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Influence of 200 years of water resource management on a typical central European river

Does industrialization straighten a river?

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Abstract

Background

Over the last 200 years, the courses of most European rivers have experienced significant irreversible changes. These changes are connected to different kinds of anthropogenic river use and exploitation, which have varied from running water mills and rafting to large-scale hydroelectric power plants, industrial water withdrawal and flood protection measures. Today, in most developed countries, water quality and ecological river development are important factors in water management. The aim of this study is to evaluate the specific impacts of different time periods during the last 200 years on river courses and their effects on current river management using the example of the 165 km-long German Rur River (North Rhine-Westphalia). The Rur River is a typical central European upland to lowland river whose catchment has been affected by various phases of industrial development.

Methods

In this study, a range of morphological changes over the last 200 years are determined based on historic maps and up-to-date orthophotos. River length, sinuosity, oxbow structures, sidearms and the number of islands are used to investigate human impact. The results are correlated with historic time periods.

Results

This analysis shows that river straightening increases, especially during the Industrial Revolution, even without direct hydraulic channelization. The period and grade of river straightening have a direct morphodynamic impact on today's river restorations. Since the Rur River is a typical upland to lowland river, the results show an additional impact by geofactors, such as landform configurations.

Conclusions

Morphodynamic development is correlated with five historic periods of industrial development between 1801 and 2019 up to the introduction of the EU - Water Framework Directive (EU-WFD). Each period shows a different influence on the watercourse, which is connected with human intervention. Even if worldwide comparisons show that the five historical phases differ slightly in their timing between regions, they are applicable to other study areas.

Key Words: tipping point, human impact, industrialization, river course development, river straightening

Background

History of Human Influence on River Systems

Rivers are one of the most anthropogenically influenced ecosystems in the world [1]. Most European rivers have experienced extensive channel changes, whereby the human impact is an important key driver [2, 3]. Since the beginning of the Holocene, the influence of humans on the environment has continuously increased [4–6]; hence, many fluvial systems have been negatively and profoundly influenced worldwide by human actions for centuries [7–12]. In the early Holocene, rivers were mainly anabranching, which changed in the late Holocene [3]. While geomorphologic changes before the late Holocene are mainly attributed to climatic factors [4, 13], the establishment of agriculture and large-scale deforestation in the Neolithic period led to a tipping point [14, 15]. Increased human land use has led to siltation of secondary channels, which changes river morphology [3].

The first hydraulic engineering measures were river straightening, dam and weir construction and the construction of mill canals and ponds [13, 16]. In the Middle Ages, as the main energy source, the establishment of water mills increased dramatically [17].

Various studies have investigated human impacts on river systems worldwide at different times [7, 8, 18, 19]. Gibling evaluates human influences using worldwide examples and creates a timeline divided into six phases from the late Pleistocene to the Holocene [19]. He emphasizes that in many cases, serious changes were connected with the Industrial Revolution and technological advances in the 20th century, which are included in his 6th phase, the Technological Era (after 1800 CE) (cf. Figure 1).

In the last two centuries, changes in land use, industry, flood protection, drinking water supply and hydroelectric power measures as well as shipping have caused further morphodynamic impacts on fluvial systems [14, 20, 21]. In particular, the development of automated production and the steel industry has caused a higher demand for hydroelectric power, process water and transportation routes provided by waterways [22–25]. In the late 19th century, the Industrial Revolution led to changes in river morphology throughout Europe [26, 27]. The alpine Rhone, Isar and Danube Rivers, for example, were channelized in the mid- to late-19th century, causing braided structures and large gravel bars to form [28]. The Tisza River in Ukraine and Hungary has shortened by approximately 30% through river training [26]. Therefore, the increased use of fossil energy from 1950 onwards can be linked to rapid river degradation and river pollution in the Western World [27, 29–31]. Although sewage systems were introduced, pollution from industry, agriculture and urban areas since the late 19th century has led to long-term changes in river ecosystems [27, 32].

Today, industries are still dependent on the water supply and hydroelectric power [33, 34], and it is expected that anthropogenic influences on rivers will continue to increase [35, 36]. Apart from that, in recent decades, a rethinking of the protection of fluvial systems has occurred. Especially in Europe, sustainable development of water bodies has become a common goal with the legislative basis of the EU-WFD [37]. Therefore, the timeframe from the Middle Ages to modern times is considered to have had the largest impact on lateral channel movement due to hydraulic structures [33].

Five Phases of River Management on the Rur River

Hence, the culture of river management has changed several times within the last 200 years. Focusing on the history of industrial development, this study period of 200 years can be divided into five phases of river management of the Rur River (cf. Figure 2). Thus, each phase has different water management characteristics on which the emphasis is placed. The phases are to be understood as cultural epochs, and the time divisions are determined using the example of the Rur catchment. Cultural epochs are generally variable in time and space [38, 39].

Interventions in water bodies in favor of industry started in the Pre-Industrial Phase (1) in the 18th century with lignite and ore mining [40–42]. In the 19th century, as a result of water conflicts between agriculture and industry, textile companies were given preferential treatment [42].

In the Industrial Phase (2), rivers were primarily used for water-demanding industries. In this phase, in the Rur catchment, water-demanding industries, such as sugar cane and paper industries, settled near rivers in Aachen as well as Jülich and Düren [42, 43]. Increased water demands of industries led to a water crisis [42] and finally to the construction of larger dams from 1900 onwards, which ultimately had a greater impact on flowing waters [44].

The Industrial Phase (2) is superseded by the Agricultural Phase (3) after World War I, where large area structural changes for food production and a shift from water power to electricity occurred. Important land use changes occurred after the late 1940s when intense agriculture and rapid urbanization developed [45]. After World War II to the early 1980s, the reclamation of floodplains for agriculture as well as expanding settlements were the main goals of river management [42, 43]. Since 1980, water quality and the environment have been the focus (Phase of Ecological Improvement, 4). In 1986, waterbodies were recognized as part of ecosystems for the first time in the Federal Water Act in Germany [46].

Today, we are in the second management cycle of the EU-WFD (Water Framework-Directive) [47], the Phase of EU-WFD (5) (cf. Figure 2). Sustainability of running waters and renaturation largely determine the actions of people [48], but industries are still large stakeholders in water management [49, 50].

In this context, the increased use of water resources as well as flood protection are often connected with riverbed regulations [25, 51], but does industrialization truly straighten a river?

Despite the massive anthropogenic influences, geofactors of riverine landscapes still affect the morphology and hydrology of rivers and their floodplains today [52]. Irreversible tipping points in watercourse development are highly dependent on the nature of the catchment area, which is why watercourses react with varying degrees of sensitivity to a particular anthropogenic impact [53, 54].

Human Influences on Morphodynamic Structures

Sinuosity, oxbows, braided and anastomosing structures

Oxbows often develop from meander cutoffs [55, 56] and therefore are a sign of river straightening. Generally, a low degree of sinuosity indicates anthropogenic disturbance [57]. According to Gibling (2018), human impacts cause changes from meandering to braided planforms and from multithread channel to single channel riverbeds [19]. With a decreasing main channel sinuosity, a change from anastomosing to braided channels is common [58]. Braided streams are generally characterized by low sinuosities [59]. Therefore, braiding is a general indicator of river straightening. When sinuosity decreases and braiding increases, the development is often accompanied by higher peak flows and higher monthly discharge variability [59]. These changes in discharge are commonly caused by human activities, such as deforestation, mining and agriculture [60]. If a channel is anastomosing or braided, it depends on the sediment supply from upstream [61]. For example, Scorpio et al. (2018) found that braided structures only formed downstream of sediment confluences that were rich in sediment in the alpine Adige River [62]. Braided rivers have a high supply rate but a low transport capacity, which leads to the deposition of material [63]. Downstream of artificial river straightening higher river bank erosion occurs due to bedload deficits [57, 64], which explains changes from anastomosing to braided channels. Anastomosing structures are more common for lower slopes and non-confining thalwegs [55]. The main sediment transport is suspended load [55]. Anastomosing channels have a relatively low ability to erode and transport sediment [63] and therefore develop towards a natural equilibrium.

Side arms and islands

A marker of a natural and unspoiled bedload balance is a high morphological development capacity leading to the formation of islands and side channels [57]. Usually, hydraulic forces in channelized river sections are too high for island formation [65]. Islands reestablish when river channelization is dismantled [65] and are therefore a sign of increasing structural diversity. The dynamic equilibrium of a river is shown in small-scale changes, such as island formations [66]. Side arms vanish during times of high sediment input due to siltation and are restored through river management actions [67]. Therefore, they increase the structural diversity of the river.

Scope of Present Study

The aim of this study is to assess the correlation between river management in the last 200 years and the changes in river courses by means of historic maps and digital orthophotos using the Rur River as an example. Comparable studies showed that these types represent valuable sources for information on river channel changes and that the period of analysis should be at least 100 years [68]. Therefore, large-scale morphological changes over the last 200 years are determined using the following indicators: river length, sinuosity, oxbow structures, sidearms and number of islands. Due to the importance of the Technological Era after Gibling (2018) [19], this period is subclassified into different river management phases. Understanding the interaction between human influences and changes in fluvial systems from the past is the key to sustainable river management in the future.

Therefore, periods of hydraulic development, including industrialization, in the study area, the Rur River catchment (North Rhine-Westphalia, Germany), are compiled from the literature (cf. Figure 2). The influence of these phases of water management on the Rur River can be distinguished from each other via clearly formulated definitions. Afterwards, different historic maps and morphodynamic indicators are used to assess whether those periods lead to specific morphodynamic changes of the river within the specific Phases 1-5. Changes in river straightening and structural diversity of the river are determined from changes in the indicators by simple formulas. Differences between low mountainous regions and lowlands are also considered to address the impact of geofactors. Finally, the transferability of the results to river systems worldwide is discussed.

Study area

To investigate the long-term effects of anthropogenic influences on fluvial systems, especially during industrialization, the Rur catchment (North Rhine-Westphalia, Germany) was chosen. Changes in smaller catchments have direct effects on the fluvial system, and morphological investigations are possible with higher spatial resolution [8, 69]. Hence, the Rur River catchment is particularly suited since it is of a moderate size with 2,361 km^2 [70]. It also extends from the mid-mountainous area of the northern Eifel Mountains in its upper reach to the lowlands of the Lower Rhine Embayment in its lower reach [71]. The springs of the 165 km-long Rur River are located in the raised bog area of the High Fens in Belgium at an altitude of 660 m above sea level [70]. In the Dutch city of Roermond, the Rur River flows into the Meuse River at an elevation of 30 m above sea level [70]. Approximately 6.7% of the Rur catchment is located in Belgium, approximately 4.6% is within Dutch territory, and almost 90% is located in Germany [72]. The catchment area of the Rur River comprises 7% of the Meuse catchment area, but it is the only river in the catchment that is significantly regulated by dams, which balance the water levels [71].

After approximately 10 river-km in Belgium, the upper reach of the Rur River flows through the Eifel, a low mountain range in Germany [73]. The Eifel is one of the most rural areas in Germany [74]. The catchment is wholly anthropogenic, marked by forestry in the highlands and grassland and farmland on the plateaus [71]. The Lower Rhine Embayment is marked by agriculture [75] and lignite open cast mining [71]. The largest cities in the catchment are Aachen, Düren, Stolberg, Eschweiler and Heinsberg in Germany and Roermond in the

Netherlands, which are all located in the middle and lower catchments of the Rur River (cf. Figure 3).

North Rhine-Westphalia has a comparatively humid but cool climate due to its proximity to the Atlantic Ocean [71, 76]. Precipitation in the Eifel Mountain region is significantly higher than that in the northern lowlands [71]. Due to its source region in Eifel, the year-round aquiferous and dam-regulated Rur River has a rain- and snow-influenced discharge regime and is affected by snowmelt from the low mountain range [43].

Related to climatic characteristics, the river regime is pluvio-nival with the highest discharge in winter and long periods of dry weather runoff in summer. Flood events occur mainly in spring and winter due to prolonged rainfall or snowmelt and in summer due to storm events. Due to the dams, the discharge of the Rur River is regulated; thus, runoff peaks are smaller [41, 43].

In the last 200 years, northern Eifel has been characterized by urbanization, grassland cover of arable land in the low mountain ranges and foothills, and reforestation measures in the Eifel forests [77]. Today, the Rur River is strongly anthropogenically influenced. Private companies, especially those in the paper industry, are still the largest water consumers in the Rur-Eifel region to date [76, 78]. Most days of the year, various reservoirs in the upper catchment withdraw a reduced amount of water, which is morphodynamically ineffective [78]. The largest settlement on the Rur River in the low mountain range is Monschau, where massive bank protection characterizes the river (cf. Figure 4 b). In the low mountain range, the Rur River is categorized as a German river type 9, indicating a silicate, low mountain range river rich in fine to coarse material. The course of the river today in the upper catchment is partially similar to the ecological mission statement, which calls for stretched to slightly sinuous, natural sections existing with numerous characteristic longitudinal benches, sliding slopes and riffle pool sequences [79, 80]. Side channels would be characteristic but are missing [79]. In the lowlands, the Rur River is categorized as a German river type 17, indicating a gravel-embossed lowland river [73]. Immense hydraulic engineering between the 1940s and 1970s led to a completely embossed straightened channel with strong incision [80]. Additionally, the flow is regulated by dams, and a large number of transverse structures restrict continuity [80].

Nevertheless, near-natural sections can be found in the lowlands between Schophoven and Kirchberg and between Jülich and Linnich (cf. Figure 4 f)) [80].

Focus Regions

The three focus regions cover one section each of the upper (A), middle (B) and lower (C) reaches of the Rur catchment (cf. Figure 6, Table 1). Focus region A and focus region B cover the Rur segments that are siliceous, low mountain rivers rich in fine to coarse material (German river type 9). In focus region C, the Rur River is characterized as a gravel-embossed lowland river (German river type 17).

Focus region A is located upstream from the dams starting at the end of the village of Monschau. In the low Eifel mountain range around Monschau, large riverbed shifts are topographically not possible. Therefore, characteristic waterway bends are used to mark the start and end of the focus region. Focus region B, which is 20 km long, covers a typical agricultural area. In this focus region, the city of Düren plays an important role in industrial development in the Rur catchment. As a transshipment point for rafted wood in the Middle Ages, it later became the main location for the paper industry, and afterwards, sugar cane factories (cf. Figure 7). Focus region B is located downstream from today’s dams, and the Inde tributary marks its lower boundary. The Wurm tributary marks the lower boundary of the 15 km-long focus region C.

Table 1: Characteristics of the focus regions.

	mid. elevation	**slope**	**average discharge**	
			winter	**summer**
	[m.a.m.s.l.]	[%]	[m^3/s]	[m^3/s]
Focus Region A	395	0.7	5.7	3.9
Focus Region B	100	0.3	12.0*	
Focus Region C	30	0.1	26.7	17.8

* No detailed data for summer/winter available

Methods

To analyze the river course development over the last 200 years, historic maps and digital orthophotos are evaluated in three focus regions (cf. Figure 5).

Map sheets were used that were previously georeferenced by the Cologne District Council. Therefore, information on accuracy and rectification errors cannot be given. However, since the analyses are based on quantitative data, for the purpose of this paper, an accurate cutoff of the focus regions in the various maps is more important than the accuracy of the georeferencing. To ensure that the focus regions in all time slices included identical river sections, their start points and end points were defined with the help of historic monuments and tributaries, which can be found in all historical maps and orthophotos. Details on the pixel size and scale of different maps are shown in Table 2.

Table 2: Information regarding the pixel size and scale of the different maps used in this study.

Map	***Year of origin***	***Size of 1 pixel [m x m]***	***Scale***	***Techniques***
Tranchot	1801-1828	1.5 x 1.5	1:25.000	Hand sketched
Uraufnahme	1836-1850	1.5 x 1.5	1:25.000	Hand sketched
Neuaufnahme	1891-1912	1.5 x 1.5	1:25.000	Chalcography and lithographic limestone; First and topographic map
TK1937	1936-1945	1.5 x 1.5	1:25.000	/
DOP1998	1998	0.3 x 0.3	/	Photogrammetric methods
DOP2003	2003	0.3 x 0.3	/	Photogrammetric methods
DOP2010	2010	0.2 x 0.2	/	Photogrammetric methods
DOP2013	2013	0.2 x 0.2	/	Photogrammetric methods
DOP2016	2016	0.1 x 0.1	/	Photogrammetric methods
DOP2019	2019	0.1 x 0.1	/	Photogrammetric methods

Digitalization of river courses and resolution

River courses are digitalized manually with QGIS as line objects approximating the middle line of the riverbed. Quality parameters for the accuracy of digitalization were introduced to make the length of the digitalized river courses comparable. The accuracy of a line object can be identified by its number of knots per length. Adding more knots leads to a better approximation of curved elements but elongates the total length. With the criterion of 4 knots per 100 m, river course comparability is ensured. The consistent distribution of knots is controlled visually using the distance matrix function. For straightened river segments, a coarser resolution is sufficient, whereas highly sinuous segments need more knots for an adequate approximation.

Additionally, morphodynamic structural elements of the Rur River are digitalized, which serve as indicators for morphodynamic activity and river straightening (cf. Figure 8). For this study, islands in the riverbed that are not part of a braided river section are digitalized as islands. They can quickly obtain vegetation [66] and are more permanent than bars [81]. Large islands that divide the channel into two approximately equal anabranches, causing the river corridor to widen, are not marked as islands but as anastomosing channels. Anastomosing channels are multithread channels in which the outflow is divided into a multitude of watercourses [59]. Braided channel structures are characterized by intertwined blurred shorelines and variable bedload deposits in the riverbed [59]. Braid bars are not vegetated [82]. Although anabranching channels can be braided [81], in this study, braided single-channel rivers and anabranching rivers are distinguished [83]. Oxbows are either permanently connected to the watercourse or separated former river sections [84], and hence are constantly or temporarily flowing through former watercourses [84]. Side arms are permanently flowing side waters, whose start and end are attached to the main course. Side arms differ from anabranches since they are smaller than the main channel.

Hand- sketched historic maps at a low resolution and vegetation in digital orthophotos lead to difficulties in digitalization, as also recognized by Roccati et al. [85]. The transition between islands and short sections of single braided channel or two anastomosing channel structures is fluent. Therefore, some structural elements are digitalized with a possible alternative (cf. Table 3).

Table 3: Decision matrix for digitalizing structural elements

Characteristics							structure	(possible) alternative
channel			river corridor	island(s)				
no. of channels	enlarged	flow distribution	widening	size	number	vegetated		
1	yes	-	no	small	more than 1	no	***braided river***	island
	maybe	-	no	small to medium	1	no	***island***	braided river (beginning/end of section)
	no	-	no			maybe	***island***	
1 or 2	yes	-	maybe	medium to large	1	yes	***island***	anastomosing river
more than 1	yes	evenly	maybe	medium to large	1 or more	yes	***anastomosing river***	island(s)
			yes	large	1 or more	yes	***anastomosing river***	
2	-	uneven	yes	large	1	yes	***side arm***	anastomosing river
		definitely uneven	yes	large	1	yes	***side arm***	

For the analysis, the first choice for the type of structural element is considered with a weight of 0.8, and the alternative is considered with a weight of 0.2. From the digitalized channels and its structural elements, indicators are computed for each time slice according to Table 4. Inaccuracies reaching 20 m in historical maps of the 19th century lead to a variation in the results of less than 0.2%. Focus regions are not affected by sheet lines or map edges. Therefore, the results can be specified without an error range.

Computing the change in the total river length of the Rur River in the three focus regions, today's river length is compared to the corresponding length from historic maps or orthophotos. A change of 0.0 means that the total river length has not changed in comparison to 2019, whereby a change of 0.1 means that the river course has been 10% longer in a previous time slice compared to today. A change of -0.1 means that the river course was 10% shorter in previous times. With this normalized approach, focus regions can be compared with each other in addition to covering unequally long river sections.

To calculate the river sinuosity, the thalweg for each focus region is computed using a digital elevation model (DEM) with a grid resolution of 25 meters (DEM25). By using a relatively coarse DEM, it is ensured that the thalweg and not the river coarse is computed (e.g., [86]).

Table 4: Morphologic indicators for channel changes and their meaning. DEM25=digital elevation model with a grid resolution of 25 meters, DOP= digital orthophoto.

INDICATOR	DESCRIPTION	MEANING
CHANGE IN TOTAL RIVER LENGTH	Total river length of the Rur River in a focus region compared to today's river length, estimated from the DOP 2019	Decrease in the river length is a sign for artificial straightening [87]
SINUOSITY	Total river length of the Rur River in a focus region divided by the thalweg [88–92], computed with the DEM 25	Reduced sinuosity often is a sign for river straightening [54, 93], an increase is a sign for tending towards a new equilibrium [87] but can also occur when the flow velocity increases [55].
RELATIVE LENGTH OF CHANNEL STRUCTURES	Total length of channel structures in a focus region divided by the river length in the focus region	An increase in the channel structures is a reaction to changes in the sediment load and/or changes in the river slope [87], often due to straightening [94]
- ANASTOMOSIN G CHANNEL	… for anastomosing channels	Anabranching rivers are often caused by flood-dominated flow regimes [63, 83]
- BRAIDED CHANNEL	… for braided river structures in single channels	Sign for excess bedload, coarse bottom substrate and high valley bottom slope [57, 95], instable state [96]
- SIDE ARM	… for side arms	Occur at flood events as a reaction to hydraulic stress; today side arms are preserved as habitats [97]
RELATIVE NUMBER OF OXBOWS	Number of oxbows in a focus region divided by the river length in km	Oxbows as channel cut-offs are a sign for river course shortening [55]
RELATIVE NUMBER OF ISLANDS	Number of islands in a focus region divided by the river length in km	Changes in islands indicate recent flood events, island formation is a sign for coarse sediment input [55]

Indicators are used to evaluate the development of river straightening (Eq. I). Additionally, whether the structural diversity of rivers is increasing is evaluated (Eq. II). If structural development is driven by fluvial processes it is very likely self-sustaining [98].

The increase in river straightening between two time slices is defined as:

$$\Delta_{Straightening} = -\Delta_{Sinuosity} + \Delta_{Braiding} + \Delta_{Oxbows} \quad \text{(Eq. I)}$$

With: $\Delta_{Sinuosity}$ Change in sinuosity between two time slices; indicator for river straightening according to [54, 58, 93]

$\Delta_{Braiding}$ Change in length of braided channel sections between two time slices; indicator for river straightening according to [58, 63, 95]

Δ_{Oxbows} Change in the number of oxbows between two time slices; indicator for river straightening according to [55]

The increase in structural diversity between two time slices is defined as:

$$\Delta_{Structural\ Diversity} = \Delta_{Side\ Arms} + \Delta_{Anastomosing} + \Delta_{Islands} \quad \text{(Eq. II)}$$

With: $\Delta_{Side\ Arms}$ Change in length of side arms between two time slices; indicator for river straightening according to [97]

$\Delta_{Anastomosing}$ Change in length of anastomosing channels between two time slices; indicator for river straightening according to [63]

$\Delta_{Islands}$ Change in the number of islands between two time slices; indicator for river straightening according to [55]

To evaluate whether the Rur River experienced significant straightening during the Industrial Phase (2), the increase in river straightening (Eq. I) is evaluated in each of the five phases. A positive value means, that the river has experienced straightening during a specific period. A negative value means, that straight river sections have been reduced. Additionally, one assumes an increase in structural diversity in the Phase of EU-WFD (5). Therefore, as a second outcome value, the increase or decrease in structural diversity within the five phases is evaluated.

Results

First, changes in river length and sinuosity in the three focus regions are evaluated. In focus region A, the river course was 2.6% shorter in the early 19th century compared to today, meaning that a small river elongation has occurred (cf. Figure 9). The river section elongated from 14.44 km to 14.82 km. In focus region B, a river course shortening of approximately 20% has occurred during the same time period. The length of the river section changed from 23.08 km to 19.20 km between the early 19th century and 2019. In focus region C, the largest river course shortening of approximately 43% has occurred since the early 19th century. Here, the length of the river section changed from 19.05 km to 13.29 km. Since the 21st century, the length of the river courses has remained static in all three focus regions.

Overall, the total river length changed the least in focus region A in the low mountain area. In the lowlands, greater changes in total river length occurred, whereby the greatest change occurred in focus region C, where the Rur River is categorized as a gravel-embossed lowland river.

The sinuosity in focus region A slightly increased from 1.11 to 1.14 over the last 200 years (cf. Figure 9). According to the criteria of Brice [92], the Rur River in focus region A is classified as sinuous in all five phases. In focus region B, the sinuosity dropped from 1.02 to 0.85, meaning that the main course of the river is shorter than the thalweg predicted by the DEM25. The largest decreases in sinuosity occurred during the Pre-Industrial (1) and Agricultural (3) Phases. With a sinuosity smaller than 1.06, the Rur River in focus region B has been straight over the last 200 years [92]. The Rur River in focus region C changed its sinuosity from 1.30 to 0.91. Therefore, the river course changed from meandering to straight [92]. Since the early 21st century, river sinuosities have stabilized with a very slight tendency to increase.

Braided channels only occur in small areas, whereby anastomosing channels can be found more often (cf. Figure 10 a). In the Pre-Industrial Phase (1), the length of anastomosing channels increased from 1.5% (approx. 0.2 km of additional channel length) of the total river length in focus region A to 3.5% (approx. 0.5 km). During the Industrial Phase (2), anastomosing channels almost vanished (approx. 0.03 km), but some braided river structures occurred (approx. 0.04 km). Since the Phase of EU-WFD (5), anastomosing channels are expanding again (back to approx. 0.2 km). In focus region B, anastomosing channels had significant lengths during the Pre-Industrial Phase (1) (approx. 6.9 km). During Phase 2, the length of the additional channel declined to approx. 0.6 km. However, braided channel sections were at their longest, with approx. 1.7 km. Since the Agricultural Phase (3), anastomosing channels have expanded slightly (approximately 1 km of additional channel length), and since the early 21^{st} century, braided channel sections have disappeared again.

Side arms are not present in focus region A, which can be explained by the steep thalweg (cf. Figure 10 b). Only one anastomosing channel is digitalized with a “side arm” as an alternative in early orthophotos (1998 and 2003). Later, a third channel occurs, marking the section as an anastomosing river. Due to dense vegetation, the channel width cannot be determined. In focus region B, the total length of the side arms decreased during the Industrial Phase (2) from >1 to 0.6 km. Today, side arms total approximately 2 km in focus region B. In focus region C, side arms were of significant length during Phase 2. Four side arms had a total length of approximately 2.6 km. Today, only one anastomosing structure is digitalized with a “side arm” as an alternative.

In focus region A, oxbows rarely occur, with less than one oxbow per river-km; however, they increased in the late 20^{th} century, when two small oxbows occurred (cf. Figure 10 c). In focus region B, oxbows occur more often. In the 19^{th} century, 12 to 48 oxbows were counted in hand-sketched maps. After Phase 2, the number of oxbows per km dropped from approximately 2.0 to 0.5 with a decreasing tendency to the present . Since the 21^{st} century, approximately five oxbows have been counted in orthophotos. In focus region C, a maximum of 24 oxbows occurred in Phase 2. Afterwards, numbers have been declining, reaching three oxbows today.

Overall, the number of islands per river-km has decreased in the last 200 years in focus region A from four to one island (cf. Figure 10 d). In focus region B, the average number of islands varies heavily between 12 islands (map of Tranchot) and one island (DOP2010). After a decrease in islands during Phase 1 in focus region C from six to two, the number of islands stayed low. In focus region C, between three and one islands were counted in the first topographical map and orthophotos.

The greatest changes in river sinuosity occur at the Rur River in focus region C during Phases 2 and 3 (cf. Figure 11). In focus region B, the decrease in river sinuosity is almost as significant as that in focus region C. The largest changes in braided and anastomosing channel sections occur in focus region B. During Phases 1 and 2, anastomosing channels decreased and braided river structures increased. During Phase 3, both braided and anastomosing channels as well as the sinuosity of the Rur River decreased in focus region B. The number of oxbows greatly varied during Phase 1, Phase 2 and Phase 3 in focus regions B and C. Additionally, the number of islands varied during this time, but for both indicators, a significant increase during the Industrial Phase (2) can be observed. Since the general focus shifted towards improving the water quality and sustainability in river management (Phases 4 and 5), the number of oxbows slightly decreased and the number of islands slightly increased in focus region B, whereas both small-scale indicators decreased in focus region C.

With these indicators (cf. Figure 11), using equations I and II, the development of river straightening and structural diversity in the five phases of river management can be evaluated (cf. Figure 12). In contrast to the other two focus regions, no river straightening is observed in focus region A. Additionally, changes in structural diversity are very small in focus region A. In the Pre-Industrial Phase (1), river straightening and structural diversity decreased in focus region B and increased in focus Region A. During the Industrial Phase (2), both river straightening and structural diversity increased in focus regions B and C, which are both located in the lowlands of the Rur catchment.

During the Agricultural Phase (3), developments were similar to those in the Pre-Industrial Phase, except structural diversity further decreased. Since the 1980s (Phase of Ecological Improvement (4) and Phase of EU-WFD (5)), river straightening has decreased, but structural diversity has only increased for focus region B.

The Rur River was only regulated in small local sections before 1950 [99]. Between 1962 and 1970, larger sections from Düren to Heinsberg were channelized, leading to an artificial shortening of the river course [42, 100].

Discussion

The results show the development of river length, sinuosity and morphodynamic indicators over five phases of river management during the last 200 years. River length and sinuosity are direct indicators of river straightening. However, the validity of indicators derived from morphodynamic structural elements needs to be discussed, since they are dependent on geological and climatic factors and river type.

River development in the Rur catchment

River straightening

In comparison to focus region A in the low mountainous area, focus regions B and C in the lowlands experienced significantly more changes over the last 200 years (cf. Figure 13 e). River straightening, which leads to channel shortening, is often connected with land reclamation for agricultural activities. A study from Brookes shows that river straightening is less likely to be used when valleys are too steep for farmland [87], as is the case in the low mountainous area of focus region A. In addition, the small changes in sinuosity and river braiding in focus region A in comparison to focus regions B and C indicate that the narrow valleys lead to a more stable river morphology [82, 101].

Changes in sinuosity from 1.02 to 0.85 in focus region B, which is characterized by farmland, indicate that the river has experienced artificial straightening. During the Pre-Industrial Phase (1), the river length in focus region B significantly decreased, although river regulation works started more than 100 years later [99]. This leads to the theory, that intense agricultural activities to make fertile floodplains usable and reduce flooding led to river straightening during this phase. In addition to agriculture, local riverbed straightening around bridges is common [102], which means that an expanding infrastructure leads to river straightening. A considerable expansion of industrial and urban settlements in focus region B (cf. Figure 7) is another explanation for river straightening in this area.

With a decreasing sinuosity and assuming an increase in oxbow and braided river structures are signs of river straightening, the Industrial Phase straightened the river. In addition, structural changes over large areas for agriculture led to river straightening in the lowlands. Some of these changes can be explained by large-scale river regulation between 1962 and 1970 in the middle and lower reaches [42, 100].

Structural Diversity

During the Industrial Phase (2), the number of islands increased, which can be explained by a higher sediment yield due to land clearance and deforestation for uprising industries [42]. The significant drop in islands during Agricultural Phase (3) in focus regions B and C can be explained by dam construction in the 20th century and the resulting regulation of discharge in the Rur River. In particular, the systems of three dams, as they are installed in the Rur River, can trap nearly all inflowing sediments [103]. In addition, the land use change, which was connected with land reclamation, explains the decrease in side arms and oxbows during the Agricultural Phase (3) in focus regions B and C (cf. Figure 13). Since the general focus shifted towards improving the water quality and sustainability in river management in the late 20th century, the number of oxbows slightly decreased and the number of islands slightly increased in focus region B, whereas both small-scale indicators decreased in focus region C. Regarding the Agricultural Phase within the Technological Era according to [19] one needs to keep in mind that in the early Anthropocene, land consumption for farming was considerably higher [104]. Hence, morphodynamic changes in the Agricultural Phase according to this study very likely intensified during the early Anthropocene.

In the 20th century, the reduction in baseflow levels due to the installation of hydroelectric power plants in many rivers led to the siltation of many side arms [105]. In addition, the increasing urbanization from the 20th century onwards has also led to increased sediment inputs into the waters at the beginning of urbanization due to land plot clearing [93]. If urban structures are largely developed, the sediment input is reduced again, but the hydrological retention of the area is greatly reduced [93]. At the end of the 20th century, restoration of side arms began to create habitats [105].

Contrary to expectations, structural diversity does not increase significantly in the Phase of EU-WFD (5). On the one hand the Phase of Ecological Improvement and the Phase of EU-WFD are much shorter than previous ones, and therefore, the river has less time to develop. On the other hand, human interference on the Rur River changed key drivers such as hydrology through damming and land use. Geology, biology and hydrology can be considered key drivers of river morphodynamics [101]. These drivers balance each other, which explains why anabranching channels are stabilized by vegetation, jet hydrology has only a minor impact, and braided river sections are not influenced by vegetation but rather by high stream power [101, 106]. When a key driver is anthropogenically over-pronounced, natural river recovery will be slow unless the impact can be balanced through (artificial) river restoration [101]. Filling incised channels or reintroducing the establishment of protected areas for beavers are two examples of countervailing measures [3, 101] restoring "wilder" river sections. For the last two decades, beavers have repopulated northwest Germany [107]. The repopulation of beavers in the Rur catchment is carried out and accompanied by local institutions. Today, numerous beavers are again living on the Rur River and especially on its tributaries [108]. Nevertheless, the analysis of orthophotos did not show evidence for these animals in the focus regions, and morphodynamic effects of the beaver population could not be observed in this work. Regardless, the repopulation holds chances for future river development [109]. Today, "controlled rewilding" on suitable river sections is promoted to create valuable habitats with native vegetation [110]. In the 19th and 20th centuries on the Wurm River, a main tributary of the Rur River, water mills from medieval times were abandoned [111, 112]. When abandoned weirs were partially removed, mill ditches were left to "rewild" [111]. This phase of "natural rewilding" was very local and soon superimposed by institutional river regulation. Thus, we expect that "controlled" or "natural rewilding" will be used for river restoration in the future. . Future studies should be conducted to determine the effects of rewilding on river morphology.

European transferability of the concept of the five phases of river management

To transfer the findings to other river systems, the transferability of the five phases of river management, which apply to the Rur catchment, needs to be discussed. Therefore, the five phases of river management in the Rur catchment are compared to the history in catchments with increasingly strong industrial development in the last 200 years. Furthermore, findings from recent GIS-based studies of anthropogenically influenced development on rivers in the Technological Era are compared to this study to find generalities.

Generally, the period from the late eighteenth century to World War I is declared a phase of European industrialization, but the growth rate varies greatly between different countries [113]. Around the fourth to fifth decades of the nineteenth century, the phase of economic preparation was completed for countries in middle Europe, and their industrial development sped up [113]. River straightening and the increase in structural diversity on the Rur River are explained by the catchment-specific development of the last 200 years.

In Poland, a preparation phase for industrialization took place in the mid-19th century [114], approximately 100 years behind the development in the Rur catchment. The landscape of the Vistula catchment has been influenced since the 13th century through water mills and settlements [17]. Over the last 200 years, landscape changes, differences in the use of process water and drainage, as well as the construction of infrastructure have impacted the development of the Vistula River [17]. Since the early 20th century, river channelization and straightening for shipping have intensified in Poland [115]. Similar to the Rur catchment, the Skawa River was not channelized for navigation, but industrialization led to irreversible changes in river morphology [116]. After World War II, industrial development in Poland sped up, so the last 75 years can be viewed as the main part of the Industrial Phase [114]. Additionally, the demand for process water was still growing 25 years ago [117]. In Poland, industrial development is accompanied by the construction of small water mills as local and independent energy sources [118]. After intense river straightening on river systems in northern Poland in the last century, the water quality decreased [119]. Since the early 21st century, the situation has improved due to oxbow and old arm restoration and its maintenance

[119]. This development is comparable to the Phase of Ecological Improvement and the Phase of EU-WFD in the Rur catchment.

For the Skawa River, which is a mountain tributary of the Vistula River, five digitalized maps from the mid-19th century to 2016 were evaluated to explain the human impact on the river [116]. Similar to the Rur River in its upper reach, the Skawa River is a gravelly embossed river [116]. Witkowski evaluated sinuosity, the braiding and anastomosing index, as well as the average number of mid-channel forms and the average distance of the outer banks of the river channel [116]. Although indicators and proceedings slightly differ from the present study, the findings are very comparable. In the early 20th century, agriculture and settlements in the floodplain of the Skawa River led to the construction of embankments [116]. Between 1864 and 1911, islands decreased, and the bed narrowed, meaning that anastomosing structures decreased [116]. On the Rur River, a drop in islands also correlates with increasing settlements and agriculture in the floodplains (cf. Figure 10). In the mid-20th century, the riverbed of the Skawa River was completely channelized [116]. Since the 21st century, more anabranching structures have occurred, and sinuosity has increased again after the removal of riverbank protections on the Skawa River [116]. The channel width has increased since the late 1970s. These developments overlap with the Phase of Ecological Improvement and the Phase of EU-WFD of the Rur River.

This means that the anthropogenic influence on the rivers is slowly adapting overall between European countries in moderate climatic zones. In summary, the examples show that the development of river management in the last 200 years is comparable in Europe.

Worldwide context

Common anthropogenic drivers of morphological changes in rivers worldwide are land cover and land use changes, dam construction, bank protection and instream mining [120]. In the early days of Industrial Phase small-scale water mills were an important energy source [121]. During the peak time of the Industrial Phase, rivers played a primary role in transportation, which led to the building of various canals [122–124]. Over the past 150 years, the Mississippi

River has been straightened mostly for navigation [66, 125]. At the same time, navigable canals in France extended [58]. In England in the early 19^{th} century, canals expanded, providing a cheap way to transport coal [126]. The Rhine, Rhône and Danube Rivers were also channelized in the 19^{th} century [127]. Swedish hydropower developed after World War I for industrial purposes, which led to river regulation [128]

Although the Rur River was not channelized for shipment, it straightened during the Industrial Revolution. Therefore, in industrialization periods , the impact of human activities straightens rivers, either by direct channel construction or by overall anthropogenic influences on the river.

Large river course structures such as anastomosing structures are not dependent on a certain climate type [63], so it can be assumed that river straightening during an industrial phase occurs independently from climate conditions and discharge regime. Nevertheless, valley configurations, base slope and sediment input are important for the formation of structures, such as braided and anastomosing sections and islands.

Conclusions

In this study, the specific human impact of different time periods on river courses during the last 200 years is investigated using the example of the Rur River (Germany, North Rhine-Westphalia), which is a typical European upland to lowland river.

Five historic phases of industrial development between 1801 and 2019 can be distinguished:

1. Pre- Industrial Phase (Mid-18^{th} – mid-19^{th} century)
2. Industrial Phase (Mid-19^{th} century – WWI)
3. Agricultural Phase (After WWI – 1980s)
4. Phase of Ecological Improvement (1980s – 2000)
5. Phase of EU-WFD (From 2000 to the present)

These phases correlate with changes in the river course, which can be explained by corresponding human interventions. The changes are detected by means of the following morphodynamic indicators sinuosity, anastomosing and braided river structures, side arms, oxbows and islands. Changes in river straightening and structural diversity are determined from these indicators by two simple equations.

The morphodynamic indicators show significant differences between focus regions in the low mountain range and in the lowlands. In total, focus regions in the lowlands are more strongly characterized by changes over the last 200 years compared to focus regions in the low mountain area. In this context, the sinuosity or river braiding indicators show that the mountainous valley configurations lead to a more stable river morphology.

The Industrial Phase, in contrast to the Pre- Industrial Phase, was characterized by intense river straightening, indicated by decreasing sinuosity and increasing numbers of oxbows and braided river structures. The Agricultural Phase led to river straightening in the lowlands due to land reclamation. Both the Phase of Ecological Improvement and the Phase of EU-WFD show no significant changes so far, which can be explained by the short time frame.

A combination of historical maps and digital orthophotos together with historical documents is very well suited for comparable investigations.

The comparison of historical periods in different regions generally shows a global transferability of the concept of the five river management phases. Since the different periods are to be understood as cultural epochs, their starting and ending points may vary in time and space, depending on factors such as wealth disparity or legislation. Therefore, they are still applicable to other study areas, especially in regions characterized by an earlier development stage of industrialization.

To complement this study, further research in regions with strongly differing historical frame conditions and physiographic differences is needed. The key to sustainable river management in the future is understanding the interaction between fluvial systems and human intervention in the past. Thus, the findings and the concept of this study can be used for further research and investigation.

Declarations

Authors' contributions

SW and VE wrote the first draft of the manuscript. All authors contributed to specific aspects of the manuscript. All authors read and approved the final manuscript.

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References

1. Bandyopadhyay S, De SK (2017) Introduction. In: Bandyopadhyay S, De SK (eds) Human Interference on River Health, vol 13. Springer International Publishing, Cham, pp 1–14
2. Scorpio V, Aucelli PPC, Giano SI et al. (2015) River channel adjustments in Southern Italy over the past 150years and implications for channel recovery. Geomorphology 251: 77–90. https://doi.org/10.1016/j.geomorph.2015.07.008
3. Brown AG, Lespez L, Sear DA et al. (2018) Natural vs anthropogenic streams in Europe: History, ecology and implications for restoration, river-rewilding and riverine ecosystem services. Earth-Science Reviews 180: 185–205. https://doi.org/10.1016/j.earscirev.2018.02.001
4. Hoffmann T, Lang A, Dikau R (2008) Holocene river activity: analysing 14C-dated fluvial and colluvial sediments from Germany. Quaternary Science Reviews 27: 2031–2040. https://doi.org/10.1016/j.quascirev.2008.06.014
5. Hoffmann T, Erkens G, Gerlach R et al. (2009) Trends and controls of Holocene floodplain sedimentation in the Rhine catchment. CATENA 77: 96–106. https://doi.org/10.1016/j.catena.2008.09.002
6. Bork H-R (1998) Landschaftsentwicklung in Mitteleuropa: Wirkungen des Menschen auf Landschaften ; 36 Tabellen, 1. Aufl. Perthes GeographieKolleg. Klett-Perthes, Gotha
7. Hoffmann T, Thorndycraft VR, Brown AG et al. (2010) Human impact on fluvial regimes and sediment flux during the Holocene: Review and future research agenda. Global and Planetary Change 72: 87–98. https://doi.org/10.1016/j.gloplacha.2010.04.008
8. Notebaert B, Verstraeten G (2010) Sensitivity of West and Central European river systems to environmental changes during the Holocene: A review. Earth-Science Reviews 103: 163–182. https://doi.org/10.1016/j.earscirev.2010.09.009
9. Broothaerts N, Verstraeten G, Notebaert B et al. (2013) Sensitivity of floodplain geoecology to human impact: A Holocene perspective for the headwaters of the Dijle catchment, central Belgium. The Holocene 23: 1403–1414. https://doi.org/10.1177/0959683613489583
10. Elkins TH (1953) THE BROWN COAL INDUSTRY OF GERMANY}. Geography 38: 18–29
11. Heyvaert VMA, Walstra J (2016) The role of long-term human impact on avulsion and fan development. Earth Surf Process Landforms 41: 2137–2152. https://doi.org/10.1002/esp.4011

12. Erkens G, Hoffmann T, Gerlach R et al. (2011) Complex fluvial response to Lateglacial and Holocene allogenic forcing in the Lower Rhine Valley (Germany). Quaternary Science Reviews 30: 611–627. https://doi.org/10.1016/j.quascirev.2010.11.019
13. Kaiser K, Keller N, Brande A et al. (2018) A large-scale medieval dam-lake cascade in central Europe: Water level dynamics of the Havel River, Berlin-Brandenburg region, Germany. Geoarchaeology 33: 237–259. https://doi.org/10.1002/gea.21649
14. Dotterweich M (2008) The history of soil erosion and fluvial deposits in small catchments of central Europe: Deciphering the long-term interaction between humans and the environment — A review. Geomorphology 101: 192–208. https://doi.org/10.1016/j.geomorph.2008.05.023
15. Dreibrodt S, Lubos C, Terhorst B et al. (2010) Historical soil erosion by water in Germany: Scales and archives, chronology, research perspectives. Quaternary International 222: 80–95. https://doi.org/10.1016/j.quaint.2009.06.014
16. Droste PJ (2003) Wasserbau und Wassermühlen an der Mittleren Rur: Die Kernlande des Herzogtums Jülich 8.-18. Jahrhundert. Zugl.: Aachen, Tech. Univ., Diss., 1999. Aachener Studien zur älteren Energiegeschichte, vol 9. Shaker, Aachen
17. Brykała D, Podgórski Z (2020) Evolution of landscapes influenced by watermills, based on examples from Northern Poland. Landscape and Urban Planning 198: 103798. https://doi.org/10.1016/j.landurbplan.2020.103798
18. Moor JJW de (2007) Human impact on Holocene catchment development and fluvial processes: The Geul River catchment, SE Netherlands. Dissertation, Vrije Universiteit Amsterdam
19. Gibling MR (2018) River Systems and the Anthropocene: A Late Pleistocene and Holocene Timeline for Human Influence. Quaternary 1: 21. https://doi.org/10.3390/quat1030021
20. Brown AG (1997) Alluvial geoarchaeology: Floodplain archaeology and environmental change. Cambridge manuals in archeology. Cambridge University Press, Cambridge
21. Frings RM, Gehres N, Promny M et al. (2014) Today's sediment budget of the Rhine River channel, focusing on the Upper Rhine Graben and Rhenish Massif. Geomorphology 204: 573–587. https://doi.org/10.1016/j.geomorph.2013.08.035
22. Committee on Rivers and Harbors (1914) Waterway Connecting the Tombigbee and Tennessee Rivers. Protocoll, Report(United States. Congress House.)
23. Lespez L, Viel V, Rollet AJ et al. (2015) The anthropogenic nature of present-day low energy rivers in western France and implications for current restoration projects. Geomorphology 251: 64–76. https://doi.org/10.1016/j.geomorph.2015.05.015
24. Curulli GI (2018) Ghost industries: Industrial water landscapes on the Willamette River in Oregon. Altralinea Edizioni, Firenze
25. Barca S (2010) Enclosing water: Nature and political economy in a Mediterranean valley, 1796 - 1916, 1. publ. White Horse Press, Winwick Cambridgeshire
26. Borsos B, Sendzimir J (2018) The Tisza River: Managing a Lowland River in the Carpathian Basin. In: Schmutz S, Sendzimir J (eds) Riverine Ecosystem Management, vol 49. Springer International Publishing, Cham, pp 541–560
27. Haidvogl G (2018) Historic Milestones of Human River Uses and Ecological Impacts. In: Schmutz S, Sendzimir J (eds) Riverine Ecosystem Management, vol 55. Springer International Publishing, Cham, pp 19–39
28. Winiwarter V, Haidvogl G, Hohensinner S et al. (2016) The long-term evolution of urban waters and their nineteenth century transformation in European cities. A comparative environmental history. Water Hist 8: 209–233. https://doi.org/10.1007/s12685-016-0172-z
29. Schmutz S, Sendzimir J (eds) (2018) Riverine Ecosystem Management. Springer International Publishing, Cham
30. Sendzimir J, Schmutz S (2018) Challenges in Riverine Ecosystem Management. In: Schmutz S, Sendzimir J (eds) Riverine Ecosystem Management, vol 69. Springer International Publishing, Cham, pp 1–16
31. Ebenstein A (2012) The consequences of industrialization: Evidence from water pollution and digestive cancers in China. The Review of Economics and Statistics 94: 186–201
32. Páll E, Niculae M, Kiss T et al. (2013) Human impact on the microbiological water quality of the rivers. J Med Microbiol 62: 1635–1640. https://doi.org/10.1099/jmm.0.055749-0
33. Cai X, Rosegrant MW, Ringler C (2003) Physical and economic efficiency of water use in the river basin: Implications for efficient water management. Water Resour Res 39: 175. https://doi.org/10.1029/2001WR000748

34. Hogeboom RJ, Knook L, Hoekstra AY (2018) The blue water footprint of the world's artificial reservoirs for hydroelectricity, irrigation, residential and industrial water supply, flood protection, fishing and recreation. Advances in Water Resources 113: 285–294. https://doi.org/10.1016/j.advwatres.2018.01.028
35. Messerli B, Grosjean M, Hofer T et al. (2000) From nature-dominated to human-dominated environmental changes. Quaternary Science Reviews 19: 459–479. https://doi.org/10.1016/S0277-3791(99)00075-X
36. Arheimer B, Donnelly C, Lindström G (2017) Regulation of snow-fed rivers affects flow regimes more than climate change. Nat Commun 8: 62. https://doi.org/10.1038/s41467-017-00092-8
37. WFD (2000) "DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2000 establishing a framework for Community action in the field of water policy" or, in short, the EU Water Framework Directive. Official Journal of the European Communities L 327: 1–72
38. Castree N (2014) The Anthropocene and Geography I: The Back Story. Geography Compass 8: 436–449. https://doi.org/10.1111/gec3.12141
39. Gale SJ, Hoare PG (2012) The stratigraphic status of the Anthropocene. The Holocene 22: 1491–1494. https://doi.org/10.1177/0959683612449764
40. Coenen M, Schüler V (2004) Braunkohle an Rur und Inde. Die Reihe Arbeitswelten. Sutton, Erfurt
41. Esser V, Buchty-Lemke M, Schulte P et al. (2020) Signatures of recent pollution profiles in comparable central European rivers – Examples from the international River Basin District Meuse. CATENA 193: 104646. https://doi.org/10.1016/j.catena.2020.104646
42. Paul J (1994) Grenzen der Belastbarkeit: Die Flüsse Rur (Roer) und Inde im Industriezeitalter. Forum Jülicher Geschichte, vol 10. Joseph-Kuhl-Gesellschaft zur Geschichte der Stadt Jülich und des Jülicher Landes, Jülich
43. Lehmkuhl F (2011) Die Entstehung des heutigen Naturraums und seine Nutzung. In: Kraus T, Pohle F (eds) Die natürlichen Grundlagen - von der Vorgeschichte bis zu den Karolingern, pp 87–129
44. Nilson E, Lehmkuhl F (2007) Landschaftstransformation am Eifelnordrand seit Beginn der industriellen Revolution: Räumliche Auswirkungen geogener Faktoren. Natur am Niederrhein: 47–60
45. Tu M, Hall MJ, de Laat PJM et al. (2004) Extreme floods in the Meuse basin over the past century: aggravated by land-use change? In: Douben N, van Os AG (eds) NCR-days 2003: Dealing with Floods within Constraints. November 6 – 8
46. (1986) Wasserhaushaltsgesetz: WHG, vol 1986
47. MKULNV NRW (2015) MAAS SÜD NRW: Steckbriefe der Planungseinheiten in den nordrhein-westfälischen Anteilen von Rhein, Weser, Ems und Maas, Bewirtschaftungsplan 2016-2021. Oberflächengewässer und Grundwasser Teileinzugsgebiet Maas/Maas Süd NRW
48. Downs PW, Gregory KJ (2004) River channel management: Towards sustainable catchment hydrosystems. Distributed in the USA by Oxford University Press, London, New York
49. Andersen O, Crow TR, Lietz SM et al. (1996) Transformation of a landscape in the upper mid-west, USA: The history of the lower St. Croix river valley, 1830 to present. Landscape and Urban Planning 35: 247–267. https://doi.org/10.1016/S0169-2046(96)00304-0
50. Furusho C, Vidaurre R, La Jeunesse I et al. (2016) Cross-cutting Perspective Freshwater. In: Bressers H, Bressers N, Larrue C (eds) Governance for Drought Resilience, vol 29. Springer International Publishing, Cham, pp 217–230
51. Tockner K, Stanford JA (2002) Riverine flood plains: present state and future trends. Envir Conserv 29: 308–330. https://doi.org/10.1017/S037689290200022X
52. Koenzen U (2005) Fluss- und Stromauen in Deutschland - Typologie und Leitbilder -: Ergebnisse des F+E-Vorhabens "Typologie und Leitbildentwicklung für Flussauen in der Bundesrepublik Deutschland" des Bundesamtes für Naturschutz ; FKZ: 803 82 100. Zugl.: Köln, Univ., Diss., 2005. Angewandte Landschaftsökologie, vol 65. Bundesamt für Naturschutz, Bonn-Bad Godesberg
53. Notebaert B, Broothaerts N, Verstraeten G (2018) Evidence of anthropogenic tipping points in fluvial dynamics in Europe. Global and Planetary Change 164: 27–38. https://doi.org/10.1016/j.gloplacha.2018.02.008

54. Khan S, Fryirs K (2020) An approach for assessing geomorphic river sensitivity across a catchment based on analysis of historical capacity for adjustment. Geomorphology 359: 107135. https://doi.org/10.1016/j.geomorph.2020.107135
55. Brierley GJ, Fryirs KA (2005) Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing, Malden, Oxford, Victoria
56. Erskine W, Melville M, Page KJ et al. (1982) Cutoff and Oxbow Lake. Australian Geographer 15: 174–180. https://doi.org/10.1080/00049188208702813
57. Pottgiesser T, Sommerhäuser M (2008) Beschreibung und Bewertung der deutschen Fließgewässertypen - Steckbriefe und Anhang
58. Kondolf GM, Piégay H (eds) (2016) Tools in fluvial geomorphology, Second edition. Advancing river restoration and management. Wiley Blackwell, Chichester, West Sussex, UK, Hoboken, NJ
59. Miall AD (1977) A review of the braided-river depositional environment. Earth-Science Reviews 13: 1–62. https://doi.org/10.1016/0012-8252(77)90055-1
60. Moor JJW de, Kasse C, van Balen R et al. (2008) Human and climate impact on catchment development during the Holocene — Geul River, the Netherlands. Geomorphology 98: 316–339. https://doi.org/10.1016/j.geomorph.2006.12.033
61. Kleinhans MG, Vries B de, Braat L et al. (2018) Living landscapes: Muddy and vegetated floodplain effects on fluvial pattern in an incised river. Earth Surf Process Landforms 43: 2948–2963. https://doi.org/10.1002/esp.4437
62. Scorpio V, Zen S, Bertoldi W et al. (2018) Channelization of a large Alpine river: what is left of its original morphodynamics? Earth Surf Process Landforms 43: 1044–1062. https://doi.org/10.1002/esp.4303
63. Knighton DA, Nanson GC (1993) Anastomosis and the continuum of channel pattern. Earth Surf Process Landforms 18: 613–625. https://doi.org/10.1002/esp.3290180705
64. Vandenberghe J, Moor JJW de, Spanjaard G (2012) Natural change and human impact in a present-day fluvial catchment: The Geul River, Southern Netherlands. Geomorphology 159-160: 1–14. https://doi.org/10.1016/j.geomorph.2011.12.034
65. Mikuś P, Wyżga B, Walusiak E et al. (2019) Island development in a mountain river subjected to passive restoration: The Raba River, Polish Carpathians. Sci Total Environ 660: 406–420. https://doi.org/10.1016/j.scitotenv.2018.12.475
66. Hudson PF, van der Hout E, Verdaasdonk M (2019) (Re)Development of fluvial islands along the lower Mississippi River over five decades, 1965–2015. Geomorphology 331: 78–91. https://doi.org/10.1016/j.geomorph.2018.11.005
67. Bravard J-P, Gaydou P (2015) Historical Development and Integrated Management of the Rhône River Floodplain, from the Alps to the Camargue Delta, France. In: Hudson PF, Middelkoop H (eds) Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe, vol 29. Springer New York, New York, NY, pp 289–320
68. Rinaldi M, Mengoni B, Luppi L et al. (2008) Numerical simulation of hydrodynamics and bank erosion in a river bend. Water Resour Res 44: 1356. https://doi.org/10.1029/2008WR007008
69. Rommens T, Verstraeten G, Bogman P et al. (2006) Holocene alluvial sediment storage in a small river catchment in the loess area of central Belgium. Geomorphology 77: 187–201. https://doi.org/10.1016/j.geomorph.2006.01.028
70. Nilson E (2006) Flusslandschaften im Wandel: Untersuchungen zur Mäanderentwicklung an zwei Maas- Tributären anhand von historischem Bild- und Kartenmaterial. In: Reineke T, Lehmkuhl F, Blümel H (eds) Grenzüberschreitendes integratives Gewässermanagement, 1. Aufl. Academia-Verl., Sankt Augustin
71. Kufeld M, Lange J, Hausmann B (2010) Das Einzugsgebiet der Rur : Ergebnisbericht der im Rahmen des AMICE-Projekts durchgeführten Literaturrecherche ; AMICE, meus, maas ; INTERREG IVB North West Europe Project (number 074C). EPAMA, Charleville-Mézières, France
72. Bogena H (2005) MOSYRUR: Water balance analysis in the Rur basin, 1. Aufl. Schriften des Forschungszentrums Jülich Reihe Umwelt, vol 52. Forschungszentrum Zentralbibliothek, Jülich
73. MKULNV NRW (2014) Maas Süd: Steckbriefe der Planungseinheiten in den nordrhein-westfälischen Anteilen von Rhein, Weser, Ems und Maas. Oberflächengewässer und Grundwasser Teileinzugsgebiet Maas/Maas Süd NRW (Stand: Juli 2014), Düsseldorf
74. Dussart F, Claude J (1971) Études récentes sur l'Eifel. In: Mérenne-Schoumaker B (ed) Bulletin de la Société géographique de Liège, Liege, Belgium, pp 163–176

75. Özerol G, Troeltzsch J (2016) Cross-cutting Perspective on Agriculture. In: Bressers H, Bressers N, Larrue C (eds) Governance for Drought Resilience, vol 11. Springer International Publishing, Cham, pp 203–215
76. Bressers H, Bressers N, Larrue C (eds) (2016) Governance for Drought Resilience. Springer International Publishing, Cham
77. Nilson E (2006) Räumlich-strukturelle und zeitlich-dynamische Aspekte des Landnutzungswandels im Dreiländereck Belgien-Niederlande-Deutschland. Aachen, Techn. Hochsch., Diss., 2006
78. Wagner A, Koenzen U, Lohr H et al. (2013) Die „beschleunigte" Befüllung des Tagebaurestsees Inden aus der Rur. Wasserwirtsch 103: 66–71. https://doi.org/10.1365/s35147-013-0426-y
79. UBA (2014) Hydromorphologische Steckbriefe der deutschen Fließgewässertypen: Anhang 1 von „Strategien zur Optimierung von Fließgewässer-Renaturierungsmaßnahmen und ihrer Erfolgskontrolle", Dessau-Roßlau
80. MNULV (2005) Gewässerstrukturgüte in Nordrhein-Westfalen: Bericht 2005, Essen
81. SCHUMM SA (1985) PATTERNS OF ALLUVIAL RIVERS. Annu Rev Earth Planet Sci 13: 5–27. https://doi.org/10.1146/annurev.ea.13.050185.000253
82. Rinaldi M, Gurnell AM, del Tánago MG et al. (2016) Classification of river morphology and hydrology to support management and restoration. Aquat Sci 78: 17–33. https://doi.org/10.1007/s00027-015-0438-z
83. Nanson GC, KNIGHTON AD (1996) ANABRANCHING RIVERS: THEIR CAUSE, CHARACTER AND CLASSIFICATION. Earth Surf Process Landforms 21: 217–239. https://doi.org/10.1002/(SICI)1096-9837(199603)21:3<217:AID-ESP611>3.0.CO;2-U
84. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (2018) Begriffe aus der Gewässerunterhaltung und Gewässerentwicklung, Juni 2018. DWA-Regelwerk, M 600. Deutsche Vereinigung für Wasserwirtschaft Abwasser und Abfall, Hennef
85. Roccati A, Faccini F, Luino F et al. (2019) Morphological changes and human impact in the Entella River floodplain (Northern Italy) from the 17th century. CATENA 182: 104122. https://doi.org/10.1016/j.catena.2019.104122
86. Guth PL (2011) Drainage basin morphometry: a global snapshot from the shuttle radar topography mission. Hydrol Earth Syst Sci 15: 2091–2099. https://doi.org/10.5194/hess-15-2091-2011
87. Brookes A (1987) The distribution and management of channelized streams in Denmark. Regul Rivers: Res Mgmt 1: 3–16. https://doi.org/10.1002/rrr.3450010103
88. Brierley GJ, Fryirs KA (2008) Geomorphology and river management: Applications of the River Styles framework. Blackwell, Malden, Mass.
89. Bromley C (2008) The morphodynamics of sediment movement through a reservoir during dam removal. PhD thesis, University of Nottingham
90. East AE, Pess GR, Bountry JA et al. (2015) Large-scale dam removal on the Elwha River, Washington, USA: River channel and floodplain geomorphic change. Geomorphology 228: 765–786. https://doi.org/10.1016/j.geomorph.2014.08.028
91. Wickert AD, Schildgen TF (2019) Long-profile evolution of transport-limited gravel-bed rivers. Earth Surf Dynam 7: 17–43. https://doi.org/10.5194/esurf-7-17-2019
92. Brice JC (1984) Planform Properties of Meandering Rivers. In: Elliott CM (ed) River meandering: Proceedings of the Conference Rivers '83. American Society of Civil Engineers, N
93. Chin A (2006) Urban transformation of river landscapes in a global context. Geomorphology 79: 460–487. https://doi.org/10.1016/j.geomorph.2006.06.033
94. Odgaard AJ (2017) River Management with Submerged Vanes. In: Sharma N (ed) River System Analysis and Management. Springer Singapore, Singapore
95. Tiwari H, Khan A, Sharma N (2017) Emerging Methodologies for Turbulence Characterization in River Dynamics Study. In: Sharma N (ed) River System Analysis and Management, vol 28. Springer Singapore, Singapore, pp 167–186
96. Mahanta C, Saikia L (2017) Sediment Dynamics in a Large Alluvial River: Characterization of Materials and Processes and Management Challenges. In: Sharma N (ed) River System Analysis and Management, vol 114. Springer Singapore, Singapore, pp 47–71
97. Haidvogl G, Hohensinner S, Preis S (2011) Rekonstruktion historischer Flusslandschaften als Grundlage im Gewässermanagement – Potential und Limits. Österr Wasser- und Abfallw 63: 174–182. https://doi.org/10.1007/s00506-011-0335-1

98. Downs PW, Thorne CR (2000) Rehabilitation of a lowland river: Reconciling flood defence with habitat diversity and geomorphological sustainability. J Environ Manage 58: 249–268. https://doi.org/10.1006/jema.2000.0327
99. Wasserverband Eifel-Rur (ed) (1999) 100 Jahre Wasserwirtschaft in der Nordeifel, Düren
100. Heimatkalender des Kreises Jülich
101. Castro JM, Thorne CR (2019) The stream evolution triangle: Integrating geology, hydrology, and biology. River Res Applic 35: 315–326. https://doi.org/10.1002/rra.3421
102. Mazumder SK (2017) Behaviour and Training of River Near Bridges and Barrages: Some Case Studies. In: Sharma N (ed) River System Analysis and Management, vol 106. Springer Singapore, Singapore, pp 263–277
103. Mulu A, Dwarakish GS (2015) Different Approach for Using Trap Efficiency for Estimation of Reservoir Sedimentation. An Overview. Aquatic Procedia 4: 847–852. https://doi.org/10.1016/j.aqpro.2015.02.106
104. Ruddiman WF (2013) The Anthropocene. Annu Rev Earth Planet Sci 41: 45–68. https://doi.org/10.1146/annurev-earth-050212-123944
105. Amoros C (2001) The concept of habitat diversity between and within ecosystems applied to river side-arm restoration. Environ Manage 28: 805–817. https://doi.org/10.1007/s002670010263
106. Škarpich V, Horáček M, Galia T et al. (2016) The effects of river patterns on riparian vegetation: A comparison of anabranching and single-thread incised channels. Moravian Geographical Reports 24: 24–31. https://doi.org/10.1515/mgr-2016-0014
107. Halley DJ, Saveljev AP, Rosell F (2020) Population and distribution of beavers Castor fiber and Castor canadensis in Eurasia. Mam Rev 10: 23. https://doi.org/10.1111/mam.12216
108. Dalbeck L (2012) Die Rückkehr der Biber – eine Erfolgsgeschichte des Artenschutzes. Zeitschrift des Kölner Zoos: 167–180
109. Robinson CT, Schweizer P, Larsen A et al. (2020) Beaver effects on macroinvertebrate assemblages in two streams with contrasting morphology. Sci Total Environ 722: 137899. https://doi.org/10.1016/j.scitotenv.2020.137899
110. Merckx T (2015) Rewilding: Pitfalls and Opportunities for Moths and Butterflies. In: Pereira HM, Navarro LM (eds) Rewilding European Landscapes, vol 14. Springer International Publishing, Cham, pp 107–125
111. Buchty-Lemke M, Lehmkuhl F (2018) Impact of abandoned water mills on Central European foothills to lowland rivers: a reach scale example from the Wurm River, Germany. Geografiska Annaler: Series A, Physical Geography 100: 221–239. https://doi.org/10.1080/04353676.2018.1425621
112. Maaß A-L, Schüttrumpf H (2019) Elevated floodplains and net channel incision as a result of the construction and removal of water mills. Geografiska Annaler: Series A, Physical Geography 101: 157–176. https://doi.org/10.1080/04353676.2019.1574209
113. Trebilcock C (2014) Industrialisation of the Continental Powers 1780-1914, The. Taylor and Francis, Hoboken
114. Kukliński AP (1989) Industrialization in Poland — Experiences and prospects. GeoJournal : Spatially Integrated Social Sciences and Humanities 18: 141–150. https://doi.org/10.1007/BF01207088
115. Gołębiowski C (2016) Inland Water Transport in Poland. Transportation Research Procedia 14: 223–232. https://doi.org/10.1016/j.trpro.2016.05.058
116. Witkowski K (2020) Man's impact on the transformation of channel patterns (the Skawa River, southern Poland). River Res Applic 1126: 659. https://doi.org/10.1002/rra.3702
117. Michalczyk Z (1997) Anthropogenic changes in water conditions in the Lublin Area. In: Maruszczak H (ed) Anthropogenic impact on water conditions: (Vistula and Oder river basins). Polish Acad. of Sciences Inst. of Geography and Spatial Organization, Warszawa
118. Igliński B (2019) Hydro energy in Poland: the history, current state, potential, SWOT analysis, environmental aspects. Int J Energ Water Res 3: 61–72. https://doi.org/10.1007/s42108-019-00008-w
119. Glińska-Lewczuk K, Burandt P (2011) Effect of river straightening on the hydrochemical properties of floodplain lakes: Observations from the Łyna and Drwęca Rivers, N Poland. Ecological Engineering 37: 786–795. https://doi.org/10.1016/j.ecoleng.2010.07.028

120. Downs PW, Piégay H (2019) Catchment-scale cumulative impact of human activities on river channels in the late Anthropocene: implications, limitations, prospect. Geomorphology 338: 88–104. https://doi.org/10.1016/j.geomorph.2019.03.021
121. Kirk T (1999) Small-Scale Hydro-Power in the UK. Water & Environment J 13: 207–212. https://doi.org/10.1111/j.1747-6593.1999.tb01036.x
122. Wrigley EA (1990) Continuity, Chance and Change: The Character of the Industrial Revolution in England. Ellen McArthur lectures, vol 1987. Cambridge University Press
123. Johnson PA, Floud R (eds) (2004) The Cambridge economic history of modern Britain: Volume 1: Industrialisation, 1700-1860. Cambridge University Press, Cambridge
124. Willan TS (1964) River navigation in England 1600-1750, New impr. Cass, London
125. Smith LM, Winkley BR (1996) The response of the Lower Mississippi River to river engineering. Engineering Geology 45: 433–455. https://doi.org/10.1016/S0013-7952(96)00025-7
126. Turnbull G (1987) Canals, Coal and Regional Growth during the Industrial Revolution. The Economic History Review 40: 537. https://doi.org/10.2307/2596392
127. Habersack H, Piégay H (2007) 27 River restoration in the Alps and their surroundings: past experience and future challenges. In: Gravel-Bed Rivers VI: From Process Understanding to River Restoration, vol 11. Elsevier, pp 703–735
128. Jakobsson E (2002) Industrialization of Rivers: A water system approach to hydropower development. Know Techn Pol 14: 41–56. https://doi.org/10.1007/s12130-002-1014-0
129. Paul J (1999) Vom reißenden Gewässer zum gebändigten Fluß.: Die Geschichte der Wasserwirtschaft im Flußgebiet der Rur vom 16. Jahrundert bis in die Zeit um 1960. In: Wasserverband Eifel-Rur (ed) 100 Jahre Wasserwirtschaft in der Nordeifel, Düren, pp 51–62
130. Schwind W (1984) Der Eifelwald im Wandel der Jahrhunderte ausgehend von Untersuchungen in der Vulkaneifel. Eifelverein, Düren
131. Intze O (1906) Die geschichtliche Entwicklung, die Zwecke und der Bau der Talsperren. Springer Berlin Heidelberg, Berlin, Heidelberg
132. Franzius O, Proetel H. (1927) Der wasserwirtschaftliche Ausbau der Rur (Roer) in der Nord-Eifel. Denkschrift und vergleichende Entwürfe. Hamel'sche Druckerei, Düren
133. Goedeking A (2012) Wann und wie treten Erfolge ein?: Veränderungen von Renaturierungen und Erfolgskontrollen an der Eifel-Rur. Natur in NRW: 43–45
134. Völker J, Mohaupt V (2016) Die Wasserrahmenrichtlinie: Deutschlands Gewässer 2015, Bonn
135. Zorn W, Warm R (1967) ZUR BETRIEBSSTRUKTUR DER RHEINISCHEN INDUSTRIE UM 1820: Fritz Redlich Zum 75. Geburtstag. Tradition: Zeitschrift für Firmengeschichte und Unternehmerbiographie 12: 497–510
136. European Environment Agency (2016) European Digital Elevation Model (EU-DEM). https://land.copernicus.eu/imagery-in-situ/eu-dem. Accessed 19 Oct 2020
137. Geofabrik GmbH (2018) gis_osm_waterways_free_1. CC BY-SA 2.0. download.geofabrik.de. Accessed 19 Oct 2020
138. Landesbetrieb Information und Technik Nordrhein-Westfalen (2020) gsk3c_EPSG25832_Shape.zip. dl-de-by-2.0. https://www.opengeodata.nrw.de/produkte/umwelt_klima/wasser/gsk3c/. Accessed 20 Oct 2020
139. Geobasis NRW 2018 Basis DLM (2018): Digitales Landschaftsmodel (DLM). dl-de/by-2-0. http://www.bezreg-koeln.de/brk_internet/geobasis/landschaftsmodelle/basis_dlm/index.html,. Accessed 20 Oct 2020
140. Eurostat (2020) Countries 2016: ref-countries-2016-01m.shp. https://ec.europa.eu/eurostat/de/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries. Accessed 20 Oct 2020
141. European Environment Agency (2016) CLC 2018. https://land.copernicus.eu/pan-european/corine-land-cover/clc2018. Accessed 19 Oct 2020

Figure captions

Figure 1: a) Tipping points of human development, b) Classification of the five phases of river management in the Rur River catchment into phases of human impacts on river courses worldwide; Source: own illustration modified after [19]

Figure 2: The fve phases of river management in the Rur catchment over the last 200 years, definition and characteristics; Source: own illustration, data according to [41–43, 45–48, 77, 129–135]

Figure 3: Overview of the Rur catchment and its location in Europe; Source: own illustration; DEM: [136]; river system: [137, 138]; towns: [139]; country borders: [140]

Figure 4: a) Upper reach near Monschau, b) Bank protection in Monschau City, c) Upper reach in focus area A, d) Rur Dam, e) Middle reach in focus area B in Düren city, and f) Example of a near-natural section in the lowlands before Düren; Source: own illustration

Figure 5: Focus region; Source: own illustration; DEM: [136]; River system and catchment area: [137, 138]; towns: [139]; country borders: [140]; German river type: [71]

Figure 6: Impressions of the Rur River from the three focus regions. a) Rur River below Monschau, b) Rur River near Düren, and c) Rur River near Heinsberg; Source: own illustration

Figure 7: Development of industry and land use in the Rur catchment from 1850 to today; Source: own illustration; River system and catchment area: [137, 138]; towns: [139]; Corine land use data: [77, 141]

Figure 8: Objects of digitalized river courses; Source: own illustration; Criteria according to [59, 83, 84]

Figure 9: Changes in river length and sinuosity in the three focus regions of the Rur River over its five phases of river management in the last 200 years; Source: own illustration

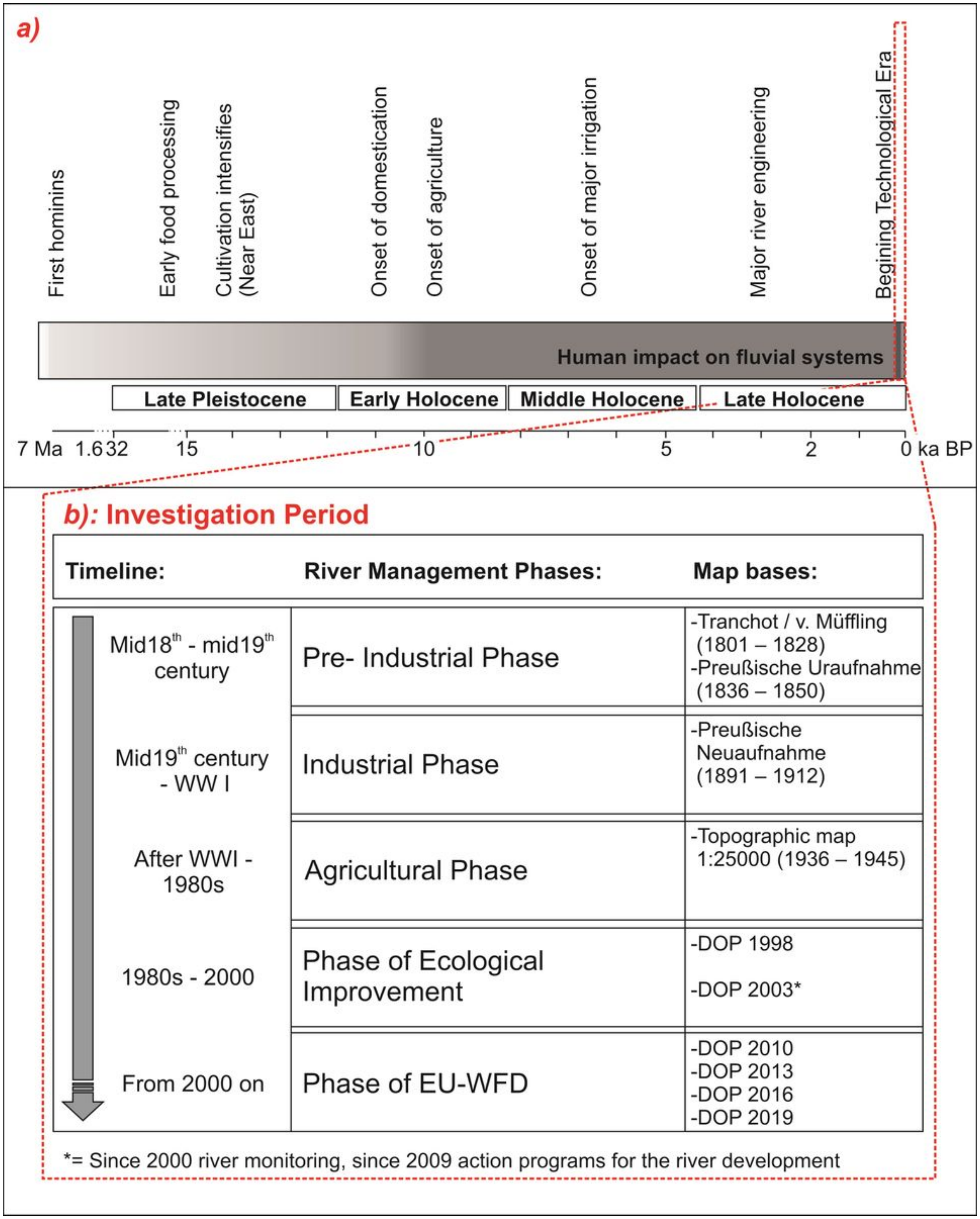
Figure 10: Change inindicators over the five phases of river management in the last 200 years in the three focus regions of the Rur River, a) changes in the length of anastomosing and braided river structures in comparison to the total river length, b) changes in the length of side arms in comparison to the total river length, c) changes in the average nuber of oxbows per river-km, and d) changes in the average number of islands per river-km; Source: own illustration

Figure 11: Development of indicators for morphodynamic activity and river straightening in the three focus regions over the five phases of water management in the last 200 years; Source: own illustration

Figure 12: Qualitative development of all indicators for river straightening and natural morphological activity after the five historical phases of the last 200 years; Source: own illustration

Figure 13: Changes in river courses in the three focus regions of the Rur River over the five phases of water management in the last 200 years. a) development of agricultural use of floodplains in the three focus regions, b) development of industrial use of floodplains in the three focus regions, c) main demand in the different phases of water management, d) amendment of the German Federal Water Act, and e) river course development of a representative section of the focus regions; Source: own illustration

Figures



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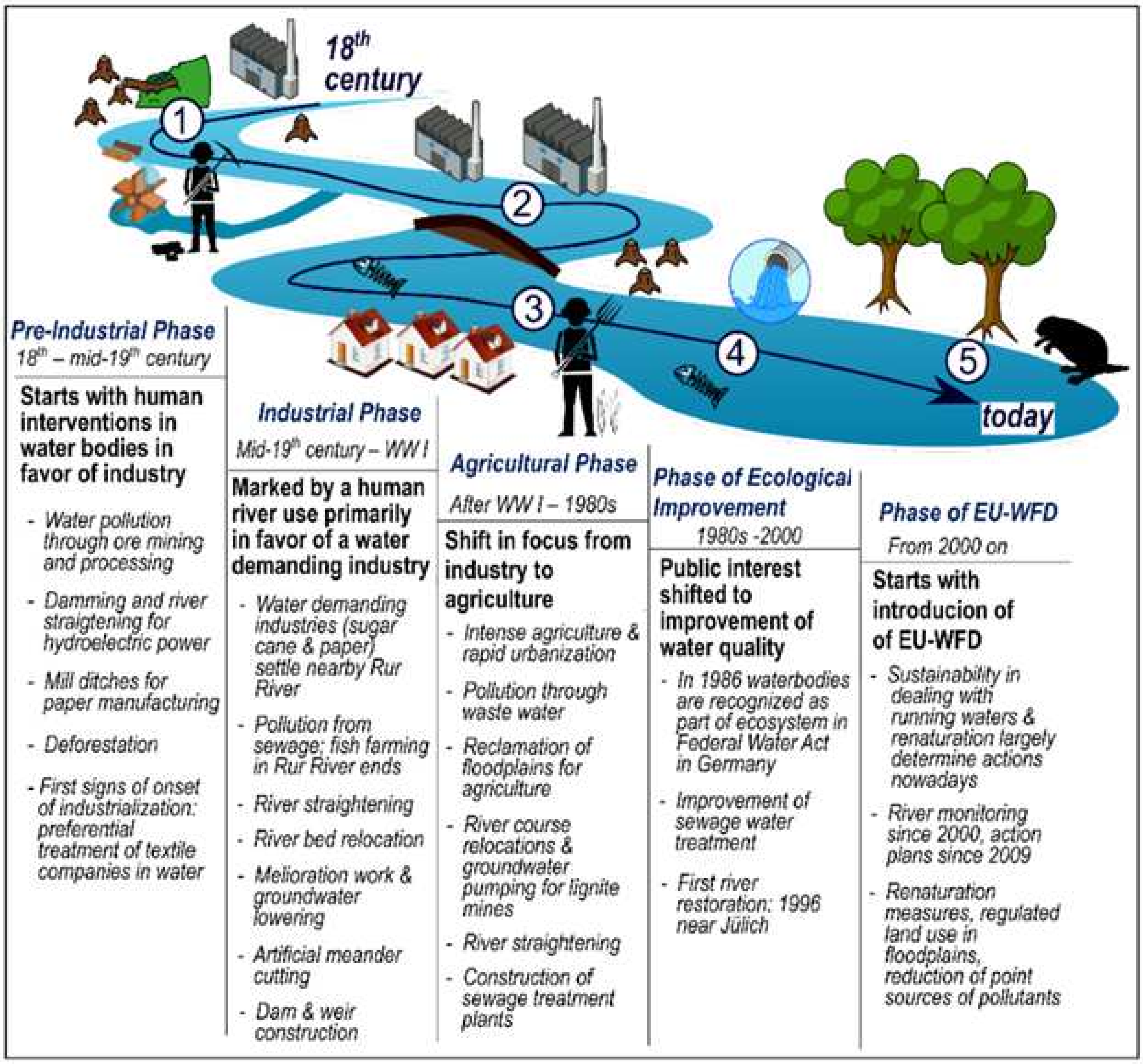

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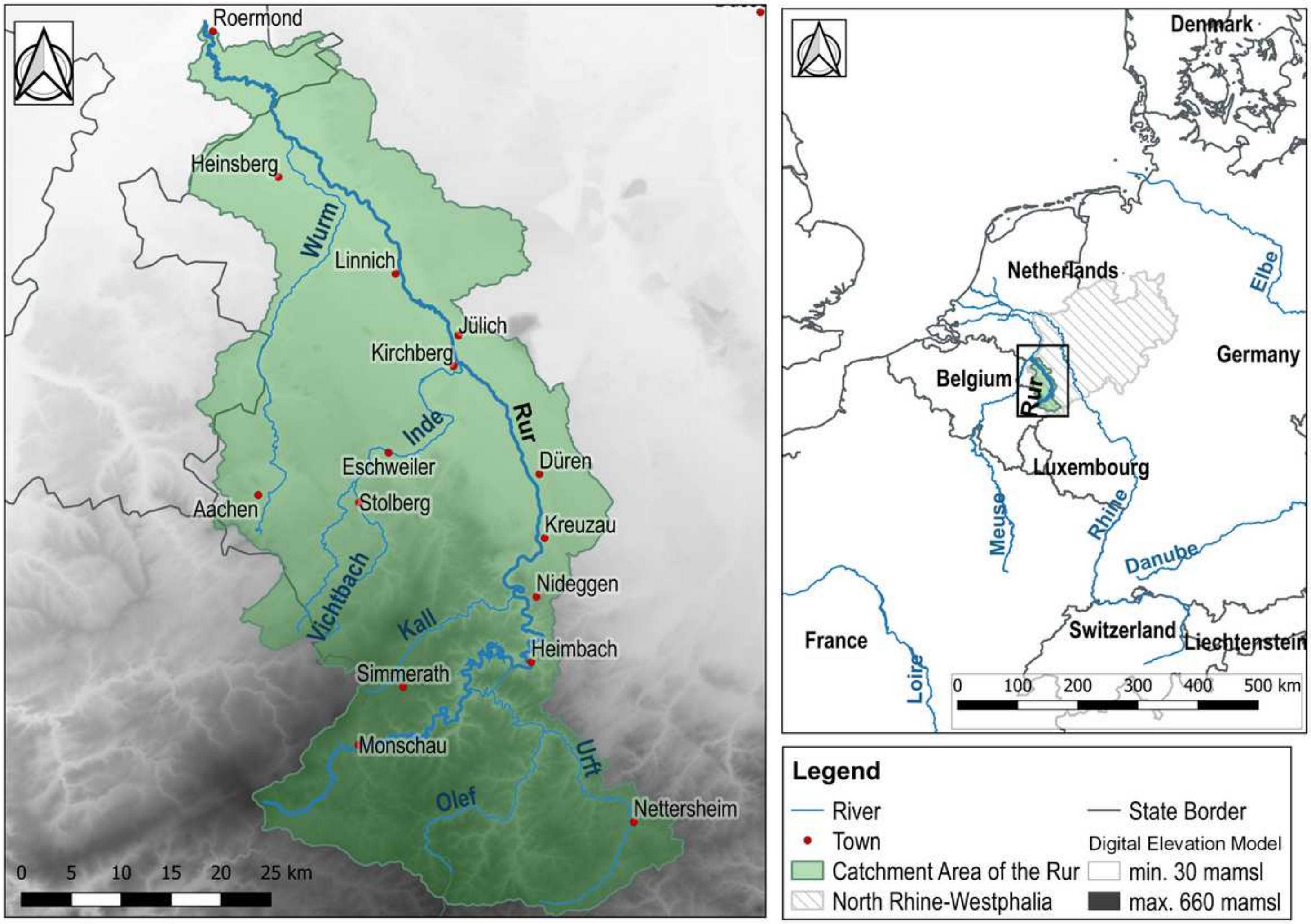

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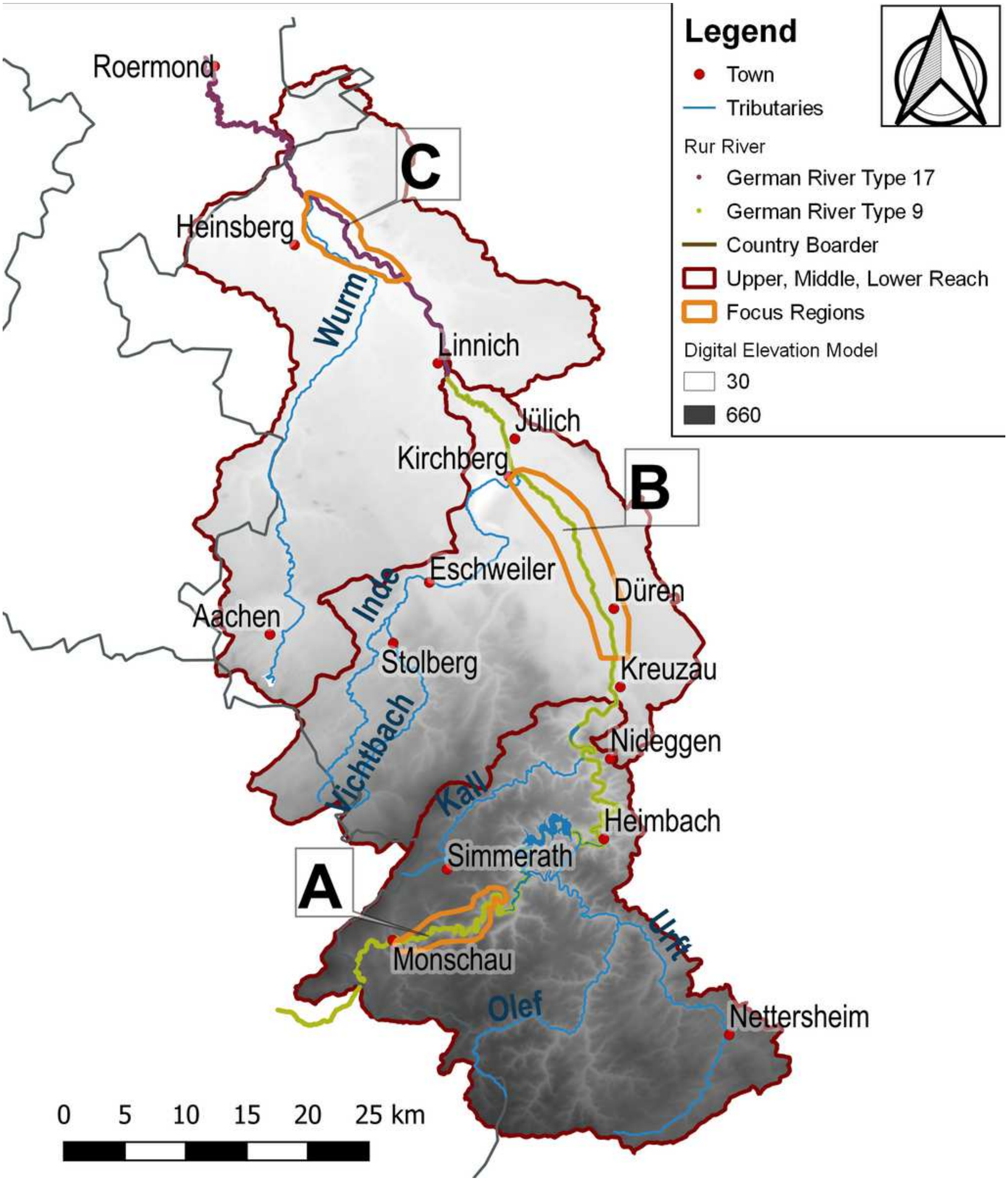

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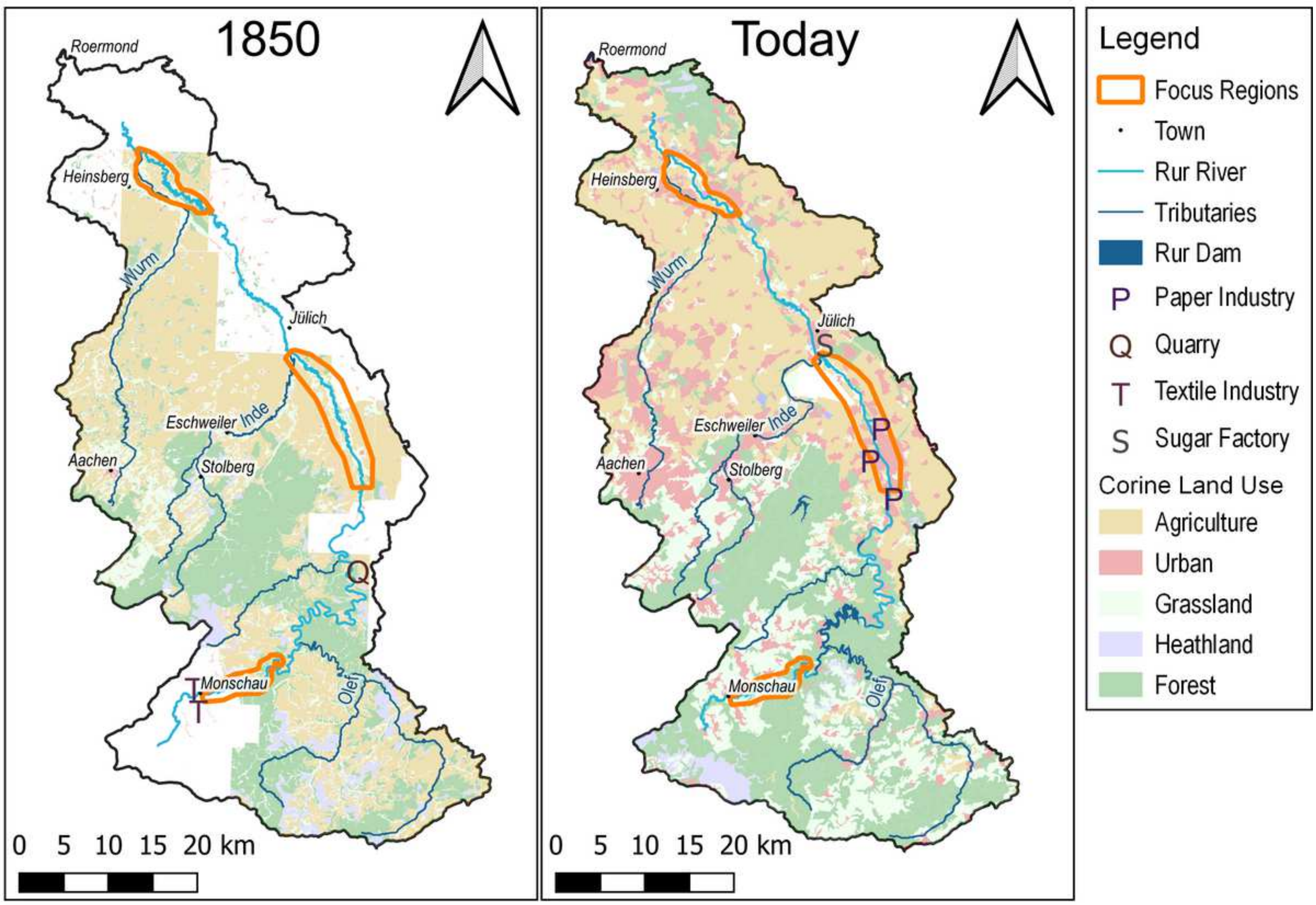

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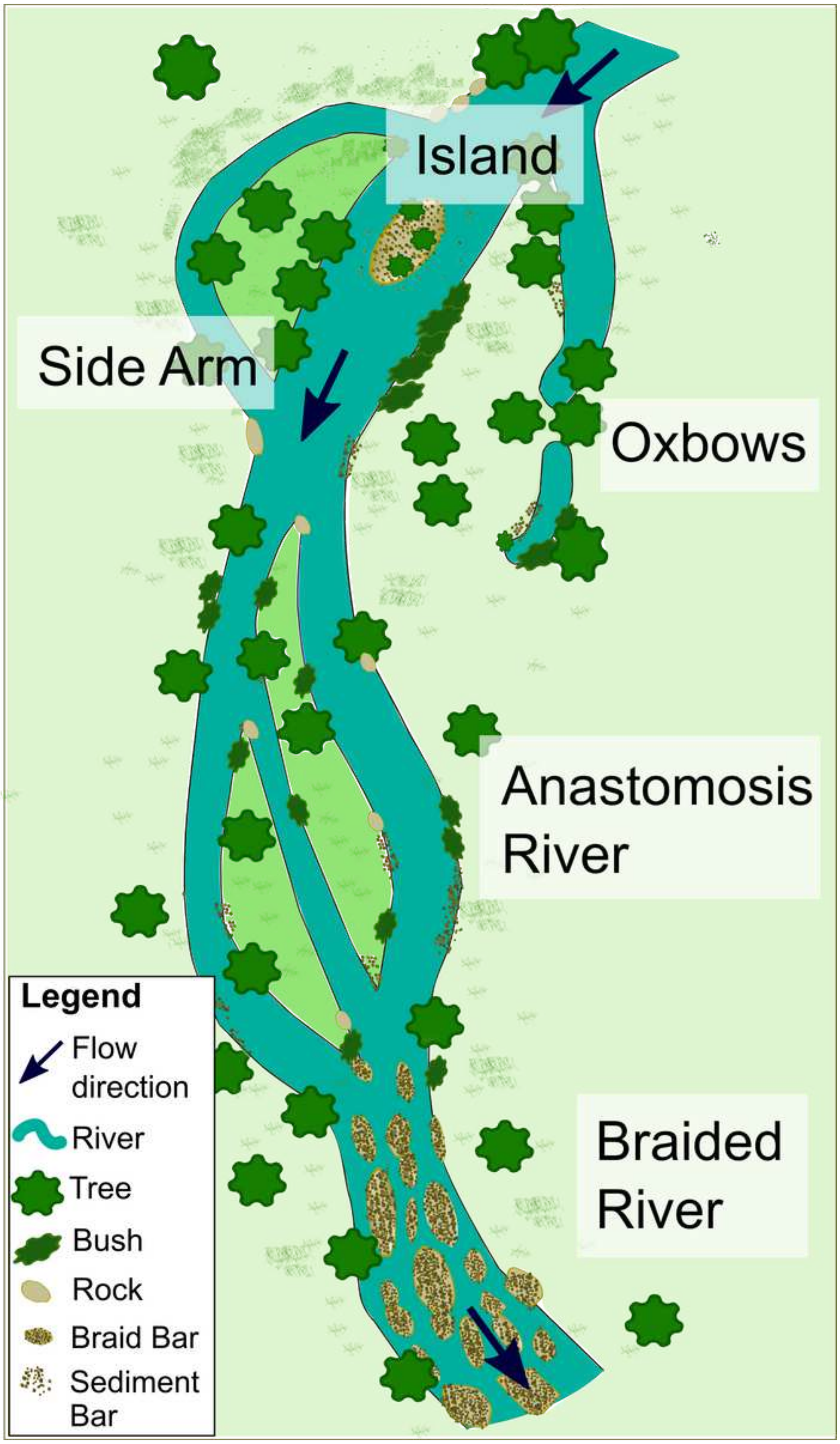


Figure 8

Objects of digitalized river courses; Source: own illustration; Criteria according to [59, 83, 84]

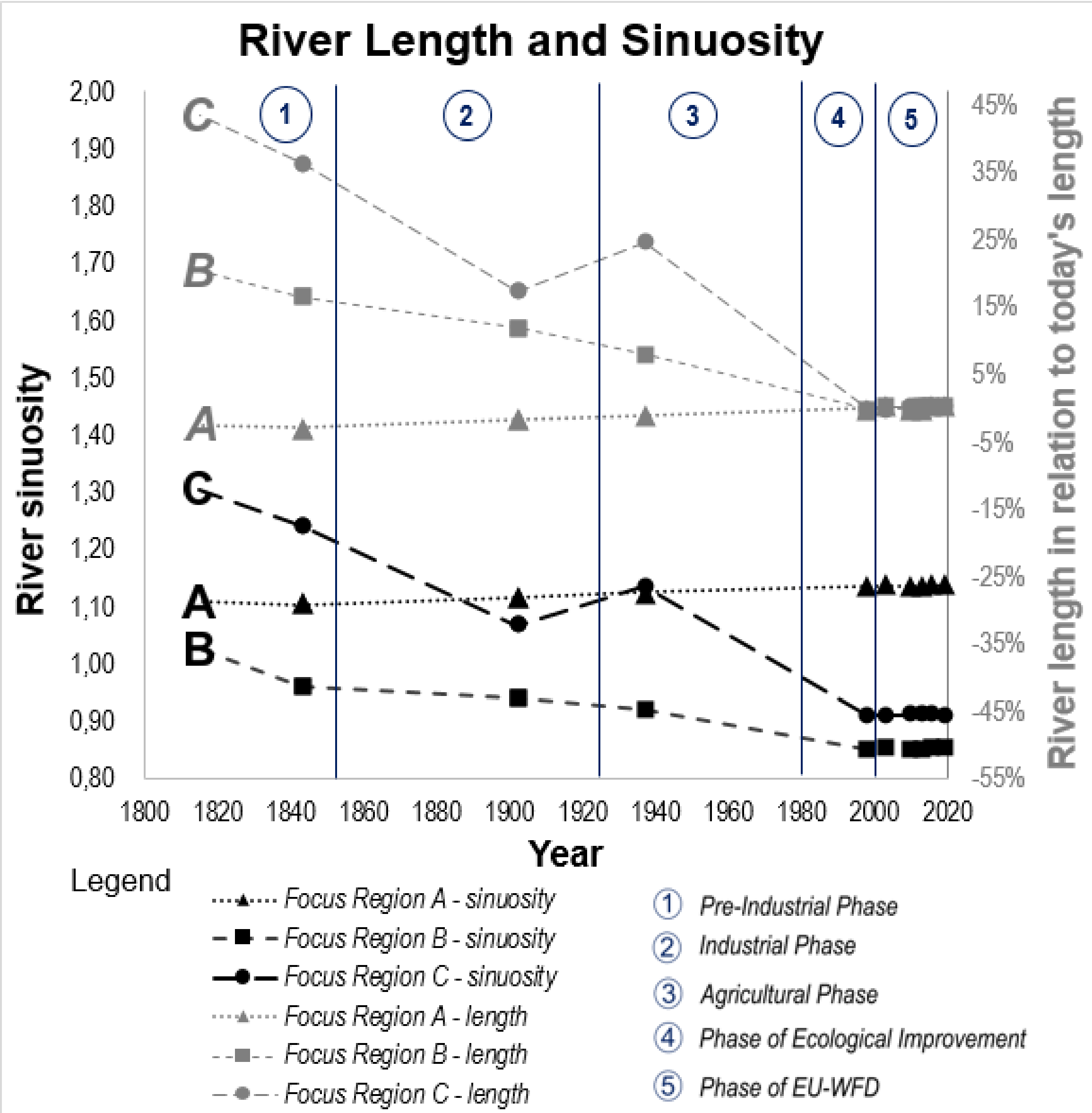
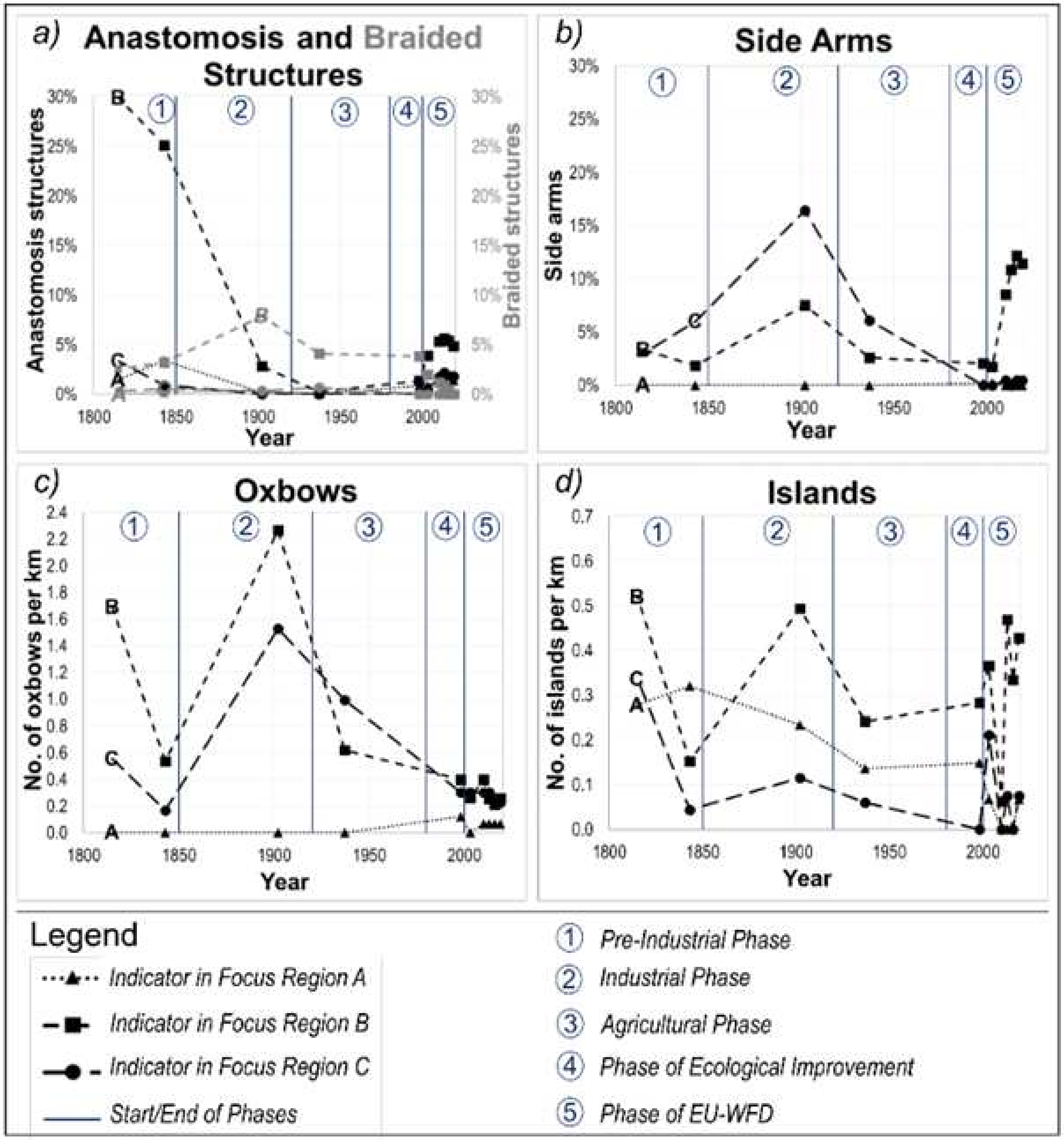


Figure 9

Changes in river length and sinuosity in the three focus regions of the Rur River over its five phases of river management in the last 200 years; Source: own illustration



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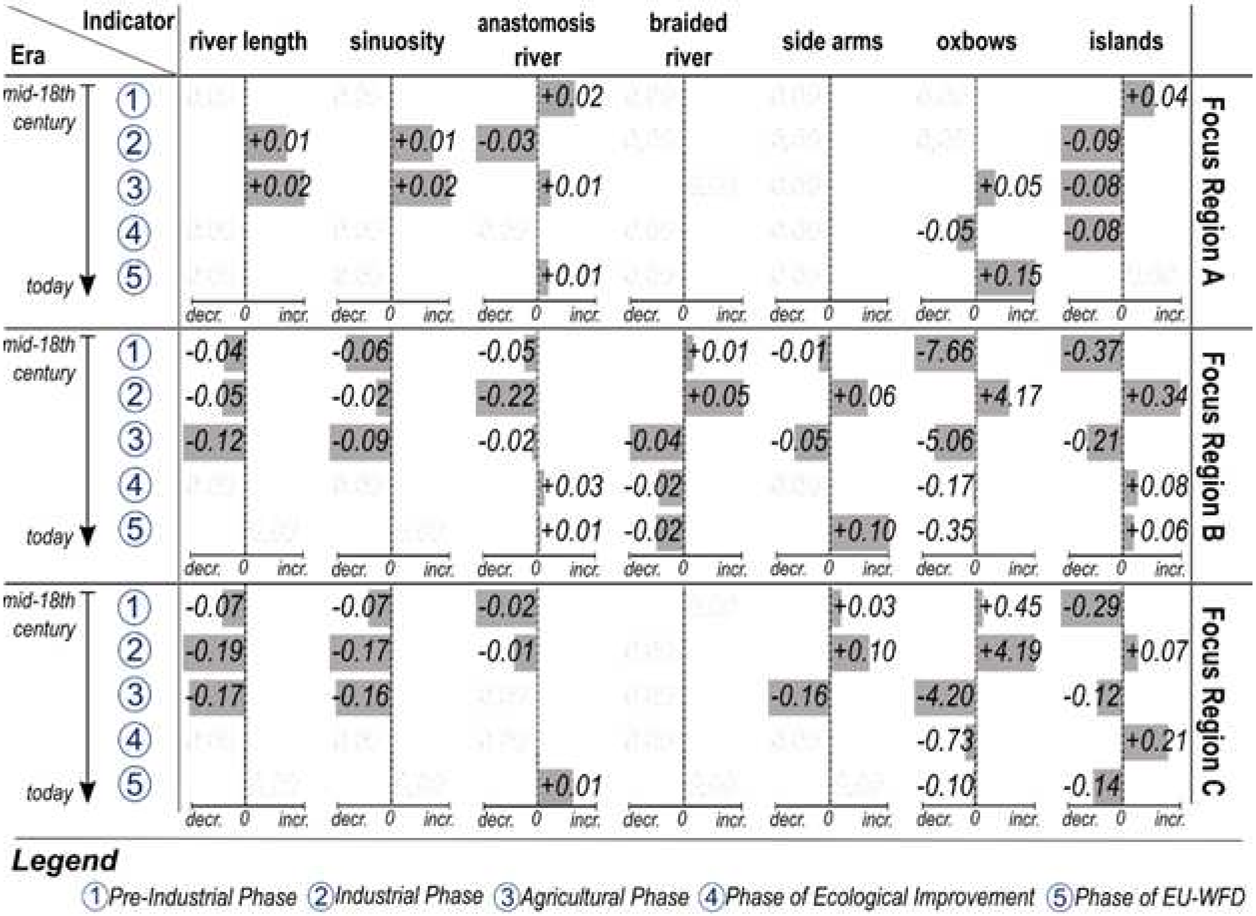

Figure 11

Development of indicators for morphodynamic activity and river straightening in the three focus regions over the five phases of water management in the last 200 years; Source: own illustration

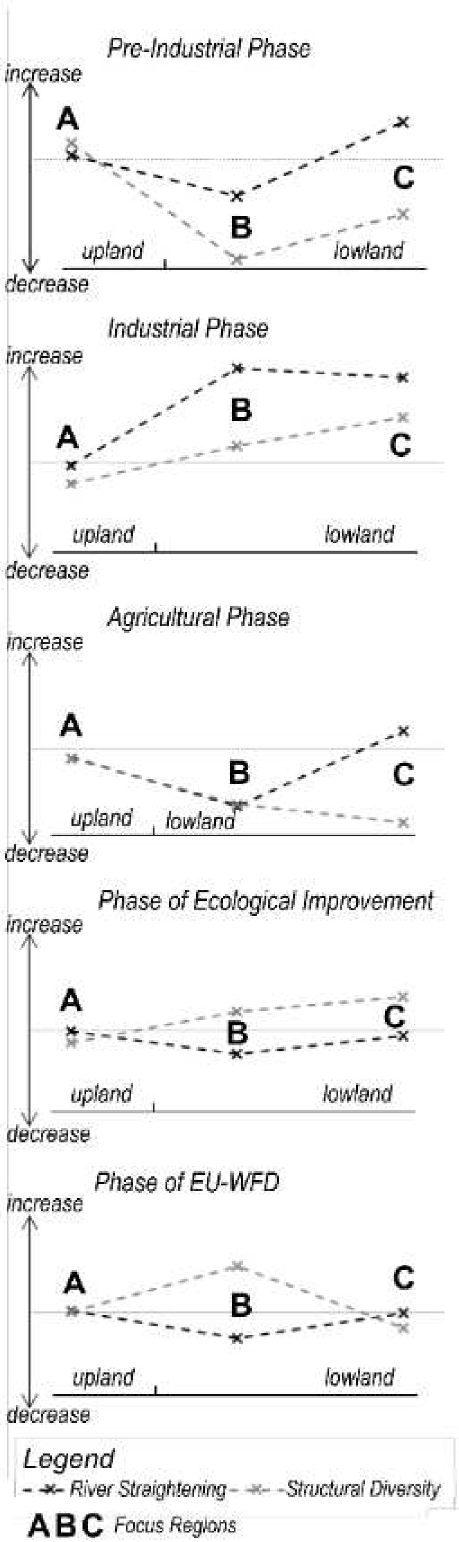

Figure 12

Qualitative development of all indicators for river straightening and natural morphological activity after the five historical phases of the last 200 years; Source: own illustration

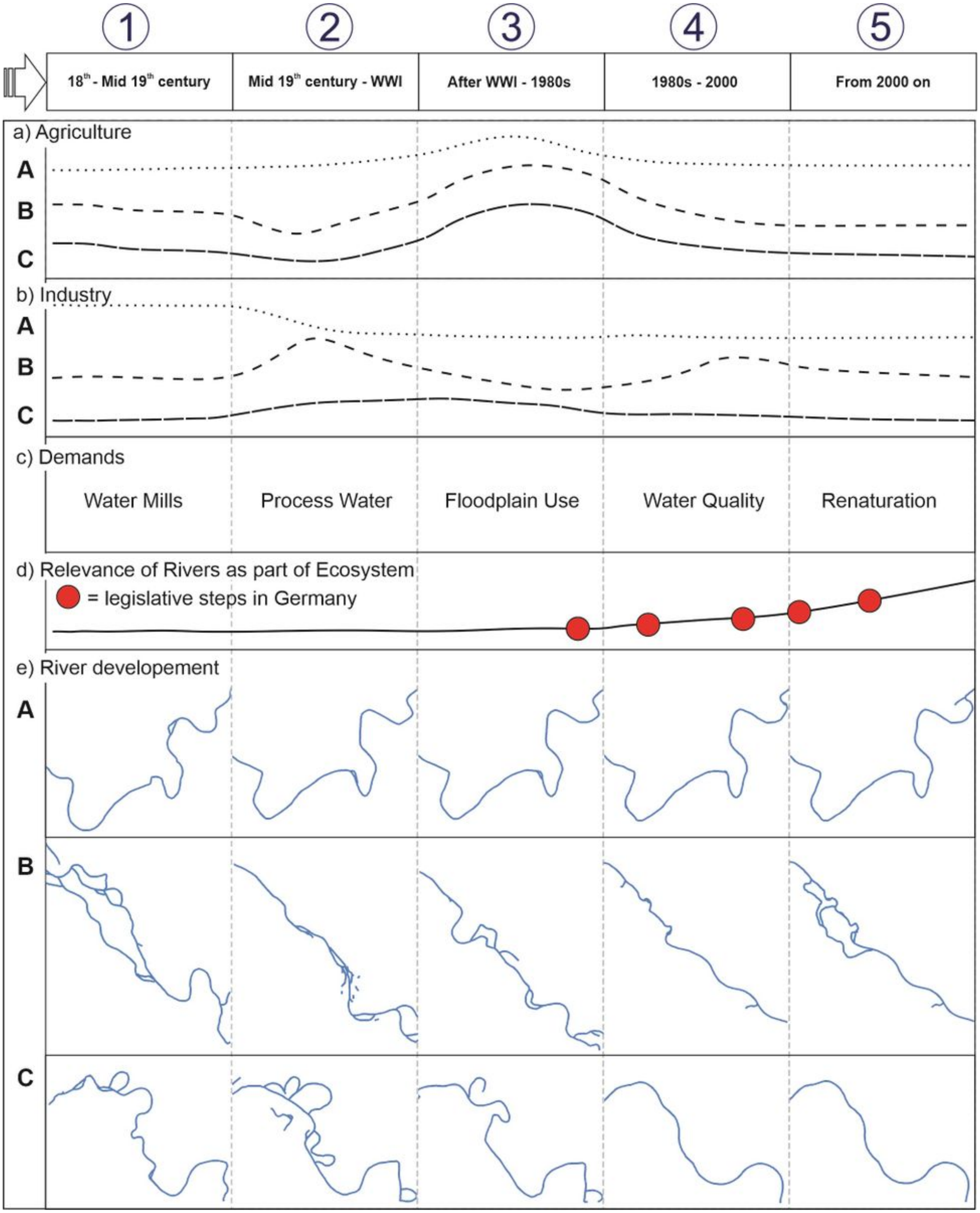

Figure 13

Changes in river courses in the three focus regions of the Rur River over the five phases of water management in the last 200 years. a) development of agricultural use of floodplains in the three focus regions, b) development of industrial use of floodplains in the three focus regions, c) main demand in the different phases of water management, d) amendment of the German Federal Water Act, and e) river course development of a representative section of the focus regions; Source: own illustration