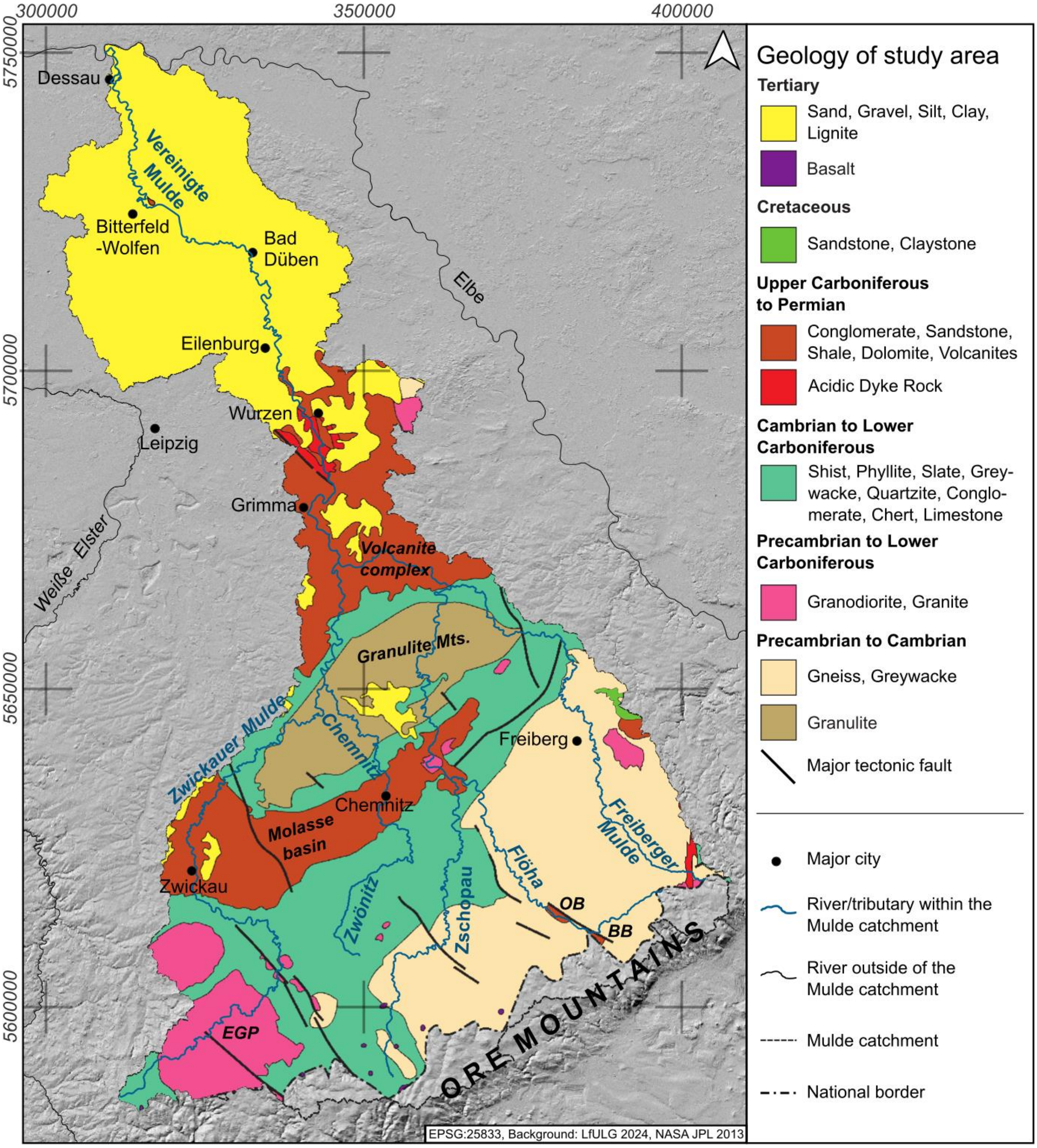


Fig. 2. Pre-Quaternary lithological map of the Mulde River catchment. EGP: Eibenstock Granite Pluton; OB: Olbernhau Basin; BB: Brandov Basin. Drawing: M. Offermann/M. Hein.

2.3 Climate

The lower and middle reaches of the Mulde River are characterized by a lowland climate in the transition zone from temperate Cfb to cold Dfb Köppen climate (Peel et al., 2007). Precipitation values range from around 600-700 mm in the lower reaches to over 1000 mm at the headwaters with average annual temperatures of 10°C to 7°C, respectively (Scholz et al., 2004).

2.4 Land use

The landscape of the Ore Mountains is predominantly characterised by forests. Along the Zwickauer Mulde River, however, there are various agricultural areas and isolated settlement areas (Mannsfeld and Syrbe, 2008). The situation is similar in the Freiberger Mulde catchment. To some extent, and in spite of reforestation measures since the 1800s, the forest-openland distribution in these upper reaches is still reflecting the centuries-long intense and timber-consuming mining activities in the Ore Mountains (Kaiser et al., 2023; Theuerkauf and Kaiser, 2024). Downstream, the agricultural utilisation of the landscape increases in the direction of the Leipzig basin, where both rivers join. In the area of the ‘Vereinigte Mulde’ River there is a mixed land use of forests and fields (Mannsfeld and Syrbe, 2008). The region saw a relatively early onset and rapid progression of industrialization in the 19th century. Therefore, the chemical water quality is heavily affected by agricultural, municipal and industrial effluents and the Mulde River is considered a highly-polluted river at least from around 1900 to the 1990s (Otto and Mleinek, 1997).

3 Materials & Methods

3.1 Cartographic resources used in this study

In recent decades, multiple studies have been published on past water body parameters before river regulation programmes were implemented. The majority of them concentrate on particular river segments (Hohensinner et al., 2013; Schielein, 2010; Zielhofer et al., 2025). However, even at a broader regional scale, old maps might be a promising tool to reconstruct historical water body structure, as this was already developed for historical channel patterns (Hohensinner et al., 2021; Witkowski, 2021).

The oldest map series for this task in the study region, fulfilling the demand for both, reliable geodetic surveying and extensive coverage were produced in the late 18th and early 19th century. At that time, driven by military and administrative motives, German states ordered medium-scaled maps depicting their territories. In 1780, Engineer-Major Friedrich Ludwig Aster was tasked with conducting a military-topographical survey of Saxony based on a state-wide triangulation. The resulting map was later coined ‘Meilenblätter von Sachsen’ (Witschas, 2002). Three copies exist, two of them are used in this study: The original was heavily used and is now stored in Dresden, the King’s copy was transferred to Prussia in the aftermath of the Battle of the Nations (1813) and is well preserved. Most of the sheets in this study were mapped until 1806, four sheets were mapped until 1821. Detailed metadata after Schmidt et al. (2024) is documented in Table S2.

Each sheet measures one square cubit (one cubit corresponds to approximately 56.6 cm) and depicts one square mile (one mile corresponds to 12,000 Dresden cubits = approximately 6.8 km). The scale is therefore 1:12.000. The map content illustrates boundaries, road networks, water bodies, woodland and meadows. Even within the villages, houses are depicted individually. The relief is characterised by the use of graphically prominent Lehmann mountain hatches (Witschas, 2002). However, a legend explaining the map symbols and pattern fills is absent.

The downstream part of the ‘Vereinigte Mulde’ River north of Gruna to Dessau-Roßlau is not covered by the ‘Meilenblätter von Sachsen’ because it was not mapped before its territorial loss to Prussia in the aftermath of the Napoleonic Wars. For this section, we used the contemporaneous ‘Quadratmeilenblätter von Brandenburg’ which were mapped between 1816 and 1821 by Carl von Decker and Karl Ferdinand von Rau following von Deckers experiences in topographic mapping during the Napoleonic Wars (von Decker, 1816).

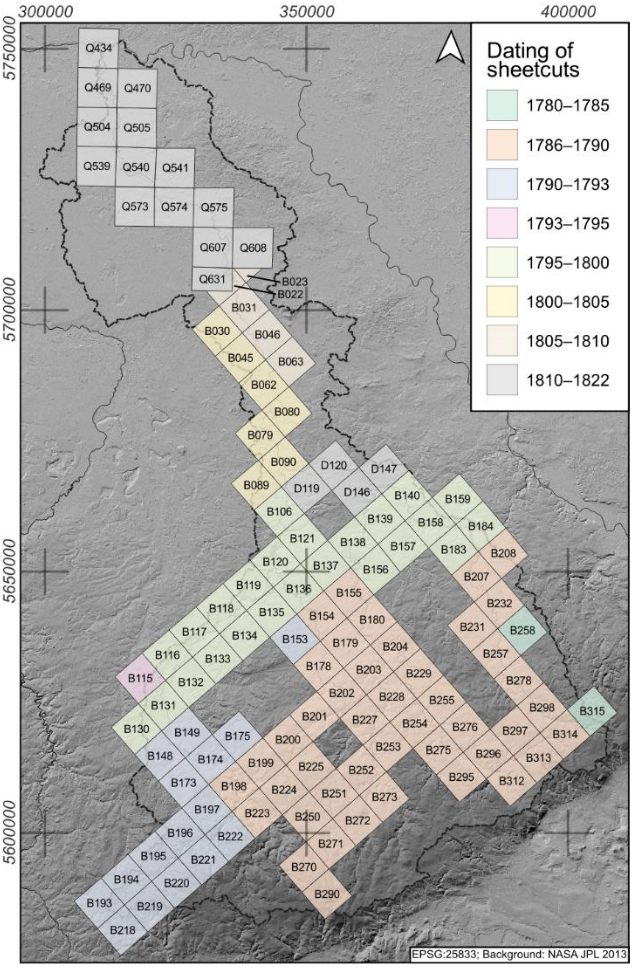


Fig. 3. Overview of Old Maps used for mapping historical channel pattern, floodplain land use and barriers. Oblique orientation/alignment: Sächsische Meilenblätter (B: Berlin copy, D: Dresden copy); straight orientation/alignment: Brandenburg Quadratmeilenblätter (Q).

3.2 Selection of parameters for historical water body structure mapping

The water body structure mapping (‘Gewässerstrukturgütekartierung’) is a procedure that was developed in accordance with the European water framework directive (Zumbroich and Müller, 1999). It records the ecologically relevant structural conditions of water bodies required to be monitored for the European water framework directive. The initial basis for the assessment is the objective and consistently comprehensible identification of structural elements of the watercourse and its surroundings, employing a predefined parameter system at on-site inspections. These structural elements are referred to as individual parameters, which are especially relevant for the assessment of the ecological functionality of watercourses. Additionally, or alternatively to detailed on-site mapping, data acquisition procedures also comprise quick map-based assessments for overview (‘Übersichtskartierung’). As this abridged overview mode is already optimized for map applications, we made use of it for retrieving information from the old map sections and also current topographic maps (DTK10, DTK25) for comparison. According to their indicator function, six main parameter groups are built up, namely course development, longitudinal profile, bed structure, transversal profile, bank structure and water environment, which are subsequently divided in 25 individual parameters.

From these 25 individual parameters for water body structure mapping, we select three parameters that might be potentially relevant for salmon habitat suitability and at the same time widely represented on historical cartographical material. The selected parameters are ***channel pattern*** (section 3.3) as proxies for substrate diversity and riffle-pool distributions, spawning habitat suitability (Geist and Dauble, 1998; Vetter, 2011b) as well as human impact on natural river structure, ***floodplain land use*** (section 3.4) as a proxy of human impact and pollution, and ***barriers*** (section 3.5) as a proxy for river connectivity. Other potentially salmon-relevant parameters like river bed substrate composition, river bed width variance, channel bars, special river course features (e.g. fallen trees) and bank vegetation have to be omitted because they are not reliably mappable solely based on old maps.

All structural parameters are recorded using a standardized 1 km² grid covering the entire Mulde River course and these of second order tributaries. Within the joint research programme DFG-SPP 2361 ‘On the Way to the Fluvial Anthroposphere’ and the virtual research environment Spacialist, the grid approach is designed to facilitate data synthesis between heterogenous sources such as written sources, old maps and modern topographic maps with different spatial and chronological scales (Lang et al., 2020; Morrison et al., 2021; Werther et al., 2021; Zielhofer et al., 2022).

3.3 Channel patterns

Distinct fluvial channel patterns evolve from an interplay of multiple factors, such as discharge(-variability), velocity, (suspended) sediment load, gradient, tectonic activity and geology, and they also react to climatic and land use changes. The given factor combination causes river styles with specific structural properties and diversities, e.g. regarding channel bars (Payne and Lapointe, 1997), stream-width variance and riffle-pool sequences. That way, channel patterns are informative of the overall geomorphic and ecological functioning alike, and can be used as an integral indicator of instream salmon habitat suitability and diversity (Brierley and Fryirs, 2004; Cianfrani et al., 2009; Moir et al., 2004; Stefankiv et al., 2019; Twidale, 2004). For classification, (i) the coherence of the stream-bed (single v. multiple threads), (ii) the sinuosity and (iii) lateral migration (or confinement) are among the most significant parameters. Usually, the single-thread types 'Straight' and 'Meandering' and the multi-threaded 'Anastomosing' and 'Braided' are distinguished, as well as various transitional forms (Alabyan and Chalov, 1998; Vandenberghe, 2002). However, due to the inherently complex nature and geographic differences of river systems, no generally accepted definitions or naming conventions exist, but have more recently been proposed (Fryirs and Brierley, 2018).

Here, we use the nomenclature and map-based approach applied by Hohensinner et al. (2021) for the comparative analysis of channel patterns over the last 200 years. The categories comprise mostly natural river types (confined, moderately confined single channel, multi-channel, sinuous, meandering, incised meander) and those with a high degree of anthropogenic structural intervention (arched regulated, linear straightened, dammed-up). A great advantage of this already proven approach is the relatively simple and time-efficient map survey that can be conducted for large areas in a comparative way.

The 'Sächsische Meilenblätter' (Sächs. Ing.-Korps and Aster, 1806, 1816) and 'Von Deckersche Quadratmeilenblätter' (von Decker and von Rau, 1822) are used for mapping the historical river channel patterns and the TK25 of Saxony (GeoSN - Landesamt für Geobasisinformation Sachsen, 2025) is used for the mapping of recent structures. Each grid cell (1 km^2), which is partially intersected by a river course, is assigned a channel pattern category. If several possible channel patterns occurred within a grid, the pattern that has the largest total share of a grid is used. Fig. 4 shows the decision tree for the classification and mapping of channel patterns in each grid.

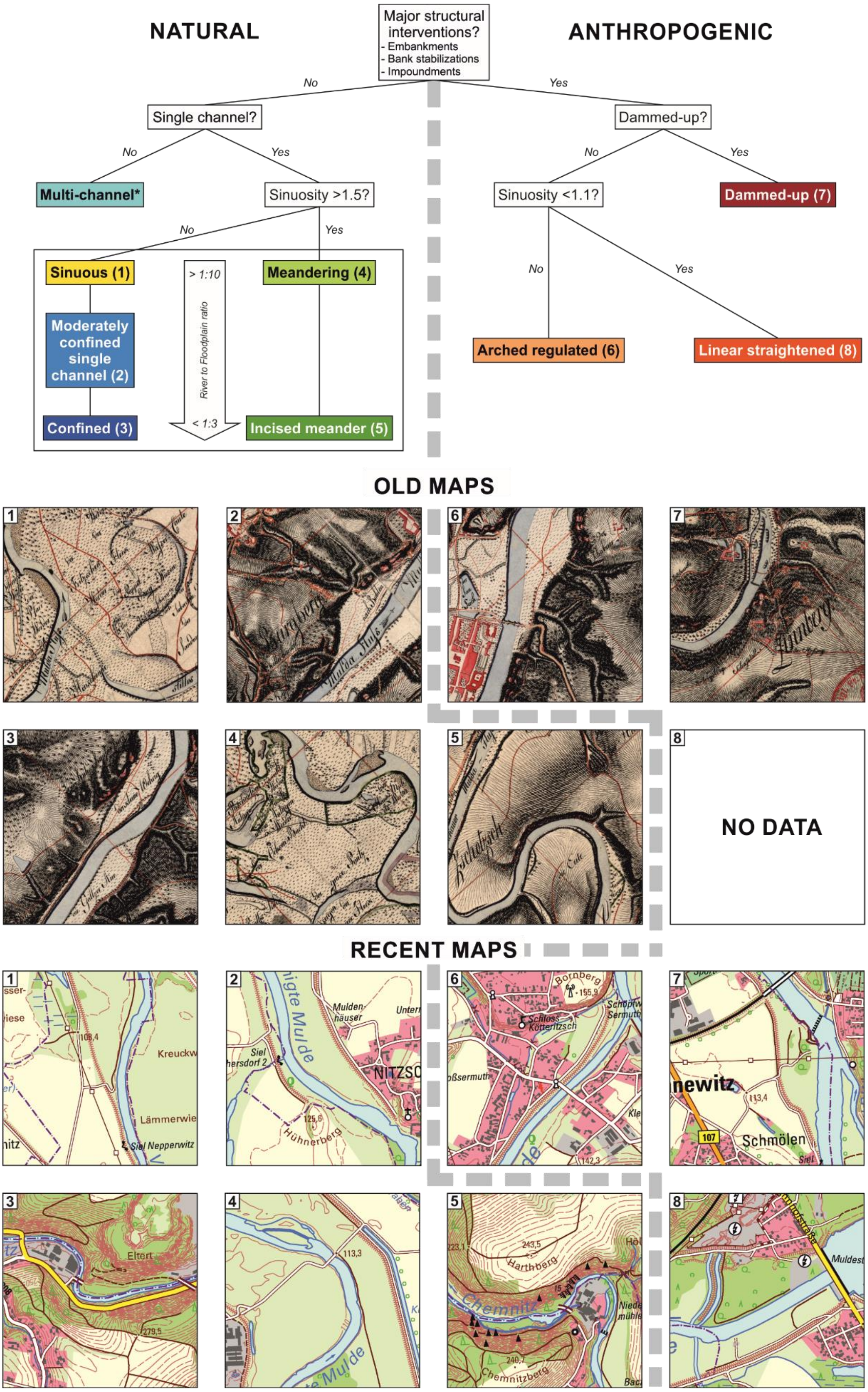


Fig. 4. Decision tree for the classification of channel patterns in each grid cell. Numbering in the map segments refers to channel pattern categories above. The asterisks (*) indicate that no multi-channel river exists in the study area, so this pattern is not recorded. Data sources: GeoSN - Landesamt für Geobasisinformation Sachsen, 2025; Sächs. Ing.-Korps and Aster, 1806

3.4 Floodplain land use

The form and intensity of land use in the catchment and particularly in the floodplain has been shown to significantly affect physico-chemical water qualities and thereby salmon habitat potential, including spawning- and migration success (Rodger et al., 2024; Soulsby et al., 2024; Stefankiv et al., 2019). Land use can i.a. critically control contaminant and nutrient influx (Krause et al., 2008; Lyubimova et al., 2016), oxygen levels, the temperature regime via shading effects (Fabris et al., 2017; Hrachowitz et al., 2010; Jackson et al., 2021), and the amount of detrimental suspended load within the river (Walling, 2005; Yu and Rhoads, 2018). According to water body structure mapping (Zumbroich and Müller, 1999) the floodplain land use can be divided into 7 categories (Fig. 5). Class 1 is not mapped in the assessment as such, as this refers to a natural floodplain forest, which cannot be clearly read from the old maps. Class 2 encompass floodplain woodland and class 3 features floodplain grassland. Classes 4 to 7 encompass mixed land uses with increasing amounts of built-up areas and agriculture. Mapped land use amounts always refer to the morphological, respectively Holocene floodplain inside a given grid cell.

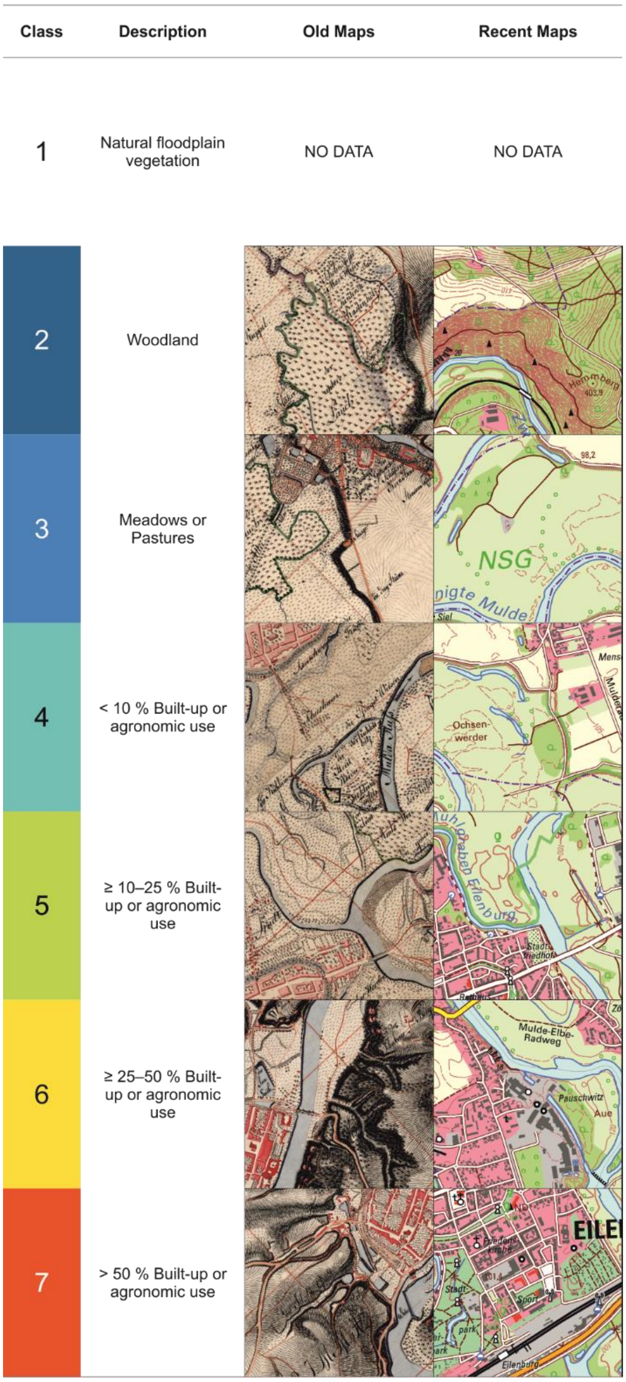


Fig. 5. Overview of criteria for mapped land use classes with example grid tiles from Old and recent maps. Data sources: GeoSN - Landesamt für Geobasisinformation Sachsen, 2025; Sächs. Ing.-Korps and Aster, 1806.

3.5 Barriers

Hydropower plants and their reservoirs are known to cause river fragmentation and impact natural flow regulation (He et al., 2024). Even when there is no reservoir present weirs create slower-moving upstream river portions because they deepen the water, reduce flow velocity, and increase sediment deposition (Mueller et al., 2011). Accumulation of multiple barriers across a river system drastically reduces the chances of migratory fish to reach their spawning grounds and in consequence, extirpation (Gowans et al., 2003; Lange et al., 2018).

For this study, we mapped structures with a potential barrier effect on the old maps. For the current situation, we refer to the Saxonian Transversal Structures database (LfULG, 2024). It records 4980 features in the Mulde River system. Of these, 323 structures are directly located in the Mulde River and examined first order tributaries. For the Vereinigte Mulde section located in Saxony-Anhalt we consult the AMBER Barrier Atlas (AMBER Consortium, 2020) documenting 6 more structures.

To allow for a semi-quantitative analysis of barriers in the Mulde River system, we create also a measure of connectivity termed cumulative barrier count. It represents the number of barriers which anadromous fish have to overcome in order to reach a respective grid cell in the Mulde River system. To account for cases where the river crosses the grid cell multiple times and/or multiple barriers are present in the grid cell, the cumulative barrier count documents the maximum number of barriers.

3.6 Atlantic salmon catch data

A total of 1593 Atlantic salmon occurrences in the period from 1432 to 2021 have been recorded for the Elbe River system in order to document the historical salmon distribution (Hegemann et al., 2025). The dataset includes 990 historical salmon catches from secondary written sources with locations. A starting point of this literature survey were the already existing review studies of Wolter (2015) and Andreska and Hanel (2015). Additional references were added.

Furthermore, recent distribution data from the GBIF.org (2025) were included in the database. Here, 615 records since 1999 were retrievable.

As a simplified approach to delimiting the distribution areas of salmon, salmon catch data were modelled according to Clavero and Hermoso (2015). The model assumes that the recorded salmon catches also include a distribution of the migratory fish downstream of the fishing location. To this end, a binary dataset for each time slice as to whether salmons are present or not is created in 16 by 16 km grid cells (Henke et al., 2025). The approach makes it possible to circumvent the imprecise nature of historical sources by accessing the simple information of whether a salmon was sighted (Clavero and Hermoso, 2015). The catch data are not necessarily representative of the salmon population, as natural and anthropogenic factors must be taken into account (Füllner et al., 2004b). The data set models the distribution of salmon in the Elbe River system. The time slices are determined in 100-year spans for the period from 1500 to 1800, and in 50-year spans for 1800-2024 due to a higher availability in the more recent periods.

4 Results

4.1 Channel patterns

Channel patterns are mapped for 796 grid cells from the old maps (Fig. 6a) as well as 792 grid cells from the recent topographic map (Fig. 6b). Our results show that channel patterns were clearly dominated by non-anthropogenic types (96,9 %) in 1822 (Table 1). The headwaters in the low mountainous areas are characterised by confined and moderately confined forms, the Vereinigte Mulde River courses in the lowlands feature meandering and sinuous patterns.

The grid data reveal a considerable decrease in all natural river patterns in the study area between 1822 and 2024. Losses range from about a quarter of total grid cells for sinuous river sections, about a third for confined and moderately confined sections and approximately half of incised meander and meandering sections. The largest total decrease is documented for moderately confined sections. In contrast, anthropogenic river pattern increased between 1822 and 2024. Dammed-up sections increased by 5350%, while arched regulated sections increased by 772% (Table 1). The relative amount of anthropogenic channel patterns rises from 3,1 % in 1822 to 38,4 % in 2024.

Table 1. Mapped channel pattern in the Mulde River system for 1822 and 2024 following the approach of Hohensinner et al. (2021).

	Channel pattern class	1822 [n]	Amount 1822 [%]	2024 [n]	Amount 2024 [%]	Relative Change [%]
Natural patterns	Confined	169	21.2%	106	13.4%	-37.3%
	Moderately confined single channel	366	46.0%	249	31.4%	-32%
	Sinuous	62	7.8%	45	5.7%	-27.4%
	Meandering	112	14.1%	53	6.7%	-52.7%
	Incised Meander	63	7.9%	35	4.4%	-44.4%
Anthropogenic patterns	Arched regulated	22	2.8%	192	24.2%	+772.7%
	Linear straightened	0	0%	3	0.4%	
	Dammed-Up	2	0.3%	109	13.8%	+5350%
	Total	796		792		

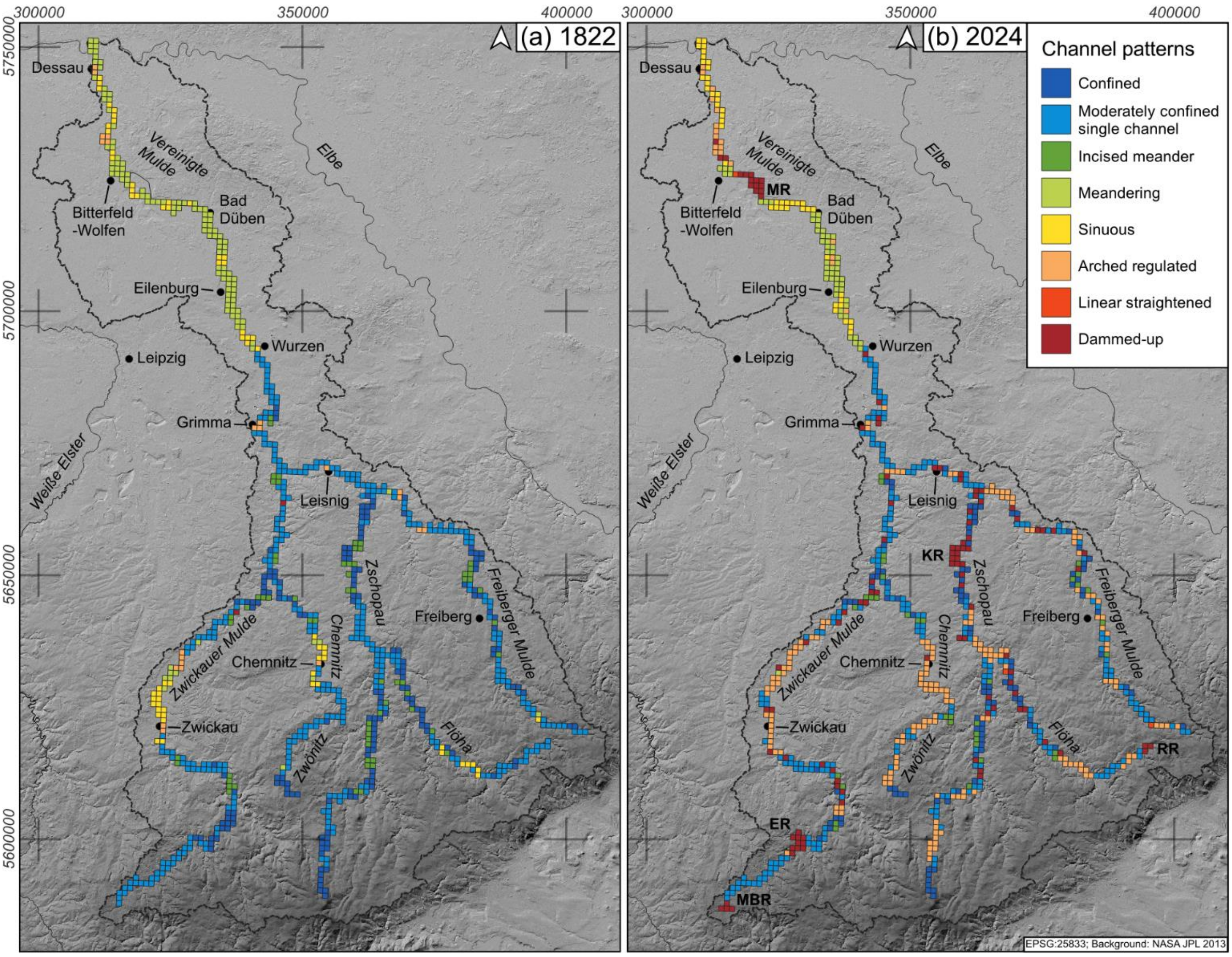


Fig. 6. Comparative mapping of channel patterns after Hohensinner et al. (2021) in the Mulde River system. Larger Reservoirs are marked: Eibenstock Reservoir (ER), Kriebstein Reservoir (KR) Mulde Reservoir (MR), Muldenberg Reservoir (MBR) and Rauschenbach Reservoir (RR). Data source: Table S1.

4.2 Floodplain land use

Floodplain land use is mapped for 979 grid cells (1 km^2) from the old maps (Fig. 7a) and 990 grids from the recent topographic map (Fig. 7b). In 1822, floodplain land use is predominantly characterized by woodlands and meadows or pastures (classes 2 and 3; 69,5 %). Together with extensively settled or agronomic areas (class 4; 21,2 %), these represent a large amount (90,7 %) of all grids. A small number of intensively settled grids is located in the urban areas of Grimma, Chemnitz and a number of smaller cities along the tributaries.

Between 1822 and 2024, land use in the Mulde floodplains intensified remarkably: the formerly dominating land use classes 2 (woodland) and 3 (grassland) only make up a quarter of mapped grids in 2024, indicating a loss of more than 60 %. Intensively used grids (classes 5 to 7) experienced the largest increase: from 9,3 % to 45,3 %. Out of these classes, grids with more than 50 % built-up area in the floodplain experienced the single largest increase of 1386% (Table 2). Even in the upper reaches the floodplains have been altered by anthropogenic mixed use.

Table 2. Mapped floodplain land use classes in the Mulde River system for 1822 and 2024.

Land use class	1822 [n]	Amount 1822 [%]	2024 [n]	Amount 2024 [%]	Relative Change [%]
1: Natural floodplain vegetation	0	-	0	-	-
2: Woodland	169	17.3 %	66	6.7%	-60.9 %
3: Meadows or Pastures	511	52.2 %	172	17.4%	-66.3 %
4: < 10 % Built-up or agronomic use	208	21.2 %	303	30.6%	+45.7 %
5: ≥ 10–25% Built-up or agronomic use	55	5.6 %	145	14.6%	+163.6 %
6: ≥ 25–50% Built-up or agronomic use	21	2.1 %	81	8.2%	+285.7 %
7: > 50% Built-up or agronomic use	15	1.5 %	223	22.5%	+1386.7 %
Total	979		990		

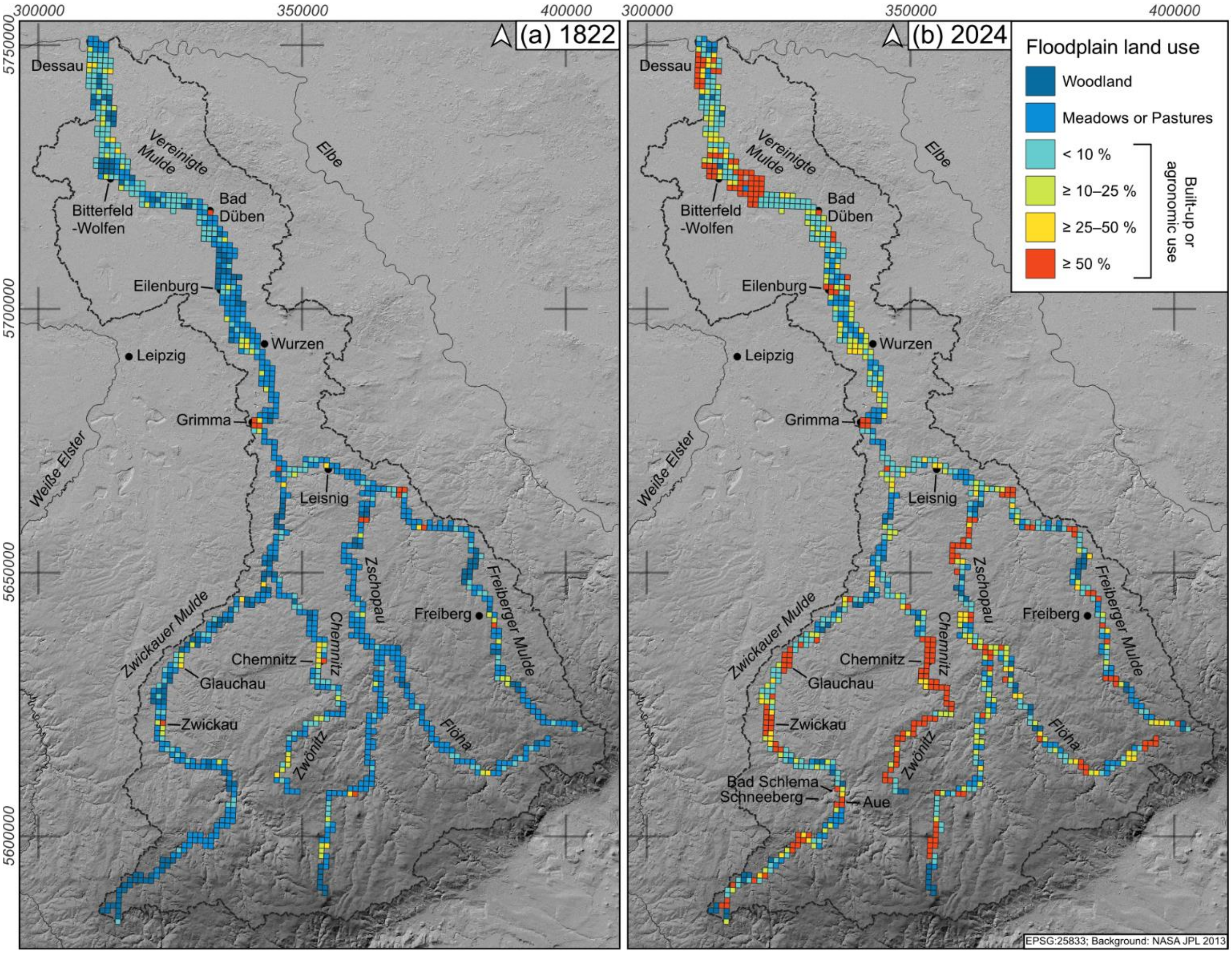


Fig. 7. Comparative mapping of floodplain land use in the Mulde River system for 1822 and 2024. Data source: Table S1.

4.3 Barriers

For 1822, we identified 104 barriers in direct connection with the studied rivers (Table 3). The lowest number of barriers is found in the Vereinigte Mulde River, the highest number in the Freiberger Mulde River. Averaged over river lengths, the Mulde River system contained a barrier every 6.3 km in 1822. The aforementioned rivers represent extremes: in the Vereinigte Mulde River migratory fishes would have had to pass a barrier every 13.3 km on average, while in the Freiberger Mulde distances between barriers were significantly (4.1 km) shorter.

The Saxonian Transversal Structures Database (LfULG, 2024) and the AMBER Barrier Atlas (AMBER Consortium, 2020) document currently 326329 barriers in the studied rivers. The Vereinigte Mulde River comprises 11 barriers, whereas the Zschopau River reveals the highest number of 122 barriers. Averaged over river lengths, the studied rivers contain a barrier every 2 km. The number of barriers tripled within all investigated rivers. In the Zschopau River, the number of barriers increased by a factor of 454%.

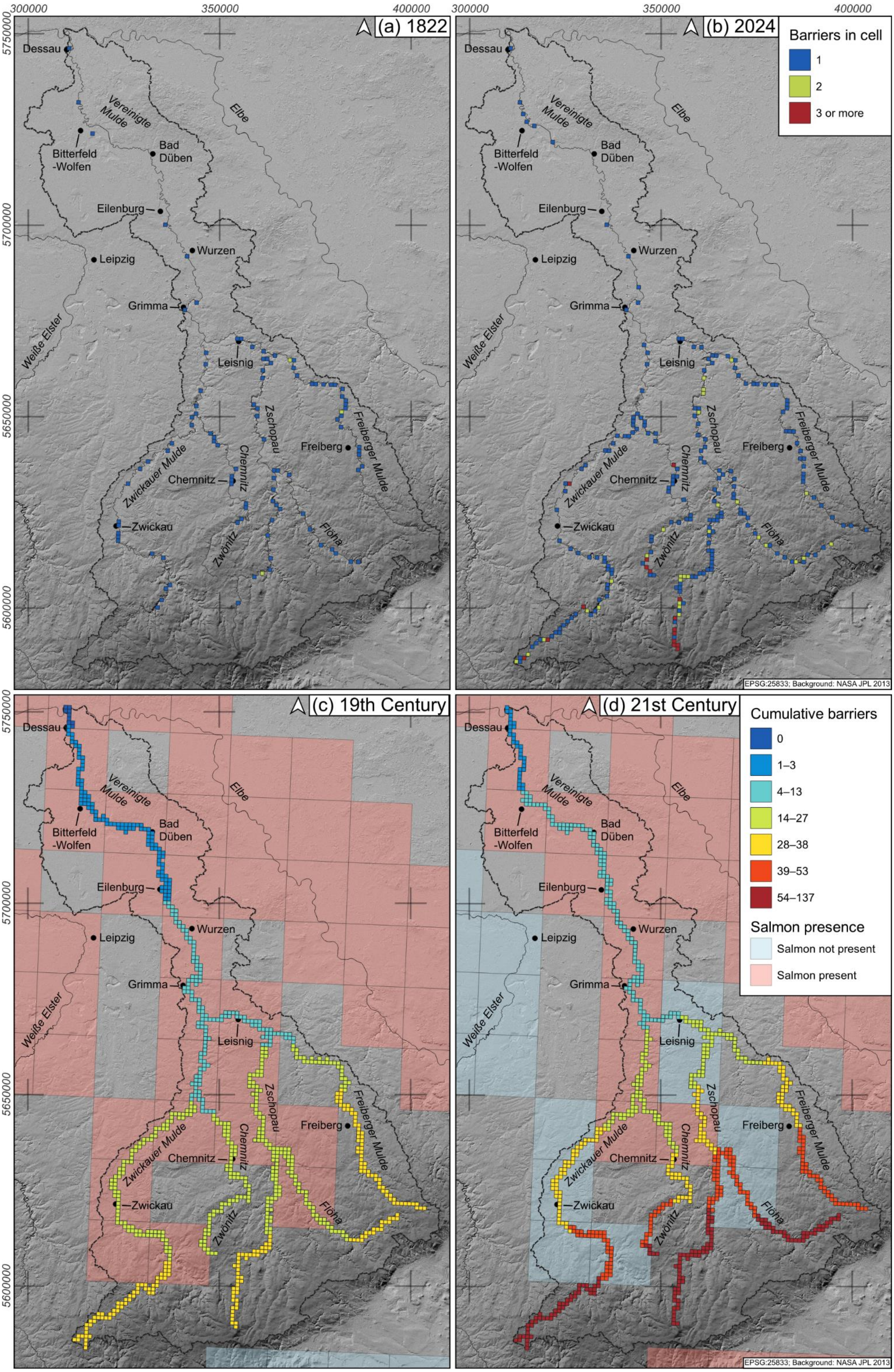
Figure 8a and b show the barriers in each grid square for time slices 1822 and 2024. In 1822 barriers in Mulde system were distributed more evenly with only three grid squares containing 2 barriers and no grid squares containing 3 or more squares. Barriers are concentrated on down- and midstream sections of Freiberger Mulde river and upstream sections of Zschopau rivers. Zwickauer Mulde shows a more even distribution with a concentration around Zwickau. Notably, the upstream sections of all tributaries contain no barriers in 1822. The increase in barrier amounts between 1822 and 2024 primarily happens in the upstream sections with the highest concentrations on the Zschopau river and Zwickauer Mulde. Formerly completely barrier free upstream sections in the Zwickauer Mulde, Zwönitz, Flöha and Freiberger Mulde today are largely dammed.

Figure 8c and 8d show the cumulated barriers in grid cells. While the Elbe and Mulde until Dessau was accessible unhindered in 1822, a weir built in 1960 in Geesthacht, southeast of Hamburg, has moved the completely accessible area far downstream. In 1822, relative unhindered access with 1-3 barriers lasted 100 km until Eilenburg, medium impeded access with 4-13 barriers reached into the Zwickauer Mulde upstream of the Chemnitz confluence and into the Chemnitz, also into the Zschopau and the midstream sections of the Freiberger Mulde. Today, relative unhindered access is only possible for the most downstream 33 km, medium impeded access only reaches the downstream parts of Zwickauer and Freiberger Mulde. In 1822, the most impeded (>27 barriers) river sections lay in the Zwickauer Mulde, the Zschopau, Flöha and the Freiberger Mulde. On the latter it comprises nearly half of its length. The situation for recent times includes two more impeded classes (>38 barriers and >53 barriers) which comprise the most upstream parts of the Mulde rivers and tributaries. Upstream migrating fish reach the Flöha River by a minimum of 38 barriers from the sea.

Table 3: Mapped barriers in the Mulde River system for 1822 and 2024. Length of rivers is also given with averaged distance between two barriers.

River	Length [km]	Barriers in 1822 [n]	Average barrier distance 1822 [km]	Barriers in 2024 [n]	Average barrier distance 2024 [km]	Relative Change [%]
Chemnitz/Zwönitz	76,5	12	6.4	46	1.7	+283.3 %
Flöha	67	10	6.7	33	2.0	+230.0 %
Freiberger Mulde	124	30	4.1	40	3.1	+33.3 %
Vereinigte Mulde	93	7	13.3	11	8.5	+57.1 %
Zschopau	130	22	5.9	122	1.1	+454.5 %
Zwickauer Mulde	167	23	7.3	77	2.2	+234.8 %
Total	658	104	6.3	329	2.0	+216.3 %

Fig. 8 (next page). Comparative mapping of barriers in each grid square (a, b) and cumulative barrier count (c, d) in the Mulde River system for 1822 and 2024. Panels (a, b) base on the recent river courses. The cumulative counts (c, d) range from the Elbe estuary towards the headwaters. The mapped classes represent septiles in the 2024 data. The 256 km^2 grid features the salmon presence for 1800 to 1899 and for 1996 to 2024. Data source: Henke et al., 2025; Table S1.



(a) 1822
(b) 2024
(c) 19th Century
(d) 21st Century
Barriers in cell
1
2
3 or more
Cumulative barriers
0
1–3
4–13
14–27
28–38
39–53
54–137
Salmon presence
Salmon not present
Salmon present
300000
350000
400000
5750000
5700000
5650000
5600000
Dessau
Vereinigte Mulde
Bitterfeld -Wolfen
Bad Düben
Elbe
Eilenburg
Leipzig
Wurzen
Grimma
Weiße Elster
Leisnig
Zschopau
Freiberger Mulde
Freiberg
Zwickauer Mulde
Chemnitz
Zwickau
Zwönitz
Flöha
EPSG:25833; Background: NASA JPL 2013

4.4 Historical data on Atlantic salmon distribution in the Elbe catchment

Figure 9a shows the total distribution area of the Atlantic salmon in the Elbe River system in all studied time periods. At the onset of the 19th century, reported Atlantic salmon distribution only reached the Saale River and upstream Elbe River reaches in the Bohemian basin (Fig. 9b). No Salmons are reported from the Mulde River in this time period. Between 1851 and 1900, the range of the salmon has the widest distribution of all time slices (Fig. 9c). It covers a large part of the Elbe River and its tributaries and extends to the headwaters of the Elbe, the Vltava and the Otava Rivers in the Czech Republic. In the Mulde River system, the range of the salmon includes the Zwickauer Mulde as far as Aue, the Chemnitz, the Zschopau and a lower section of the Flöha (Fig. 8c). Salmon were also found in the Schwarze Elster and the Saale (Fig. 9c).

From 1900 to 1949, the range of the Atlantic salmon is comparatively limited. It extends up the Elbe to the town of Ústí nad Labem and up the Saale to between the tributaries of the Weiße Elster and Unstrut rivers (Fig. 9d).

Between 1950 and 1995, the Atlantic salmon became extinct in the Elbe River system (Fig. 9e).

From 1996 an increase in the range of the Atlantic salmon can be seen again with the onsetting reintroduction programs (Füllner et al., 2004b). The fishes migrated up the Ohře River as far as Karlovy Vary, but according to the available data, no further upstream on the Elbe (Fig. 9f). However, individuals were again recorded in the Mulde (Fig. 8d) and, for the first time, in smaller tributaries e.g. the Stepenitz in the lower reaches of the Elbe.

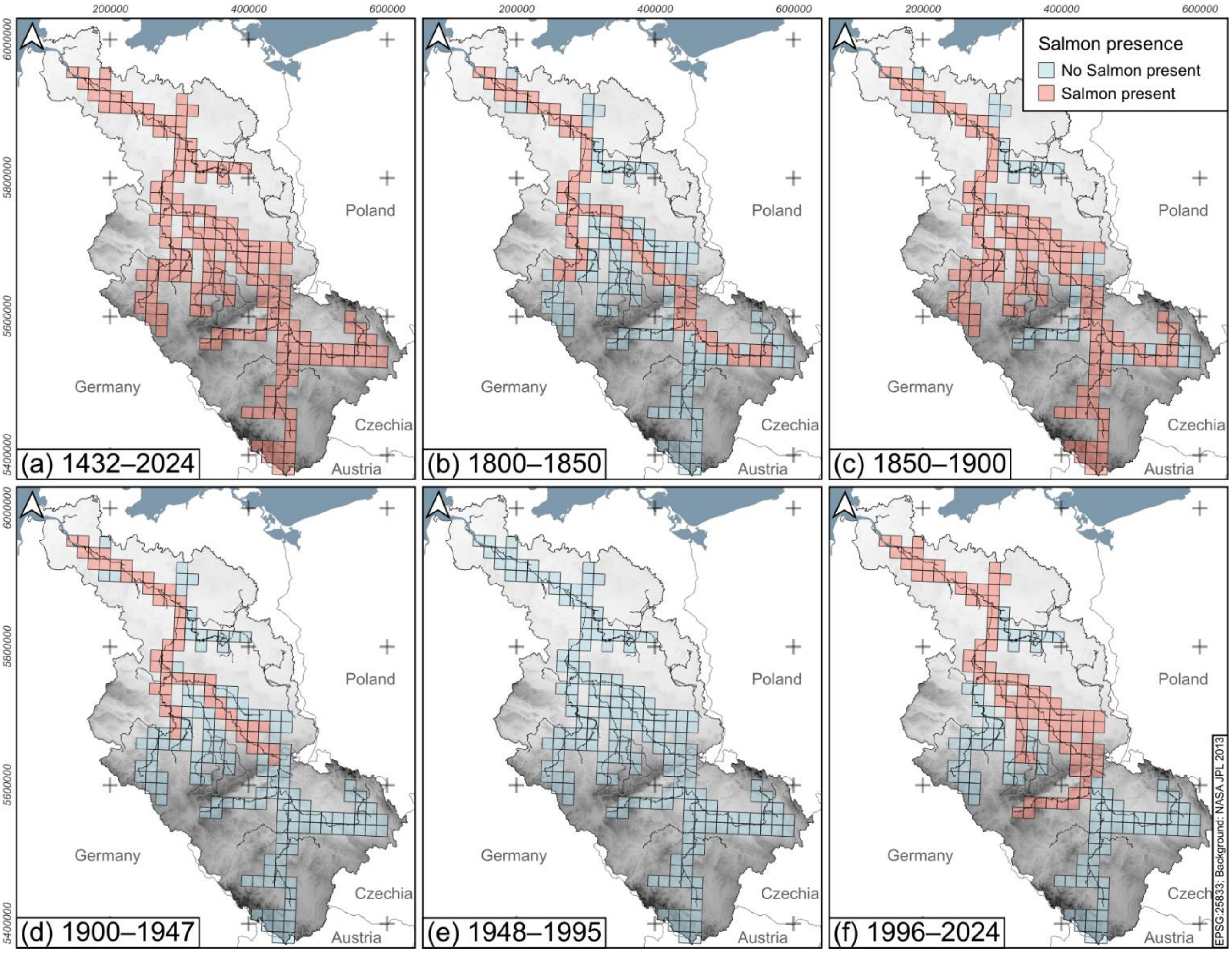


Fig. 9. Overview of modelled Salmon habitat ranges. Comparative mapping of historical and recent Atlantic salmon occurrences in the Elbe River system. Data source: Henke et al., 2025.

5 Discussion

5.1 Channel pattern – spatial variability, temporal changes and ecohydrological functioning

5.1.1 Lithological control of pre-industrial channel patterns

The results of the 1822 channel pattern mapping are considered to reflect a pre-industrial state, not yet exceedingly blurred in our categorization by anthropogenic impacts. Hence, we resort to the data of this time slice for inspecting the lithological control on the formation of distinct channel patterns in the Mulde River system. It is a well-known phenomenon that lithological properties and the alignment of tectonic faults exert a strong influence on the formation of specific river types (Goudie, 2016; Montgomery, 2004; Twidale, 2004). In that regard, the Mulde catchment can be divided into (i) a bedrock-dominated southern part of the low mountain range and (ii) a smaller northern lowland part, downstream of the city of Wurzen, which is characterized by unconsolidated Tertiary and Quaternary sediments (Fig. 2 and 6).

(i) In the ***southern part***, all rivers mainly flow concordantly with the major incline of the Ore Mountain fault block, but in some segments also trend in parallel alignment with the Variscan strike (NE-SW) or with its cross-faults, i.e. perpendicularly to the latter (NW-SE). Courses along Variscan faults are e.g. inferred for the uppermost and lowermost reaches of the Zwickauer Mulde, the uppermost reaches of the Flöha, and the central segments of the Zwönitz and the Zschopau rivers. In contrast, cross-fault induced courses can be interpreted for central parts of the Freiberger Mulde, the middle to lower reaches of the Flöha, the lowermost reaches of the Chemnitz River, and the first stretches of the Vereinigte Mulde River (Fig. 2). In several instances, this tectonic pattern leads to large-scale rectangular course changes supposedly at the junction of faults, as evident for the Flöha, the Zwönitz and the Vereinigte Mulde around the city of Grimma. Such fault-line valleys are usually relatively narrow and fairly straight (Twidale, 2004). Even though this general tendency vastly holds true for our channel pattern data, we propose that valley metrics and especially the respective river types are at least just as much controlled by lithologies. The hard, erosion-resistant magmatic and metamorphic rocks predominant in the southern part of the catchment favour the formation of small-width valleys hosting rivers with *confined* or *moderately confined* channel patterns (Goudie, 2016; c.f. Schanz and Montgomery, 2016; Wagenbreth and Steiner, 1990). Hence, these two categories cover most of the southern part of the Mulde River system (Fig. 6). These two types are not easily distinguished lithologically based on a geological map. An exception is the Eibenstock Granite Pluton (EGP), that tentatively allows for slightly wider valleys (moderately confined) as opposed to the more confined channel patterns that form outside of the pluton (Fig. 2 and 6). *Incised meanders* that occur over short stretches in all rivers are likely inherited from the time before the Tertiary uplift of the fault-block (c.f. Dente et al., 2021; Wagenbreth and Steiner, 1990). Conversely, the occurrence of wider valleys accommodating rivers with a *sinuous* channel pattern is inextricably linked with the distribution of softer, more friable sedimentary rocks from the Upper Carboniferous to Permian period. These lithologies, being less resistant to lateral fluvial planation, are mainly found throughout the Molasse Basin (affecting the Zwickauer Mulde and the Chemnitz river) and the two small fault-related Olbernhau (OB) and Brandov Basins (BB) along the Flöha River (Figs. 2 and 6). North of Zwickau, a stretch of *arched regulated* channel exists even in the early 19th century. According to the valley and floodplain morphologies, however, this segment would originally qualify as *sinuous* as well, if anthropogenic bank enforcements and course changes were disregarded. Therefore, the allocation of the *sinuous* channel pattern is nearly congruent with the extent of the aforementioned basin structures. Apart from planform geometry, lithological differences can also affect the longitudinal profile, i.e. the gradient of a river. Figure 10 shows the composite profile of current gradients of major rivers in the Mulde River system. While the smaller inflections are almost entirely caused by artificial impoundments and their respective backwaters, large-scale slope changes refer to natural knickpoints (e.g. at total river length of 210 km and 190 km in the Freiberger Mulde and Chemnitz river, respectively). Since the degree and manner of bedrock control on the formation and propagation of knickpoints is a longstanding matter of debate (Goudie, 2016; Schanz and Montgomery, 2016), their explanation would require detailed on-site investigations which is why we refrain from a geological interpretation of these features.

(ii) For the ***northern part*** of the catchment, the Mulde River transgresses from the uplands dominated by bedrock into the lowlands, where thick and highly-erodible Cenozoic loose sediments determine the fluvial architectures. The river mainly follows the low gradient towards its base level which is the confluence with the Elbe River. The course is gently guided by the several kilometres wide valley of the Upper Pleistocene (Weichselian) Lower Terrace, whose deposits are constantly reworked and overlain by up to 3 meters of Holocene overbank fines (Vetter, 2011b). Fault-induced course adjustments are not discernible in this part. Accordingly, the *meandering* channel pattern is by far the most frequent category under pre-industrial conditions (Fig. 6). Shorter *sinuous* stretches occur subordinately, but are occasionally the product of recent neck cut-offs temporarily lowering the sinuosity below 1.5, so that the *meandering* pattern cannot be assigned. In other instances, a slight unilateral confinement exists, when the Mulde River is positioned at the edge of the Weichselian valley and creates a cutbank into more resistant glacial and sometimes Tertiary deposits. This is the case just downstream of Bad Düben, where the river is forced to bypass a ridge of the Saalian terminal moraine (Eissmann, 2002a) and at Gruna, north of Eilenburg, where the Mulde River erodes into Saalian and Elsterian deposits on its left bank even exposing small Tertiary lignite seams at low water levels.

5.1.2 Temporal changes in channel pattern

In 1822, the upper Mulde River courses are dominated by confined and moderately confined single channel pattern types (Fig. 6a). In the lower reaches of the Vereinigte Mulde River, sinuous and meandering channel pattern are common. The mapped channel patterns reveal arched regulated segments around Zwickau, the town of Glauchau (closely downstream) and in Chemnitz, where they coincide with the wider valleys of the Molasse Basin (Figs. 2, 6). Arched regulated stretches also occur at the lower course of the Freiberger Mulde River (towns of Döbeln and Rosswein) and in Grimma. All of these instances can be related to urban centers with important textile production (Kiesewetter, 2007; Mieck, 2012). This dependence on hydropower provided by the rivers necessitated a certain degree of constructional interference.

The aforementioned, advanced proto-industrial structures in conjunction with a solid demographic and economic basis in Saxony paved the way for industrialization (Hahn, 2005; Kiesewetter, 2007). It was eventually ignited by the establishment of large-scale coal mining in the first half of the 19th century mainly throughout the Molasse Basin but also in various small deposits such as the Olbernhau (OB) and Brandov Basins (BB) (Fig. 2). That way, Saxony experienced the earliest and most radical industrialization of all German states and is considered a pioneer region for the Central European development (Hardach, 1991). Leading sectors were the (i) textile industry perpetuated in the locations of previous textile production and many additional ones (e.g. Frankenberg at the Zschopau River; town of Flöha at the confluence of Zschopau and Flöha Rivers), (ii) engine construction (esp. in Zwickau, Chemnitz and the city of Zschopau), for which the region became one of the world market leaders before the First World War, as well as (iii) the paper industry (Friedreich, 2020; Mieck, 2012). The latter was established in several industrial villages throughout the region (e.g. Kriebstein at the Zschopau River and Grünhainichen at the Flöha River) often in narrow valleys with access to hydro-energy, process water and timber alike. Inseparably linked to this evolution was rapid population growth and the expansion of the transport-, supply- and sustainment-infrastructure. This concerns i.a. the construction of (i) roads and railway tracks along narrow valleys from the mid-19th century (Friedreich, 2020; Kiesewetter, 2007) with the necessity for bank enforcement and flood protection measures, (ii) dams equipped with turbines for electricity generation from the late 19th century and ultimately (iii) large water reservoirs to ensure drinking water supply for the emerged big cities and to moderate discharge fluctuations of the rivers (Theuerkauf and

Kaiser, 2024). Those reservoirs were mainly built in the 1920s (reservoirs Kriebstein (KR) and Muldenberg (MR)) and the second half of the 20th century (reservoirs Eibenstock (ER) and Rauschenbach (RR), see Fig. 6). ´

Therefore, in 2024, anthropogenic channel patterns have increased significantly. The *dammed-up* category appears in former *confined* and *incised meander* channel pattern (Fig. 6b), which is primarily due to the construction of hydropower plants and the associated construction of dams. Several freshwater reservoirs have also been built in the Mulde River tributaries (Fig. 6b). *Arched regulated* channel pattern are recorded primarily in urban areas such as around Chemnitz or Freiberg (Fig. 6b). The increase of flood protection measures can also be recognised much more frequently on the recent topographic map and leads to a poorer classification towards *arched regulated* channel pattern of the lower course of the Vereinigte Mulde River.

5.1.3 Ecohydrological functioning of channel pattern: Suitability of the river bed as a habitat for migratory fishes

By analysing the channel pattern types, integral statements can be made about the suitability of the river bed as a habitat for migratory fishes. The roughness of the riverbed, the shear forces and the flow conditions (turbulent/laminar) are factors that determine the formation of mesohabitats in watercourses. *Meandering* and *sinuous* channel pattern are prominent in the lower reaches of the Mulde River system and reveal a high width variance that describes the frequency of width changes in the bank-full river bed (Zumbroich and Müller, 1999). Water width and water depth are closely related. Wide river courses are shallow and vice versa. Thereby, the width of a channel is also directly related to flow velocities and in turn, it affects the grain size composition of the river bed (Vetter, 2011a, b) and the longitudinal variability of mesohabitats (Zumbroich and Müller, 1999) which are important requirements for the different life stages of salmons (Füllner et al., 2004a). *Incised meander* and *confined* channel pattern reveal low latitudinal width variance and might reduce salmon habitat suitability (Füllner et al., 2004a).

Channel pattern influences the natural presence of channel bars in the river bed. Channel bars feature local and clearly separated bed load accumulations in rivers that are stretched in the direction of flow. Typical form elements are point bars, attached bars, concave bars, mid-channel bars, and multiple bars (Hooke and Yorke, 2011; LANUV, 2023). Most of these are longitudinal bars that are formed by grain-selective sedimentation and form a finer substrate compared to the adjacent bed substrate (Zumbroich and Müller, 1999). Channel bars are particularly salmonid-relevant. The ecological importance of channel bars lies in the fact that their presence indicates a structurally rich and dynamically balanced river bed (MUNLV, 2022). Channel bars provide habitat diversity and serve as important spawning and nursery habitats for fish. In addition, they create large velocity gradients due to friction effects and thus enable the formation of calm zones during flood events (Pan et al., 2022), which is particularly important for the rearing of juvenile fish. Nevertheless, the presence of channel bars is not necessarily to be expected in every section of the pre-industrial river course (Zumbroich and Müller, 1999). For instance, in straight reaches of *meandering* rivers they are known to be extremely rare, if they occur at all (Hooke and Yorke, 2011).

Due to a high variability of ecological niches in natural channel pattern types, organisms with very different habitat requirements can live in close proximity to each other (Newson and Newson, 2000). Anthropogenic changes in the channel pattern type have an influence on shear forces, flow conditions and the ratio of erosion to deposition resulting in a direct impact on aquatic mesohabitats (Newson and Newson, 2000).

Human interventions such as straightening, damming or the construction of power plants can have a particularly strong effect on the distribution of salmon (MUNLV, 2006). Therefore, it is particularly interesting to document changes from near-natural towards anthropogenic channel pattern types.

The width variance as an important factor for the ecological connectivity of rivers (LANUV, 2011) is higher in near-natural channel pattern and occurs at shorter distances than in anthropogenically influenced areas. In 2024, urban river sections show a very poor width variance due *arched regulated* and *linear straightened* channel pattern.

5.1.4 Validity and applicability of the channel pattern parameter in the Mulde River system

The mapping of the recent river channel pattern types from recent topographical maps is possible in the same mode as the classification from the old map sheets, indicating a high applicability of the Hohensinner et al. (2021) approach. The applied grid approach can generally be considered as a suitable method, as it allows large datasets to be divided into manageable sections, thus facilitating data processing. With this method, channel pattern can be quantitatively assessed over long distances, allowing comprehensive analysis between different river systems. Furthermore, mapped pre-industrial channel patterns can be predominantly explained with lithology and the closely related topographical conditions. This indicates a high validity of the used approach.

5.2 Floodplain land use – spatial variability, temporal changes and ecohydrological functioning

5.2.1 Controlling factors on floodplain land use

For the interpretation and contextualization of changes in floodplain land use within the past 200 years, a subdivision of the Mulde catchment in a southern and a northern part can be considered. This seems appropriate because of a remarkable coincidence between **natural factors and territorial affiliation** from the 19th century onwards, both obviously affecting the intensity and form of floodplain land use: While the southern, bedrock-dominated part has been under Saxonian governance for hundreds of years, most of the northern, gravel bed-dominated part was ceded from Saxony to Prussia in 1815 with the border situated between Wurzen and Eilenburg (Fig. 2). Only the lowest Mulde River reaches around the confluence with the Elbe River belonged to the state of Anhalt. Due to this spatial coincidence, the two parts of the catchment have seen largely coherent internal developments with respective co-evolutions.

(i) For the **southern part** of the Mulde River system, floodplain land use clearly reflects the pre-industrial stage of urbanization and economic development in 1822. The intensity of land use is low corresponding with near-natural state of the floodplain (Fig. 7). However, the river sections around already mentioned textile industry centers and Waldheim show already intense floodplain land use. Particularly upstream of Freiberg and in the upper courses of the Zwönitz and Zschopau Rivers, increased floodplain land use can be attributed to ore mining. Historical mining has had a strong influence on the entire region from the 12th century until its gradual decline in the 18th and 19th centuries and has led to grave environmental damage (Annia Greif, 2015; Theuerkauf and Kaiser, 2024).

(ii) Regarding floodplain land use in the **northern part** of the Mulde River downstream of Wurzen, proto-industrial structures were less well established in 1822 (Mieck, 2009) with three notable exceptions: (1) Near Eilenburg, in the 17th century a millrace has been branched off from the Mulde River and has been canaled through the city, promoting mechanized textile production (Felgel et al., 1993). (2) In Bad Düben, lucrative mining of Tertiary deposits for alum production used for dyeing and tanning existed from the 16th to 19th century directly at the Mulde River (Lampadius, 2022). This wood-demanding process also released sulphuric effluents into the stream and a huge spoil tip still forms a cutbank of the Mulde near the city. (3) Dessau being the major city in the Duchy of Anhalt and one of the centres of German enlightenment fulfilled the infrastructural and socio-economic prerequisites for a further development with high investments in educational institutions (Brockmeier, 2010). Outside of these nuclei, the region had a pronounced rural character, which is plainly reproduced in low intensities of floodplain land use (Fig. 7).

The Vereinigte Mulde River is infamous for its short but fierce flood surges (Puhlmann, 1997) and exceedingly strong lateral migration dynamics, attested by the multitude of natural meander cut-offs and oxbow lakes. These natural preconditions may have complicated the construction and maintenance of commercial sites along the river.

5.2.2 Strong increase in floodplain land use during the last centuries

In the southern part of the Mulde River system, anthropogenic classes in floodplain land use have increased by several hundred percent around the mentioned industrial centres and cities in the infrastructurally developed narrow valleys (Fig. 7; Table 2). By comparison, relatively few changes have been recorded for the lowermost reaches of the Zwickauer and Freiberger Mulde Rivers and for the first sections of the Vereinigte Mulde River. Beyond these industrialization processes, anthropogenic floodplain land use classes succeed to display the location of one of the world's largest uranium mining operations in the region of Aue, Schneeberg and Bad Schlema (Fig. 7b). This were carried out by the Soviet state-owned enterprise 'Wismut' in the 20th century (Albrecht et al., 2022; Paul, 1991).

In the northern part of the Mulde River system, the effects of industrial propagation over the last two centuries (Mieck, 2012; Schönfelder et al., 2009) can be seen in current floodplain land use that readily captures the centres of development in Dessau, Bitterfeld-Wolfen and Eilenburg (Fig. 7b). Beyond those, the overall activity increased due to villages growing into the floodplain and a higher share of agricultural use at the expense of strongly diminished woodlands.

5.2.3 Ecohydrological functioning of floodplain land use: parameter of human impact and pollution

As part of the water body structure mapping, floodplain land use is a parameter of anthropogenic impacts on the natural fluvioscape (Zumbroich and Müller, 1999) and may influence migratory fish stocks. Low water temperatures, high water quality and high oxygen saturation are essential for salmon spawning waters. Decreases in riparian forests, agrarian fields, craft or urban areas result in river pollution, water warming and fluctuating water quality (Füllner et al., 2004a; Waterstraat and Wachlin, 2012). Furthermore, floodplain drainage, but also surface runoff within urban areas and on farmland, lead to increased suspension load and silt-clay sediment input in rivers (Füllner et al., 2004b). Organic-rich fine sediments are often washed in, which reduce the oxygen content of rivers (Waterstraat and Wachlin, 2012).

Throughout the **entire Mulde catchment**, the industrial development that was set in motion in the 19th century has been perpetuated in the Mulde River system until the late 20th century. During that time, industrial companies maintained low standards regarding effluent treatment (Naujoks and Fischer, 1991; Petschow et al., 1990), so that in the late 1980s, the Mulde River was considered one of the most severely polluted rivers in Europe with adverse hydrogeochemical repercussions even in remote regions such as Hamburg and the Wadden Sea (Böhme, 2003). After the demise of the GDR, the water quality of the river rapidly and significantly improved within just a few years (Otto and Mleinek, 1997). However, to this day, large-scale uranium (and historical) mining heaps are still situated near or within the floodplain (Theuerkauf and Kaiser, 2024), and the industrial and mining legacy is still archived in the overbank deposits, leading to legal restrictions for agricultural use in some areas (Bräuer and Herzog, 1997). During flood events, these deposits get reactivated, which results in abrupt temporary deteriorations of the river's chemical quality (Klemm et al., 2005; Knittel et al., 2005; Wilken et al., 1994).

5.2.4 Validity and applicability of the floodplain land use parameter in the Mulde River system

Using the grid approach, the semiquantitative parameter of floodplain land use provides a comparative overview in the Mulde River system of multitemporal scales. The mapping approach is applicable for old maps and modern topographical maps without any restrictions. However, the simple classification system allows no distinction as to whether the build-up areas are industrial, urban or otherwise characterised. This means that conclusions about the degree of river pollution are strictly limited. However, the parameter offers the possibility of carrying out large-scale assessments and using it to delineate areas that can then be analysed for potential sources of pollution in more intensive studies.

5.3 Barriers – spatial variability, temporal changes and ecohydrological functioning

5.3.1 Controlling factors on barrier occurrences in the Mulde River system

Barriers have been built for a long time and serve a variety of purposes. The medieval period saw a significant increase in the construction of barriers, which is thought to be closely linked to the widespread employment of hydropower in the form of water mills (Lenders et al., 2016).

Regarding the number and distribution of barriers in the Mulde River system in 1822 (Fig. 8a), lasting effects of ore mining can be interpreted. Out of 104 barriers, the highest numbers and densities appear to be linked to mining hotspots, e.g. the Freiberger Mulde and the Zschopau River (Tab. 3). Historical mining activity is known to have a high demand for hydropower, e.g to operate pumping stations (for the expulsion of gallery waters) and hammer mills, and it also requires large amounts of timber, for the rafting of which, barriers are utilized as well (Cembrzyński, 2019). However, the former textile production equally relied on hydropower and several other crucial reasons for constructing barriers existed, such as water-mills (for grain and timber) and fish weirs. Hence, a definite assignment of any barrier to a specific purpose is challenging within the scope of our investigations.

Regarding the Vereinigte Mulde River in the northern part of the Mulde River system, the state of an overall structurally weak region is also evidenced by the low number of barriers of which only seven exist in 1822 (Fig. 8a). This includes the Eilenburg weir which diverts the aforementioned millrace and a mill- and fish weir in Dessau, which is already documented since the 13th century (Reichhoff and Refior, 1997).

5.3.2 Strong increase in barrier installations during the last centuries

From 1822 to 2024, the number of barriers increased from 104 to 329 in the Mulde River system (Table 3, Fig. 10), with the largest today being 57 m high (Eibenstock reservoir, Fig. 6b). This development can also be observed in the cumulative numbers of barriers (Fig. 8b). Un- or lowly obstructed river sections have moved downstream, while barriers needed to pass to reach mountainous upstream sections have multiplied by up to 3. For example, the source of the Zschopau River is reached by passing 137 barriers.

The 19th and 20th centuries rise in numbers and density of barriers is not equally distributed across the Mulde River system. Regarding the **mountainous southern part**, most affected are (in that order) the Zschopau, Chemnitz/Zwönitz and the Flöha Rivers, in which the average distance between two barriers dropped from around 6 to < 2 km on average (Table 3), whereas for many sections it can even fall below 1 km (Fig. 10). A big proportion of these newly-acquired barriers serve the purpose of electricity generation. The fact that in the southern Mulde River system the Freiberger Mulde River which showed the highest barrier density in proto-industrial times now features the lowest one, arguably highlights an apparent spatial shift of economic development away from the Freiberg mining town despite the presence of a globally renowned university for mining and engineering (Munke, 2020).

Since 1822, the northern part of the Mulde River system only gained few additional barriers, but with the Muldestausee reservoir, albeit a significant one (Figs. 6b and 10). For more than two decades since its construction in 1976, it completely interrupted the ecological connectivity of the Mulde River (Geisler, 1998). More recently, the reservoir and the downstream weirs in Raguhn and Jessnitz were given a secondary purpose as hydroelectric power stations.

5.3.3 Ecohydrological functioning of barriers: parameter of ecohydrological connectivity

The construction of barriers such as fish weirs, mill weirs and dams with reservoirs results in a modification of the natural fluvial-geomorphological structure, of the sediment balance and of the ecohydrological connectivity (Downward and Skinner, 2005; Fehér et al., 2014; He et al., 2024; Meybeck and Vörösmarty, 2005). As a result, the ecological consequences of barriers are manifold. The access to spawning sites for anadromous fishes like salmon may be obstructed (Chen et al., 2023). However, non-migrating fishes and invertebrate species can also be affected as most of these are unable to traverse even small dams, resulting in the disruption of natural habitats. The installation of fish ladders or passes can help to mitigate these issues by maintaining the continuity of fish habitats. Nevertheless, traversing fish passes causes delay, energy loss and a higher fish mortality (Rivinoja et al., 2001). Over the course of longer fish migrations, even minor effects may add up across river networks to pose greater threats to affected species (Loures and Pompeu, 2019). Furthermore, the construction of barriers alter the natural sediment transport with riverbed aggradation upstream of the dam and subsequent river incision downstream (Graf, 2006; Morris and Fan, 2010).

Regarding the Mulde River system in general, it will take time to reset the structural interferences into the river which were inherited from the era of industrialization. Although efforts have been made in the past three decades to improve ecological potential and connectivity, e.g. by equipping a big share of barriers with fish ladders, the sheer number and density of these barriers, especially in the upper catchment, remains problematic.

5.3.4 Validity and applicability of the barrier parameter in the Mulde River system

More detailed information about potential passability is available for many of the current barriers in the Mulde River system (Table 4).

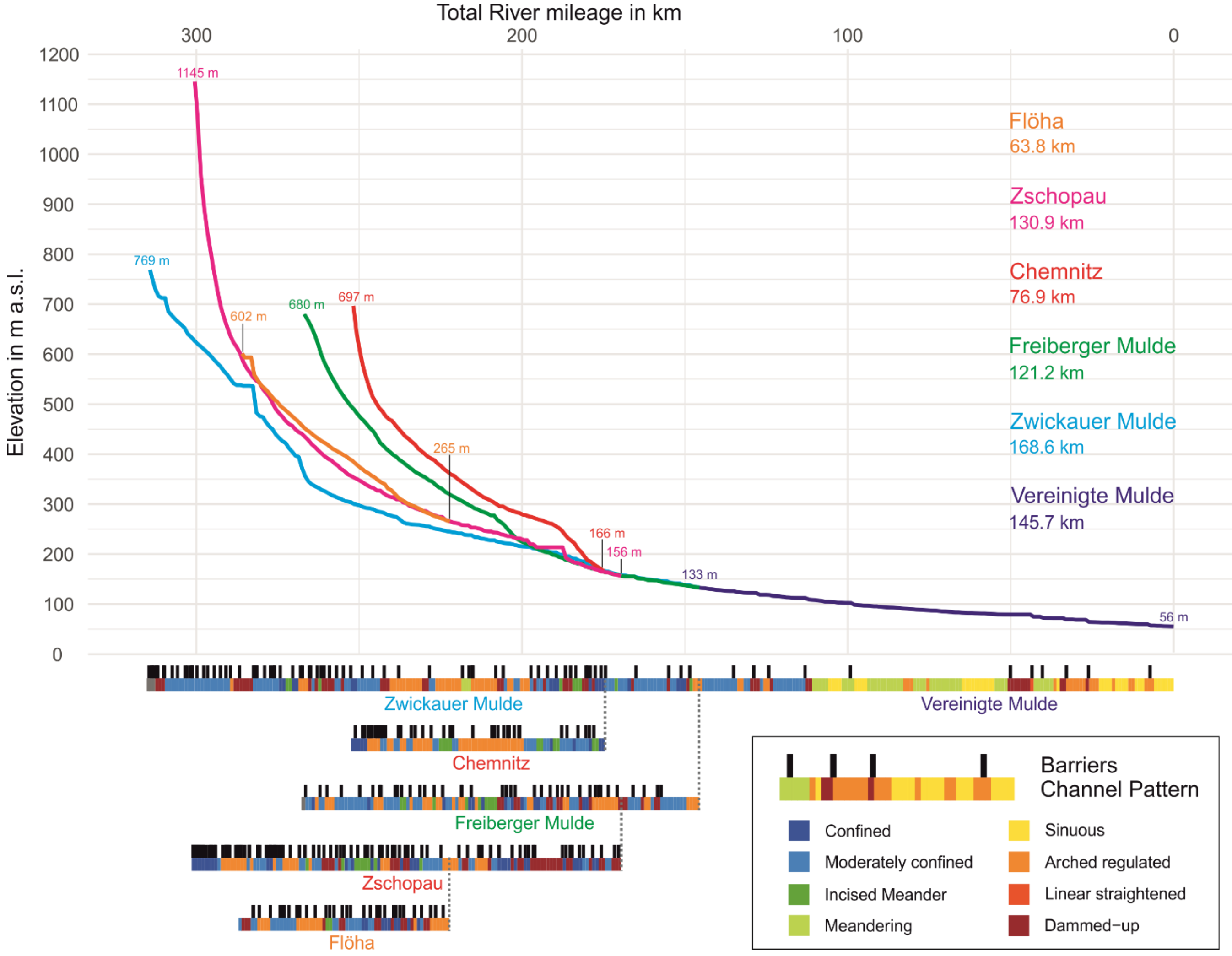


Fig. 10. Longitudinal profiles of the Mulde River and major tributaries showing barriers and channel patterns of the 2024 time slice. Data sources: AMBER Consortium, 2020; LfULG, 2024; NASA JPL, 2013; Table S1.

Table 4: Height and passability data for 2024 barriers. All data columns represent counts (n). Data source: AMBER Consortium, 2020; LfULG, 2024.

		Height			**Passability**				
River	Barriers	**No Data**	**1 - 3 m**	> 3 m	**No Data**	**Not passable**	**Passable**	**Up-stream**	**Down-stream**
Vereinigte Mulde	11	6	3	2	6	0	2	1	2
Zwickauer Mulde	77	2	40	8	18	33	11	15	0
Chemnitz/Zwönitz	46	2	15	2	20	11	11	3	1
Freiberger Mulde	40	0	30	2	5	21	4	9	1
Zschopau	122	0	61	10	41	53	13	14	1
Flöha	33	1	20	3	6	18	3	6	0

Total	329	11	169	27	96	136	44	48	5

This information cannot be easily transferred to earlier times, as any renovation work or weir heightening are not documented. Therefore, our diachronic comparative approach is limited exclusively to the presence or absence of barriers.

A comparison between the dammed-up channel patterns and the barriers is possible if one starts from the dammed-up channel pattern (Fig. 10). Conversely, however, it is not possible to conclude from the barriers that there is a dammed-up channel pattern, because the backflow effect is usually not transferable to the grid cell, especially with the smaller barriers.

5.4 Potential and limits of the historical dataset on Atlantic salmon distribution in the Elbe catchment

The dataset on the salmon catches enables a spatial and temporal reconstruction of salmon occurrences in the Elbe River system (Fig. 9) and represents an extension of an earlier dataset which was compiled by Wolter (2015). For the first time, the data set is provided as an open access dataset (Hegemann et al, 2025). The salmon catch record is based on secondary documented historical sources (Fig. 11a, b). Whereas the data since 1850 might reflect a reliable base due to a systematic documentation of numerous fisheries, including in the context or as part of artificial spawning programs, the data from the Early Modern Period and the Middle Ages are patchier.

Fig. 11 Histogram of documented salmon catches in (a) the Elbe catchment, (b) the Mulde catchment and (c) the Leisnig archive from 1432 to 2024. The time interval before 1850 in (a) and (b) bases only on secondary written sources. Pale blue shaded bars indicate time intervals without any salmon documentation. Empty white bars indicate time intervals with salmon occurrences but

without concrete catch numbers. Data sources: (a) and (b): Hegemann et al., 2025; (c): HStA Dresden 10036 Finanzarchiv, Loc 37651, Rep 42, Sect 1, Leisnig, Nr. 0003.

In order to further evaluate the data quality, we conduct a first micro-historical pilot study by exemplarily surveying previously unanalysed primary written sources in the Saxonian *Hauptstaatsarchiv* (Fig. 11c) and comparing the results with the previous dataset based on secondary sources only. The subject of the case study is the electoral salmon weir (*Lachsfang*) in the Freiberger Mulde River near Leisnig (Fig. 1c). It was built in 1617/18 on the orders of Sophie of Brandenburg (1568-1622). The Amt Leisnig had been granted to her in 1602 as part of her dower (Essegern, 2007) and the salmon catch was mainly used to supply her kitchen (SächsHStA, n.d.). The salmon catch was located by the weir of the Leisnig upper mill (Obermühle), which was first mentioned in 1378 and leased to the town council in 1548 (Kunze, 2007). The electoral family maintained the salmon catch until the second half of the 18th century. From then on it was considered increasingly unprofitable due to frequent damage and constantly rising repair costs and was finally abandoned.

The comparison of the three histograms (Fig. 11a-c) clearly shows that a systematic survey of primary written sources will highly enhance the historical knowledge on Early Modern salmon catches with regard to the total numbers of catches but also with regard to the somewhat simpler question about salmon presence and absence during a specific time interval and space. Therefore, Early Modern data only from secondary written sources are not suitable for a robust quantitative historical analysis but can only serve as a starting point.

5.5 Outlook: Potential and limits of the water body data and the preliminary historical data on Atlantic salmon distribution in the Mulde River system

Our data on historical water body structure allows a spatial and temporal assessment of the variability and change in channel patterns, floodplain land use and cumulative barriers for the Mulde River system. Using our semi-quantitative grid approach, the data on the water body structure from 1822 and 2024 can be compared with the data on historical salmon catches on a centennial scale. For the salmon catches, we used the complete data set from 1801 to 1900, as this is much more reliable especially for the second half of the 19th century, than the probably very incomplete data set just from the first half of the 19th century.

Comparison between channel patterns and salmon presence indicates a higher portion of meandering and sinuous channel patterns in grid cells with salmon presence for both time intervals (Fig. 12). In the 2024 time slice, grid cells without salmon presence display a higher portion of anthropogenic channel patterns.

A further comparison is promising for floodplain land use intensities and salmon presence in the Mulde River system. Grid cells with salmon presence show lower floodplain land use intensities (classes 2-4) for both time slices (Fig. 13). This effect further increases for the 2024 data set.

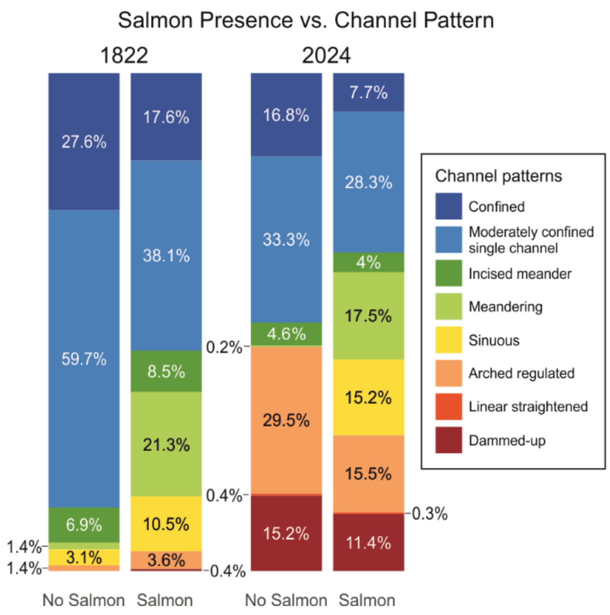


Fig. 12. Stacked barplots of channel patterns after Hohensinner et al. (2021) for grid cells with and without salmon presence in the Mulde River system for the 19th and 21st centuries. Data source: Table S1.

The combination of both the historical salmon catches and the cumulative barrier data show a decline in salmon presence with an increasing number of cumulative barriers for both time intervals (Fig. 8). There is also a decline in salmon presence in the upper reaches of the Mulde River in the 21st century (Fig. 8b), which may be associated with the significant increase in cumulative barriers over the last 200 years. This is also reflected for the entire Mulde River system (Fig. 14). Accordingly, the evidence for salmon presence decreases noticeable as the number of cumulative barriers increases.

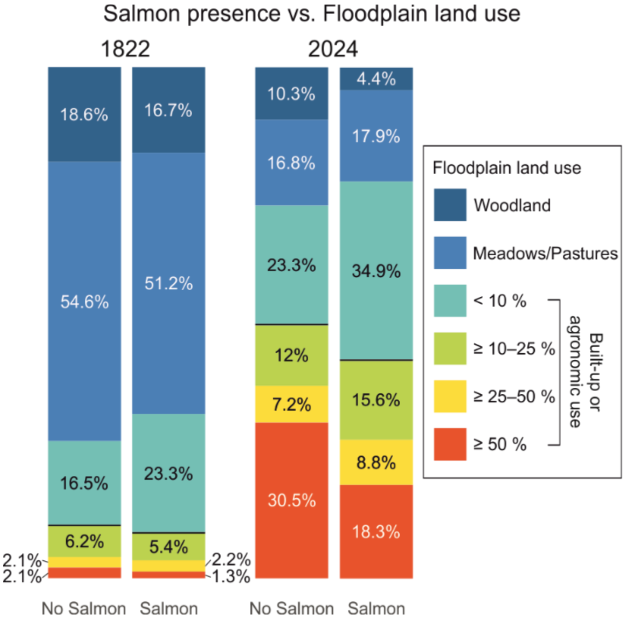


Fig. 13. Stacked barplots of floodplain land use for grid cells with and without salmon presence in the Mulde River system for the 19th and 21st centuries. Data source: Table S1.

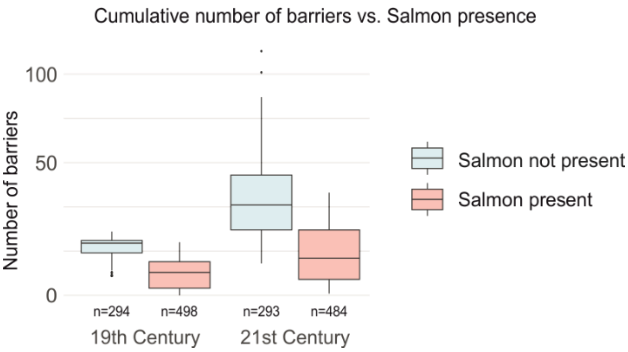


Fig. 14. Boxplot of cumulative number of barriers and salmon habitat ranges for the entire Mulde River system. N gives the number of grid cells with or without Salmon evidence for the respective time slices. Data source: Table S1.

The comparative analysis of historical water body structures and historical salmon occurrences must be interpreted carefully. Our data sets only form an initial stage here. Nevertheless, the perspective is promising, since larger spatial comparisons, and therefore an integration of further river systems, will enlarge the spatial heterogeneity of water body structures. In addition, the semi-quantitative grid approach can also be improved by the consideration of additional time intervals (Zielhofer et al., 2025) and by the consideration of primary historical sources especially for the Medieval and Early Modern Periods.

6 Conclusions

In this study, three parameters are developed and applied, which comparatively document changes in the water body structure in the Mulde River system between 1822 and 2024. The parameters are based on the analysis of old maps and the most recent topographical map. All three parameters, ‘channel pattern’, ‘floodplain land use’ and ‘barriers’ showed very good applicability with regard to the two analysed map series. They allow for the first time a comparative assessment of the water body structure within a historical perspective for the Mulde River system.

The natural **channel patterns** show a spatial differentiation in terms of upper and lower reaches on the one hand and the bedrock on the other. The anthropogenic impact in the Mulde River system is evident by the noticeable increase in anthropogenic channel patterns (dammed-up, arched regulated and linear straightened).

Floodplain land use serves as a parameter for the intensity of the anthropogenic impact on floodplain habitats but also as a proxy parameter for potential sources of pollution in the floodplain. Between 1822 and 2024 the proportion of agronomic use and built-up areas highly increased with a simultaneous decline in natural wood- and grasslands.

Regarding the barriers, the **cumulative number of barriers** serves as a proxy for river connectivity. A noticeable number of barriers already existed in 1822 in the Mulde River system and it has increased significantly again to this day.

Using all three water body structure parameters within a **semi-quantitative grid approach**, the intensities of the human impact on river connectivity and river habitat suitability can be documented multi-temporally and spatially indicating **a decrease in ecohydrological diversity** in the Mulde River system during the last two centuries. From a methodological point of view, our semi-quantitative approach is transferable and provides many possibilities for future comparative large-scale evaluations of river systems.

Regarding the potential impact of historical Mulde River connectivity and habitat suitability, we build an **open access database on historical Atlantic salmon presence** in the first order Elbe River system. Within the Elbe River system, the Atlantic salmon became extinct in the second half of the 20th century. This is evidenced in our study due to a gap in positive inventory reports during this time. In the previous 19th century the available written sources reached a maximum in documented salmon catches, which can be attributed to the meticulously written documentation within the framework of artificial spawning programs in the Elbe catchment during the second half of the 19th century. There are also records of salmon catches for the period after the salmon were reintroduced at the end of the 20th century, which reliably document the consistent presence of Atlantic salmon in the Elbe River system during the last three decades.

The Atlantic salmon database dates back to 1432. However, due to a lack of a systematic historical survey of high medieval to early modern primary written sources, the database is not applicable or should be handled with great caution for the time before 1850. This is indicated by our first historical survey on primary written sources at HStA Dresden, which indicates rich Atlantic salmon presence in the downstream Freiberger Mulde River during the 17th century, even in time intervals that were characterized by larger gaps in the initial Atlantic salmon data base of the Elbe River system.

As an outlook for further work, we conducted a first compilation of Atlantic salmon presence in the Mulde River system for the well documented second half of the 19th century and of the parameters of the water body structure that were derived from the historical Meilenblätter. Doing so, this indicates less historical salmon presence in grid cells with a high number of cumulative barriers and with more intense land-use. This is in accordance with the 2024 dataset, where salmon presence is lower in grid cells with higher cumulative numbers of barriers and more intense land use.

Author contribution

MO: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. MH: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. RH: Data curation, Investigation. KG: Data curation, Investigation, Writing – review & editing. LH: Data curation, Investigation. YH: Data curation, Investigation. NS: Data curation, Investigation. HS: Data curation, Investigation. EL: Data curation, Investigation, Writing – original draft, Writing – review & editing. SO: Software, Writing – review & editing. JRV: Methodology, Supervision, Writing – review & editing. LW: Funding acquisition, Supervision, Writing – review & editing. CZ: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest. Some authors are members of the guest editorial board of the E&G Quaternary Science Journal Special Issue 'Fluvial Architecture of Fluvial Anthropospheres'.

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