

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

Does industrialization straighten a river?

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34 **Abstract**

35 **Background**

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

46

47 **Methods**

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

52

53 **Results**

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

59

60 **Conclusions**

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

66

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

69

70

71 **Background**

72 **History of Human Influence on River Systems**

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

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

86 Various studies have investigated human impacts on river systems worldwide at different times
87 [7, 8, 18, 19]. Gibling evaluates human influences using worldwide examples and creates a
88 timeline divided into six phases from the late Pleistocene to the Holocene [19]. He emphasizes

89 that in many cases, serious changes were connected with the Industrial Revolution and
90 technological advances in the 20th century, which are included in his 6th phase, the
91 Technological Era (after 1800 CE) (cf. Figure 1).

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

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

112

113 **Five Phases of River Management on the Rur River**

114 Hence, the culture of river management has changed several times within the last 200 years.
115 Focusing on the history of industrial development, this study period of 200 years can be divided

116 into five phases of river management of the Rur River (cf. Figure 2). Thus, each phase has
117 different water management characteristics on which the emphasis is placed. The phases are
118 to be understood as cultural epochs, and the time divisions are determined using the example
119 of the Rur catchment. Cultural epochs are generally variable in time and space [38, 39].

120 Interventions in water bodies in favor of industry started in the Pre-Industrial Phase (1) in the
121 18th century with lignite and ore mining [40–42]. In the 19th century, as a result of water conflicts
122 between agriculture and industry, textile companies were given preferential treatment [42].

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

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

136 Today, we are in the second management cycle of the EU-WFD (Water Framework-Directive)
137 [47], the Phase of EU-WFD (5) (cf. Figure 2). Sustainability of running waters and renaturation
138 largely determine the actions of people [48], but industries are still large stakeholders in water
139 management [49, 50].

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

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

147

148 **Human Influences on Morphodynamic Structures**

149 ***Sinuosity, oxbows, braided and anastomosing structures***

150 Oxbows often develop from meander cutoffs [55, 56] and therefore are a sign of river
151 straightening. Generally, a low degree of sinuosity indicates anthropogenic disturbance [57].
152 According to Gibling (2018), human impacts cause changes from meandering to braided
153 planforms and from multithread channel to single channel riverbeds [19]. With a decreasing
154 main channel sinuosity, a change from anastomosing to braided channels is common [58].
155 Braided streams are generally characterized by low sinuosities [59]. Therefore, braiding is a
156 general indicator of river straightening. When sinuosity decreases and braiding increases, the
157 development is often accompanied by higher peak flows and higher monthly discharge
158 variability [59]. These changes in discharge are commonly caused by human activities, such
159 as deforestation, mining and agriculture [60]. If a channel is anastomosing or braided, it
160 depends on the sediment supply from upstream [61]. For example, Scorpio et al. (2018) found
161 that braided structures only formed downstream of sediment confluences that were rich in
162 sediment in the alpine Adige River [62]. Braided rivers have a high supply rate but a low
163 transport capacity, which leads to the deposition of material [63]. Downstream of artificial river
164 straightening higher river bank erosion occurs due to bedload deficits [57, 64], which explains
165 changes from anastomosing to braided channels. Anastomosing structures are more common
166 for lower slopes and non-confining thalwegs [55]. The main sediment transport is suspended
167 load [55]. Anastomosing channels have a relatively low ability to erode and transport sediment
168 [63] and therefore develop towards a natural equilibrium.

169 ***Side arms and islands***

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

178

179 **Scope of Present Study**

180 The aim of this study is to assess the correlation between river management in the last 200
181 years and the changes in river courses by means of historic maps and digital orthophotos using
182 the Rur River as an example. Comparable studies showed that these types represent valuable
183 sources for information on river channel changes and that the period of analysis should be at
184 least 100 years [68]. Therefore, large-scale morphological changes over the last 200 years are
185 determined using the following indicators: river length, sinuosity, oxbow structures, sidearms
186 and number of islands. Due to the importance of the Technological Era after Gibling (2018)
187 [19], this period is subclassified into different river management phases. Understanding the
188 interaction between human influences and changes in fluvial systems from the past is the key
189 to sustainable river management in the future.

190 Therefore, periods of hydraulic development, including industrialization, in the study area, the
191 Rur River catchment (North Rhine-Westphalia, Germany), are compiled from the literature (cf.
192 Figure 2). The influence of these phases of water management on the Rur River can be
193 distinguished from each other via clearly formulated definitions. Afterwards, different historic
194 maps and morphodynamic indicators are used to assess whether those periods lead to specific
195 morphodynamic changes of the river within the specific Phases 1-5. Changes in river

196 straightening and structural diversity of the river are determined from changes in the indicators
197 by simple formulas. Differences between low mountainous regions and lowlands are also
198 considered to address the impact of geofactors. Finally, the transferability of the results to river
199 systems worldwide is discussed.

200

201 **Study area**

202 To investigate the long-term effects of anthropogenic influences on fluvial systems, especially
203 during industrialization, the Rur catchment (North Rhine-Westphalia, Germany) was chosen.
204 Changes in smaller catchments have direct effects on the fluvial system, and morphological
205 investigations are possible with higher spatial resolution [8, 69]. Hence, the Rur River
206 catchment is particularly suited since it is of a moderate size with 2,361 km² [70]. It also extends
207 from the mid-mountainous area of the northern Eifel Mountains in its upper reach to the
208 lowlands of the Lower Rhine Embayment in its lower reach [71]. The springs of the 165 km-
209 long Rur River are located in the raised bog area of the High Fens in Belgium at an altitude of
210 660 m above sea level [70]. In the Dutch city of Roermond, the Rur River flows into the Meuse
211 River at an elevation of 30 m above sea level [70]. Approximately 6.7% of the Rur catchment
212 is located in Belgium, approximately 4.6% is within Dutch territory, and almost 90% is located
213 in Germany [72]. The catchment area of the Rur River comprises 7% of the Meuse catchment
214 area, but it is the only river in the catchment that is significantly regulated by dams, which
215 balance the water levels [71].

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

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

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

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

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

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

252

253 **Focus Regions**

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

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

269

Table 1: Characteristics of the focus regions.

	mid. elevation	slope	average discharge	
	[m.a.m.s.l.]	[%]	winter [m ³ /s]	summer [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

270 * No detailed data for summer/winter available

271

272 **Methods**

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

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

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

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

284

285

286 **Digitalization of river courses and resolution**

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

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

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

Table 3: Decision matrix for digitalizing structural elements

Characteristics							structure	(possible) alternative
no. of channels	channel		river corridor	island(s)				
	enlarged	flow distribution	widening	size	number	vegetated		
	yes	-	no	small	more than 1	no	braided river	island
1	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	

316

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

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

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

333

334 *Table 4: Morphologic indicators for channel changes and their meaning. DEM25=digital elevation model with a grid*
 335 *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]
- ANASTOMOSING 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]

336

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

340

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

342 $\Delta_{Straightening} = -\Delta_{Sinuosity} + \Delta_{Braiding} + \Delta_{Oxbows}$ (Eq. I)

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

345 $\Delta_{Braiding}$ Change in length of braided channel sections between two time slices;
346 indicator for river straightening according to [58, 63, 95]

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

349

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

351 $\Delta_{Structural Diversity} = \Delta_{Side Arms} + \Delta_{Anastomosing} + \Delta_{Islands}$ (Eq. II)

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

354 $\Delta_{Anastomosing}$ Change in length of anastomosing channels between two time slices;
355 indicator for river straightening according to [63]

356 $\Delta_{Islands}$ Change in the number of islands between two time slices; indicator for
357 river straightening according to [55]

358

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

366

367 **Results**

368 First, changes in river length and sinuosity in the three focus regions are evaluated. In focus
369 region A, the river course was 2.6% shorter in the early 19th century compared to today,

370 meaning that a small river elongation has occurred (cf. Figure 9). The river section elongated
371 from 14.44 km to 14.82 km. In focus region B, a river course shortening of approximately 20%
372 has occurred during the same time period. The length of the river section changed from 23.08
373 km to 19.20 km between the early 19th century and 2019. In focus region C, the largest river
374 course shortening of approximately 43% has occurred since the early 19th century. Here, the
375 length of the river section changed from 19.05 km to 13.29 km. Since the 21st century, the
376 length of the river courses has remained static in all three focus regions.

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

381 The sinuosity in focus region A slightly increased from 1.11 to 1.14 over the last 200 years (cf.
382 Figure 9). According to the criteria of Brice [92], the Rur River in focus region A is classified as
383 sinuous in all five phases. In focus region B, the sinuosity dropped from 1.02 to 0.85, meaning
384 that the main course of the river is shorter than the thalweg predicted by the DEM25. The
385 largest decreases in sinuosity occurred during the Pre-Industrial (1) and Agricultural (3)
386 Phases. With a sinuosity smaller than 1.06, the Rur River in focus region B has been straight
387 over the last 200 years [92]. The Rur River in focus region C changed its sinuosity from 1.30
388 to 0.91. Therefore, the river course changed from meandering to straight [92]. Since the early
389 21st century, river sinuosities have stabilized with a very slight tendency to increase.

390 Braided channels only occur in small areas, whereby anastomosing channels can be found
391 more often (cf. Figure 10 a). In the Pre-Industrial Phase (1), the length of anastomosing
392 channels increased from 1.5% (approx. 0.2 km of additional channel length) of the total river
393 length in focus region A to 3.5% (approx. 0.5 km). During the Industrial Phase (2),
394 anastomosing channels almost vanished (approx. 0.03 km), but some braided river structures
395 occurred (approx. 0.04 km). Since the Phase of EU-WFD (5), anastomosing channels are
396 expanding again (back to approx. 0.2 km). In focus region B, anastomosing channels had
397 significant lengths during the Pre-Industrial Phase (1) (approx. 6.9 km). During Phase 2, the

398 length of the additional channel declined to approx. 0.6 km. However, braided channel sections
399 were at their longest, with approx. 1.7 km. Since the Agricultural Phase (3), anastomosing
400 channels have expanded slightly (approximately 1 km of additional channel length), and since
401 the early 21st century, braided channel sections have disappeared again.

402 Side arms are not present in focus region A, which can be explained by the steep thalweg (cf.
403 Figure 10 b). Only one anastomosing channel is digitalized with a “side arm” as an alternative
404 in early orthophotos (1998 and 2003). Later, a third channel occurs, marking the section as an
405 anastomosing river. Due to dense vegetation, the channel width cannot be determined. In
406 focus region B, the total length of the side arms decreased during the Industrial Phase (2) from
407 >1 to 0.6 km. Today, side arms total approximately 2 km in focus region B. In focus region C,
408 side arms were of significant length during Phase 2. Four side arms had a total length of
409 approximately 2.6 km. Today, only one anastomosing structure is digitalized with a “side arm”
410 as an alternative.

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

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

424 The greatest changes in river sinuosity occur at the Rur River in focus region C during Phases
425 2 and 3 (cf. Figure 11). In focus region B, the decrease in river sinuosity is almost as significant
426 as that in focus region C. The largest changes in braided and anastomosing channel sections
427 occur in focus region B. During Phases 1 and 2, anastomosing channels decreased and
428 braided river structures increased. During Phase 3, both braided and anastomosing channels
429 as well as the sinuosity of the Rur River decreased in focus region B. The number of oxbows
430 greatly varied during Phase 1, Phase 2 and Phase 3 in focus regions B and C. Additionally,
431 the number of islands varied during this time, but for both indicators, a significant increase
432 during the Industrial Phase (2) can be observed. Since the general focus shifted towards
433 improving the water quality and sustainability in river management (Phases 4 and 5), the
434 number of oxbows slightly decreased and the number of islands slightly increased in focus
435 region B, whereas both small-scale indicators decreased in focus region C.

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

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

448 The Rur River was only regulated in small local sections before 1950 [99]. Between 1962 and
449 1970, larger sections from Düren to Heinsberg were channelized, leading to an artificial
450 shortening of the river course [42, 100].

451

452 **Discussion**

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

458

459 **River development in the Rur catchment**

460 ***River straightening***

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

469 Changes in sinuosity from 1.02 to 0.85 in focus region B, which is characterized by farmland,
470 indicate that the river has experienced artificial straightening. During the Pre-Industrial Phase
471 (1), the river length in focus region B significantly decreased, although river regulation works
472 started more than 100 years later [99]. This leads to the theory, that intense agricultural
473 activities to make fertile floodplains usable and reduce flooding led to river straightening during
474 this phase. In addition to agriculture, local riverbed straightening around bridges is common
475 [102], which means that an expanding infrastructure leads to river straightening. A
476 considerable expansion of industrial and urban settlements in focus region B (cf. Figure 7) is
477 another explanation for river straightening in this area.

478 With a decreasing sinuosity and assuming an increase in oxbow and braided river structures
479 are signs of river straightening, the Industrial Phase straightened the river. In addition,
480 structural changes over large areas for agriculture led to river straightening in the lowlands.
481 Some of these changes can be explained by large-scale river regulation between 1962 and
482 1970 in the middle and lower reaches [42, 100].

483 ***Structural Diversity***

484 During the Industrial Phase (2), the number of islands increased, which can be explained by a
485 higher sediment yield due to land clearance and deforestation for uprising industries [42]. The
486 significant drop in islands during Agricultural Phase (3) in focus regions B and C can be
487 explained by dam construction in the 20th century and the resulting regulation of discharge in
488 the Rur River. In particular, the systems of three dams, as they are installed in the Rur River,
489 can trap nearly all inflowing sediments [103]. In addition, the land use change, which was
490 connected with land reclamation, explains the decrease in side arms and oxbows during the
491 Agricultural Phase (3) in focus regions B and C (cf. Figure 13). Since the general focus shifted
492 towards improving the water quality and sustainability in river management in the late 20th
493 century, the number of oxbows slightly decreased and the number of islands slightly increased
494 in focus region B, whereas both small-scale indicators decreased in focus region C. Regarding
495 the Agricultural Phase within the Technological Era according to [19] one needs to keep in
496 mind that in the early Anthropocene, land consumption for farming was considerably higher
497 [104]. Hence, morphodynamic changes in the Agricultural Phase according to this study very
498 likely intensified during the early Anthropocene.

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

506 Contrary to expectations, structural diversity does not increase significantly in the Phase of
507 EU-WFD (5). On the one hand the Phase of Ecological Improvement and the Phase of EU-
508 WFD are much shorter than previous ones, and therefore, the river has less time to develop.
509 On the other hand, human interference on the Rur River changed key drivers such as
510 hydrology through damming and land use. Geology, biology and hydrology can be considered
511 key drivers of river morphodynamics [101]. These drivers balance each other, which explains
512 why anabranching channels are stabilized by vegetation, jet hydrology has only a minor
513 impact, and braided river sections are not influenced by vegetation but rather by high stream
514 power [101, 106]. When a key driver is anthropogenically over-pronounced, natural river
515 recovery will be slow unless the impact can be balanced through (artificial) river restoration
516 [101]. Filling incised channels or reintroducing the establishment of protected areas for beavers
517 are two examples of countervailing measures [3, 101] restoring “wilder” river sections. For the
518 last two decades, beavers have repopulated northwest Germany [107]. The repopulation of
519 beavers in the Rur catchment is carried out and accompanied by local institutions. Today,
520 numerous beavers are again living on the Rur River and especially on its tributaries [108].
521 Nevertheless, the analysis of orthophotos did not show evidence for these animals in the focus
522 regions, and morphodynamic effects of the beaver population could not be observed in this
523 work. Regardless, the repopulation holds chances for future river development [109]. Today,
524 “controlled rewilding” on suitable river sections is promoted to create valuable habitats with
525 native vegetation [110]. In the 19th and 20th centuries on the Wurm River, a main tributary of
526 the Rur River, water mills from medieval times were abandoned [111, 112]. When abandoned
527 weirs were partially removed, mill ditches were left to “rewild” [111]. This phase of “natural
528 rewilding” was very local and soon superimposed by institutional river regulation. Thus, we
529 expect that “controlled” or “natural rewilding” will be used for river restoration in the future. .
530 Future studies should be conducted to determine the effects of rewilding on river morphology.

531

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

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

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

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

560 [119]. This development is comparable to the Phase of Ecological Improvement and the Phase
561 of EU-WFD in the Rur catchment.

562 For the Skawa River, which is a mountain tributary of the Vistula River, five digitalized maps
563 from the mid-19th century to 2016 were evaluated to explain the human impact on the river
564 [116]. Similar to the Rur River in its upper reach, the Skawa River is a gravelly embossed river
565 [116]. Witkowski evaluated sinuosity, the braiding and anastomosing index, as well as the
566 average number of mid-channel forms and the average distance of the outer banks of the river
567 channel [116]. Although indicators and proceedings slightly differ from the present study, the
568 findings are very comparable. In the early 20th century, agriculture and settlements in the
569 floodplain of the Skawa River led to the construction of embankments [116]. Between 1864
570 and 1911, islands decreased, and the bed narrowed, meaning that anastomosing structures
571 decreased [116]. On the Rur River, a drop in islands also correlates with increasing settlements
572 and agriculture in the floodplains (cf. Figure 10). In the mid-20th century, the riverbed of the
573 Skawa River was completely channelized [116]. Since the 21st century, more anabranching
574 structures have occurred, and sinuosity has increased again after the removal of riverbank
575 protections on the Skawa River [116]. The channel width has increased since the late 1970s.
576 These developments overlap with the Phase of Ecological Improvement and the Phase of EU-
577 WFD of the Rur River.

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

581 ***Worldwide context***

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

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

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

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

600

601

602 **Conclusions**

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

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

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

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

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

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

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

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

635 To complement this study, further research in regions with strongly differing historical frame
636 conditions and physiographic differences is needed. The key to sustainable river management
637 in the future is understanding the interaction between fluvial systems and human intervention

638 in the past. Thus, the findings and the concept of this study can be used for further research
639 and investigation.

640

641

642 **Declarations**

643

644 **Authors' contributions**

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

647

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656

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658 The authors declare that they have no competing interests.

659

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662

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665

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- 1035

1036 **Figure captions**

1037 Figure 1: a) Tipping points of human development, b) Classification of the five phases of river
1038 management in the Rur River catchment into phases of human impacts on river courses
1039 worldwide; Source: own illustration modified after [19]

1040

1041 Figure 2: The five phases of river management in the Rur catchment over the last 200 years,
1042 definition and characteristics; Source: own illustration, data according to [41–43, 45–48, 77,
1043 129–135]

1044

1045 Figure 3: Overview of the Rur catchment and its location in Europe; Source: own illustration;
1046 DEM: [136]; river system: [137, 138]; towns: [139]; country borders: [140]

1047

1048 Figure 4: a) Upper reach near Monschau, b) Bank protection in Monschau City, c) Upper reach
1049 in focus area A, d) Rur Dam, e) Middle reach in focus area B in Düren city, and f) Example of
1050 a near-natural section in the lowlands before Düren; Source: own illustration

1051

1052 Figure 5: Focus region; Source: own illustration; DEM: [136]; River system and catchment
1053 area: [137, 138]; towns: [139]; country borders: [140]; German river type: [71]

1054

1055 Figure 6: Impressions of the Rur River from the three focus regions. a) Rur River below
1056 Monschau, b) Rur River near Düren, and c) Rur River near Heinsberg; Source: own illustration

1057

1058 Figure 7: Development of industry and land use in the Rur catchment from 1850 to today;
1059 Source: own illustration; River system and catchment area: [137, 138]; towns: [139]; Corine
1060 land use data: [77, 141]

1061

1062 Figure 8: Objects of digitalized river courses; Source: own illustration; Criteria according to [59,
1063 83, 84]

1064

1065 Figure 9: Changes in river length and sinuosity in the three focus regions of the Rur River over
1066 its five phases of river management in the last 200 years; Source: own illustration

1067

1068 Figure 10: Change in indicators over the five phases of river management in the last 200 years
1069 in the three focus regions of the Rur River, a) changes in the length of anastomosing and
1070 braided river structures in comparison to the total river length, b) changes in the length of side
1071 arms in comparison to the total river length, c) changes in the average number of oxbows per
1072 river-km, and d) changes in the average number of islands per river-km; Source: own
1073 illustration

1074

1075 Figure 11: Development of indicators for morphodynamic activity and river straightening in the
1076 three focus regions over the five phases of water management in the last 200 years; Source:
1077 own illustration

1078

1079 Figure 12: Qualitative development of all indicators for river straightening and natural
1080 morphological activity after the five historical phases of the last 200 years; Source: own
1081 illustration

1082

1083 Figure 13: Changes in river courses in the three focus regions of the Rur River over the five
1084 phases of water management in the last 200 years. a) development of agricultural use of
1085 floodplains in the three focus regions, b) development of industrial use of floodplains in the
1086 three focus regions, c) main demand in the different phases of water management, d)
1087 amendment of the German Federal Water Act, and e) river course development of a
1088 representative section of the focus regions; Source: own illustration

Figures

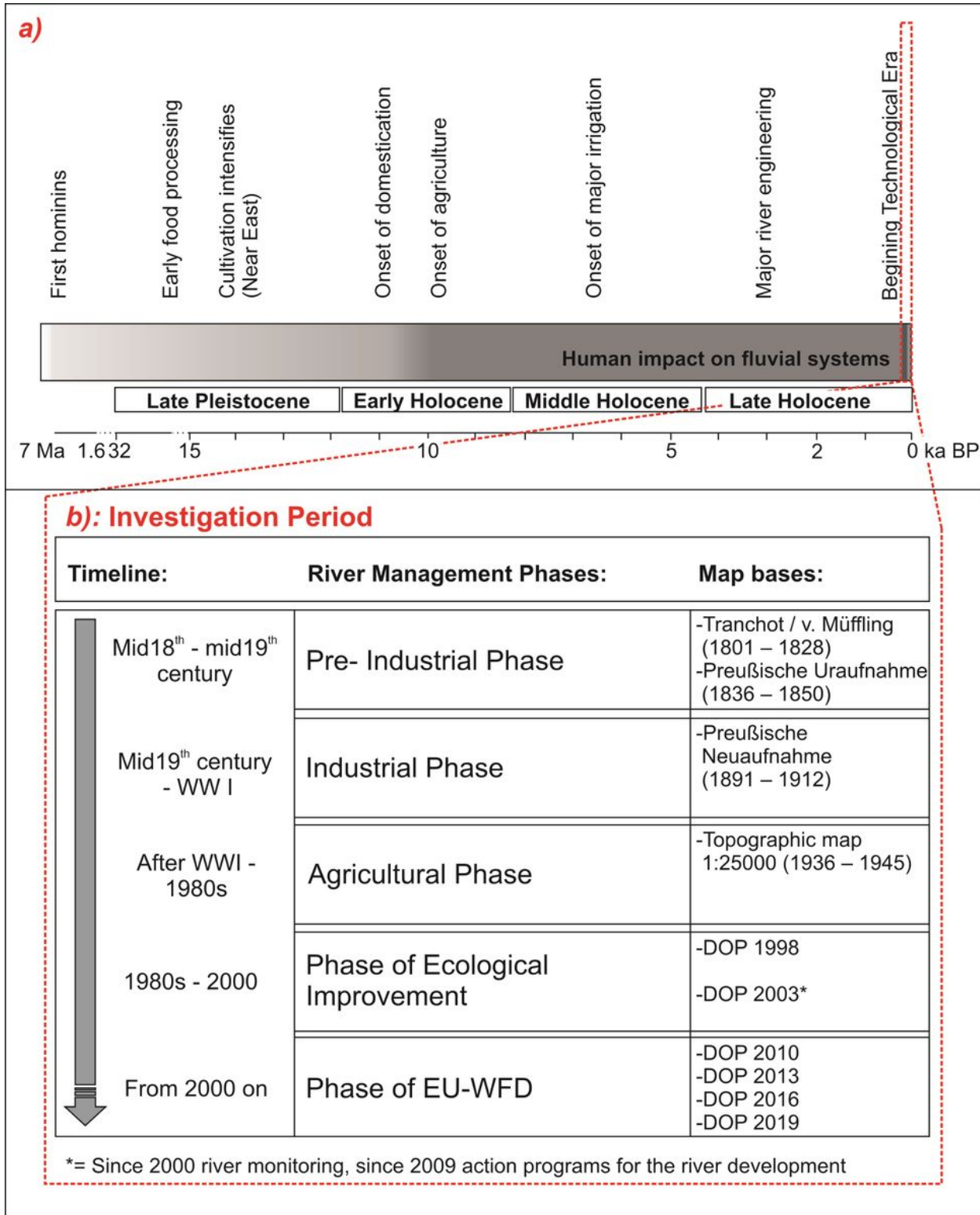


Figure 1

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]

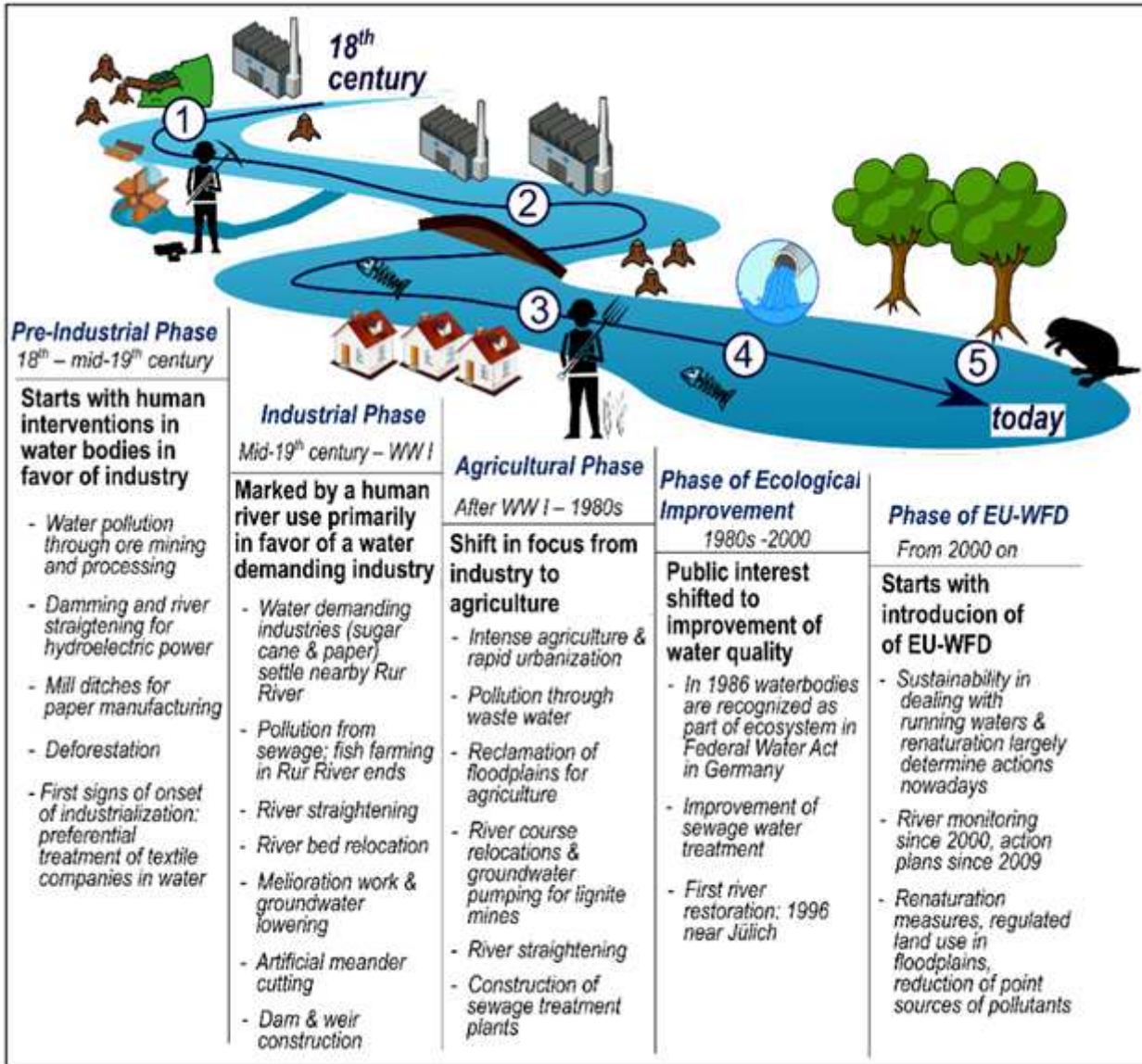


Figure 2

The five 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]

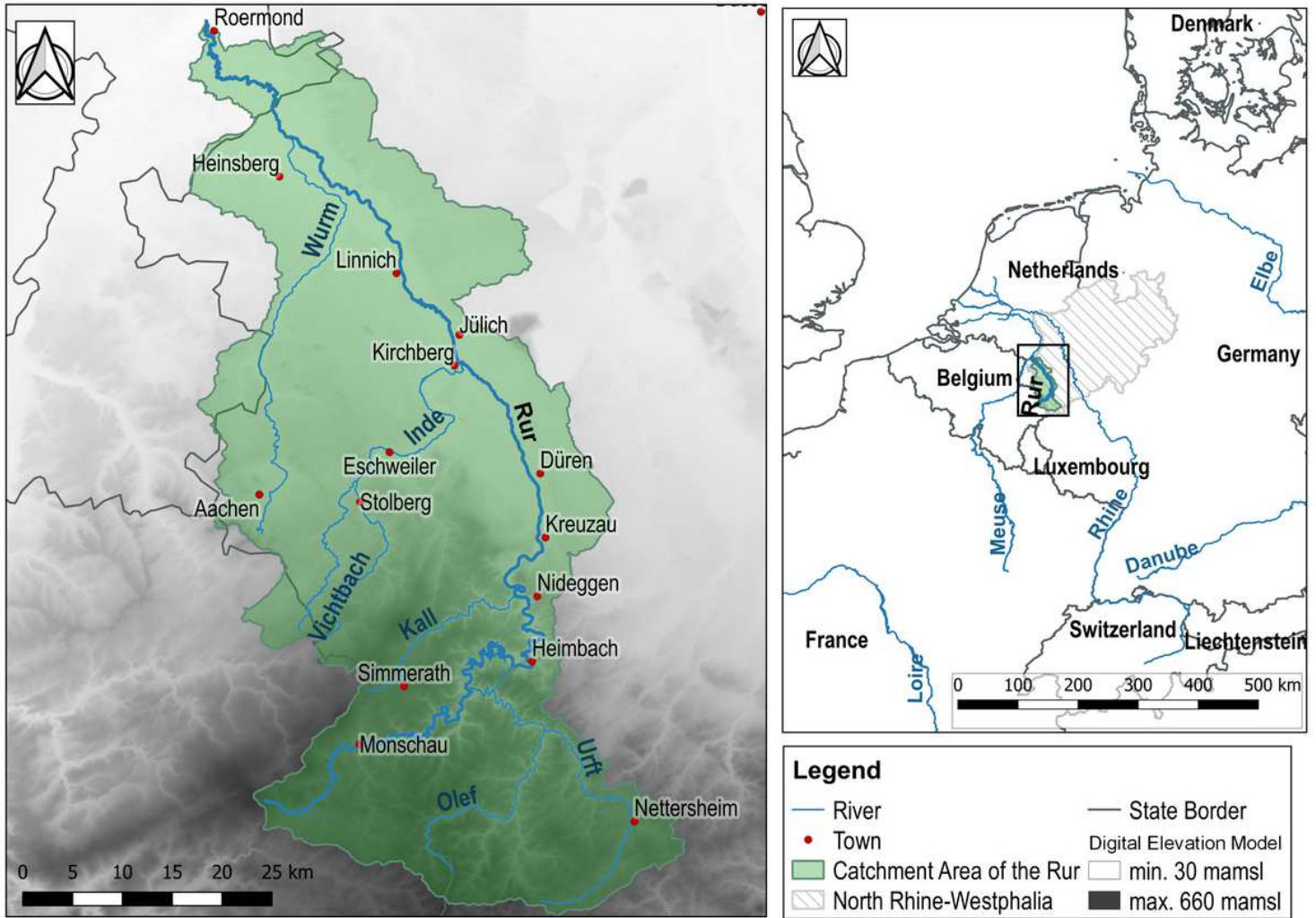


Figure 3

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

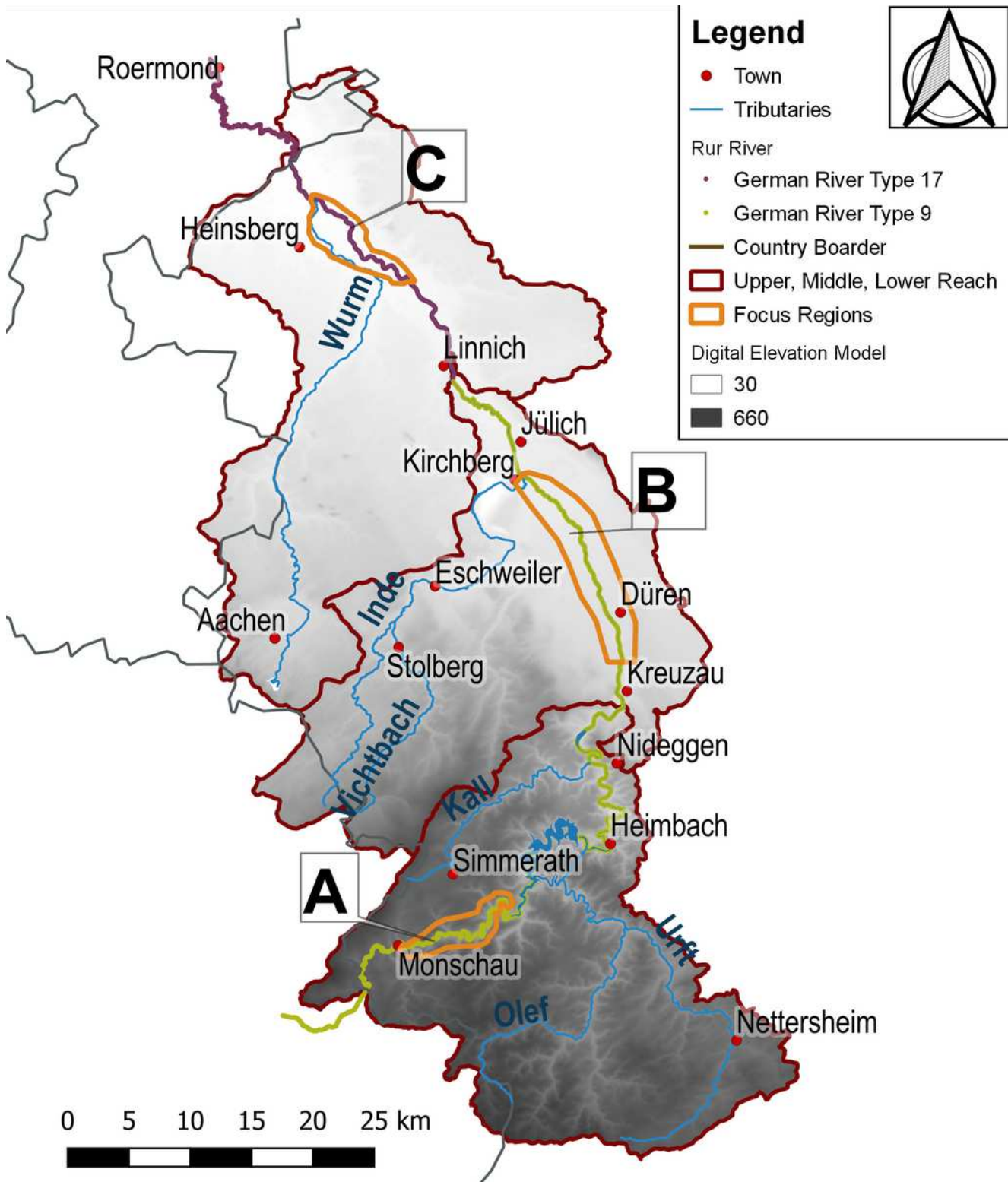


Figure 5

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

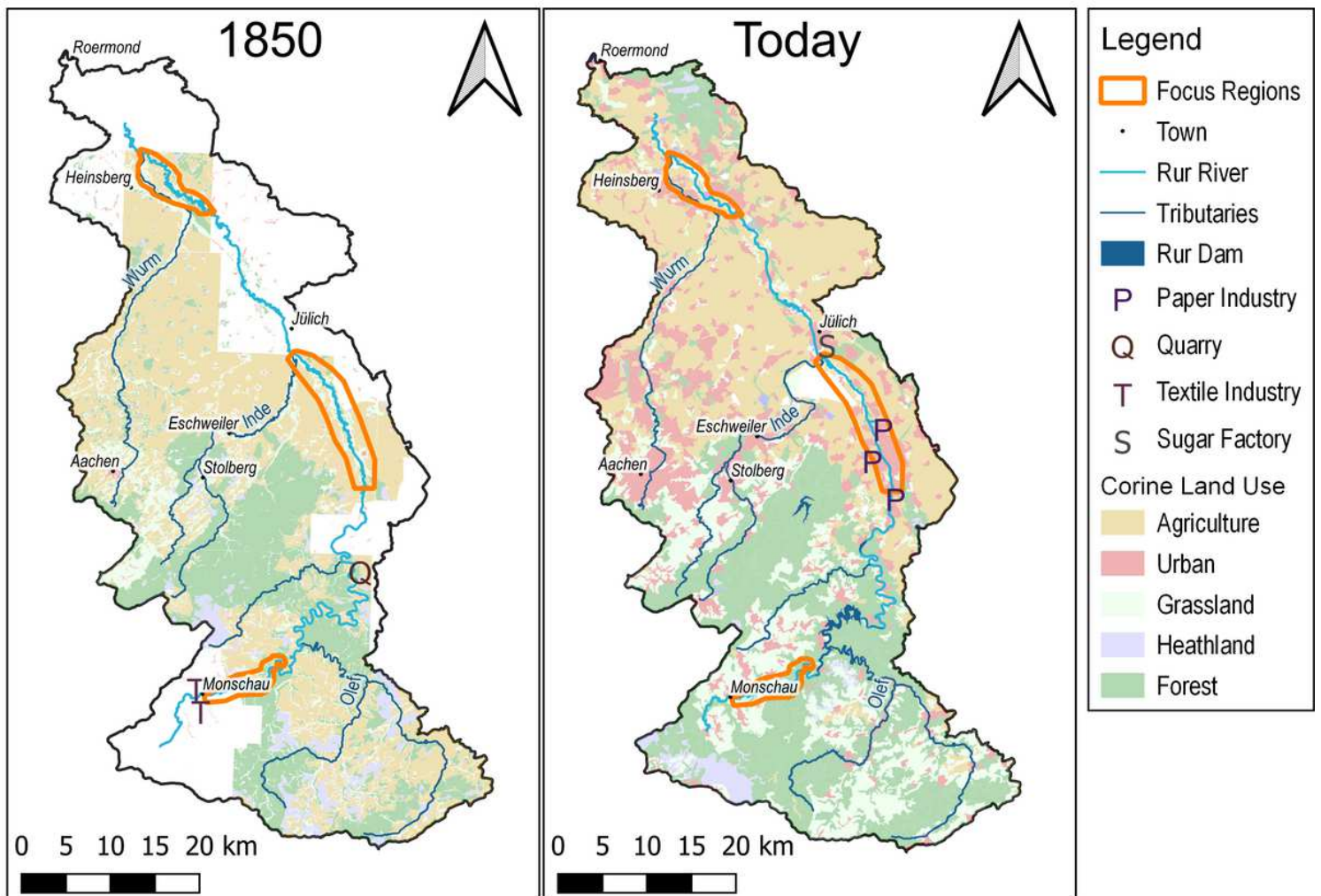


Figure 7

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]

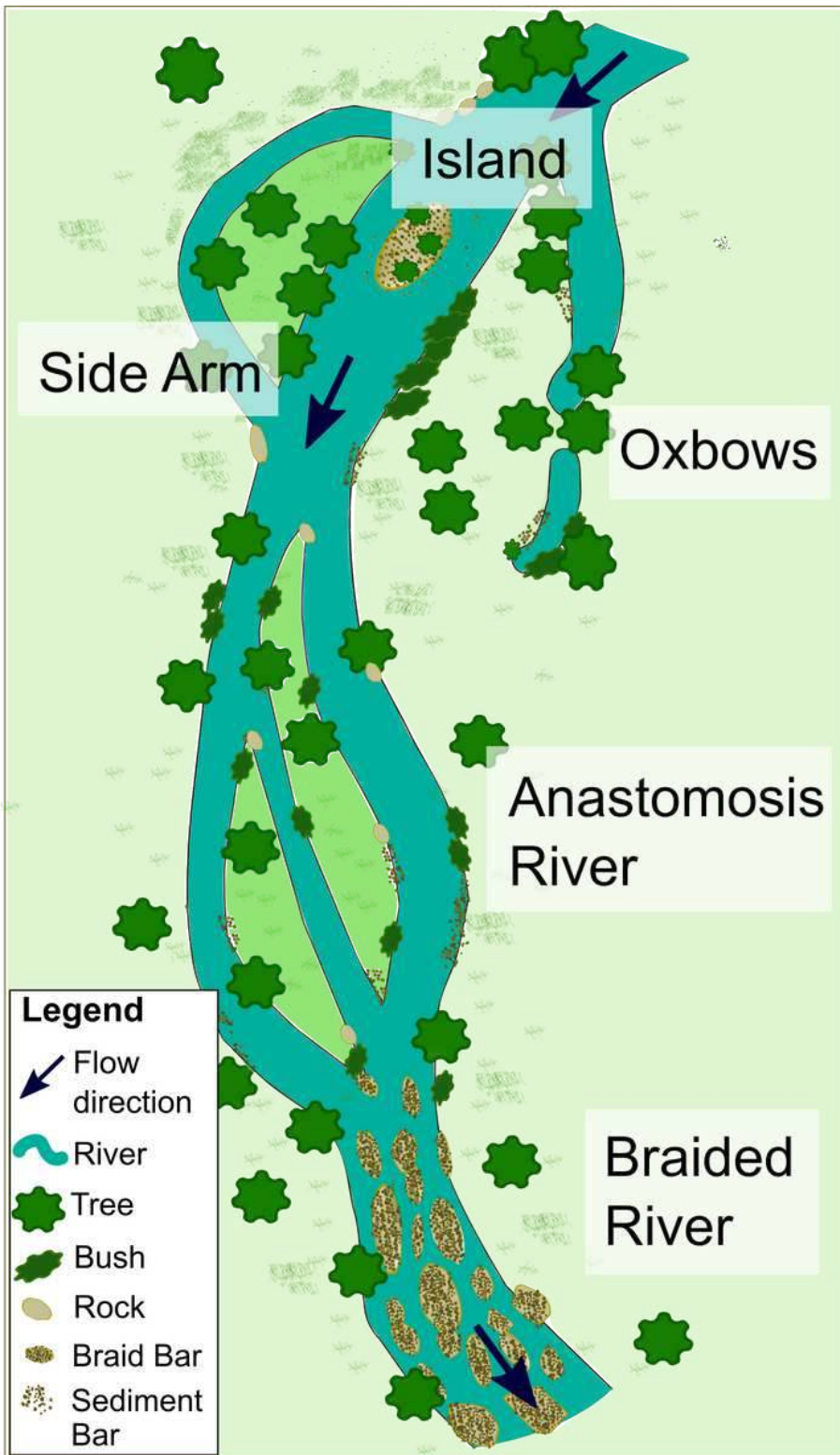


Figure 8

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

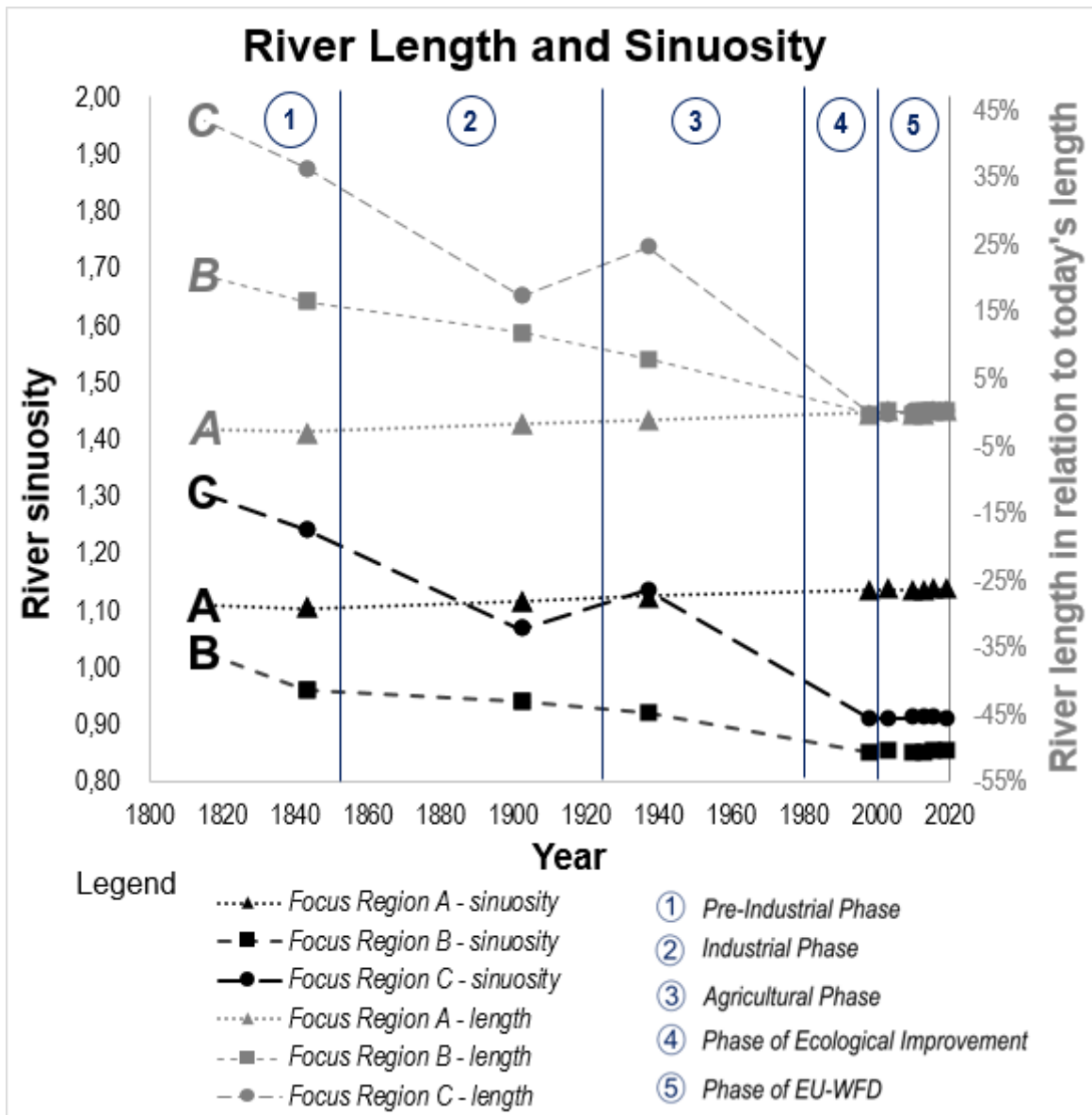


Figure 9

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

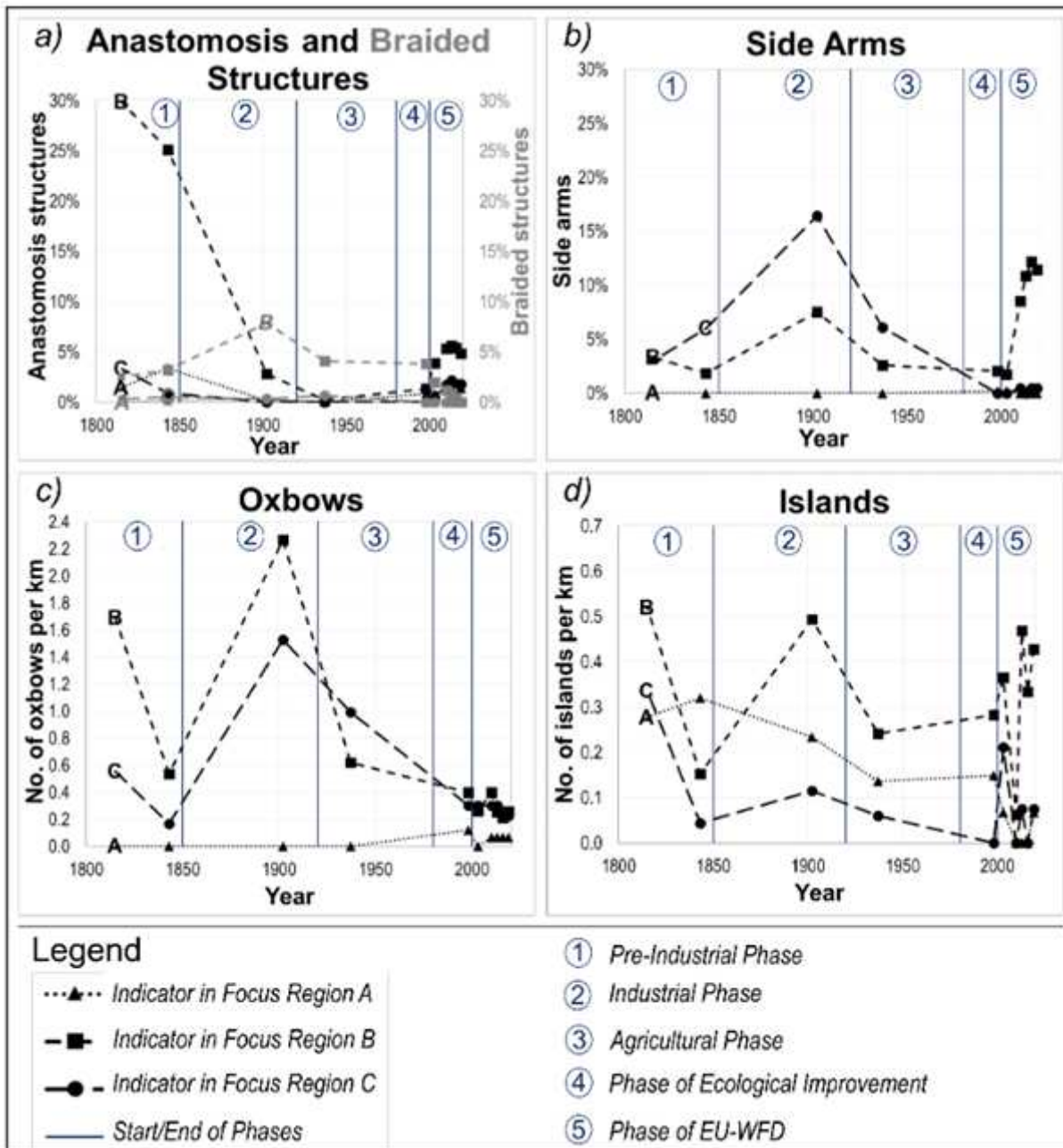
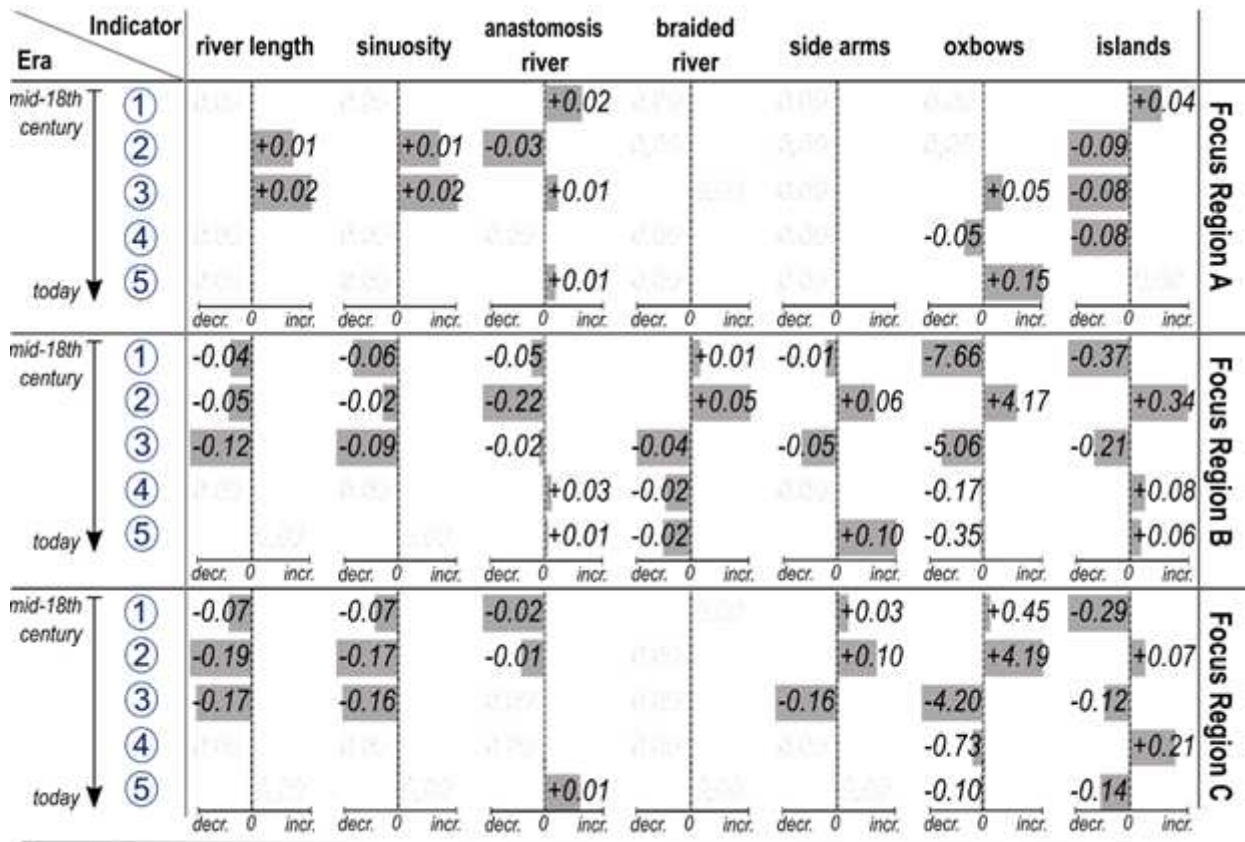


Figure 10

Change in indicators 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 number of oxbows per river-km, and d) changes in the average number of islands per river-km; Source: own illustration



Legend

① Pre-Industrial Phase ② Industrial Phase ③ Agricultural Phase ④ Phase of Ecological Improvement ⑤ Phase of EU-WFD

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

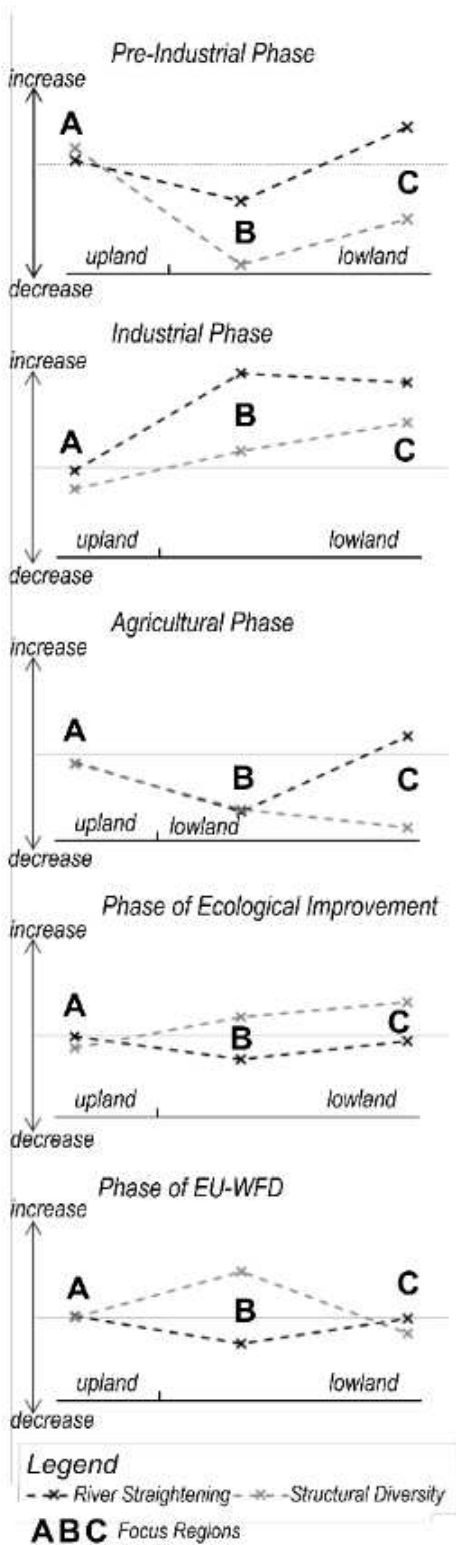


Figure 12

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

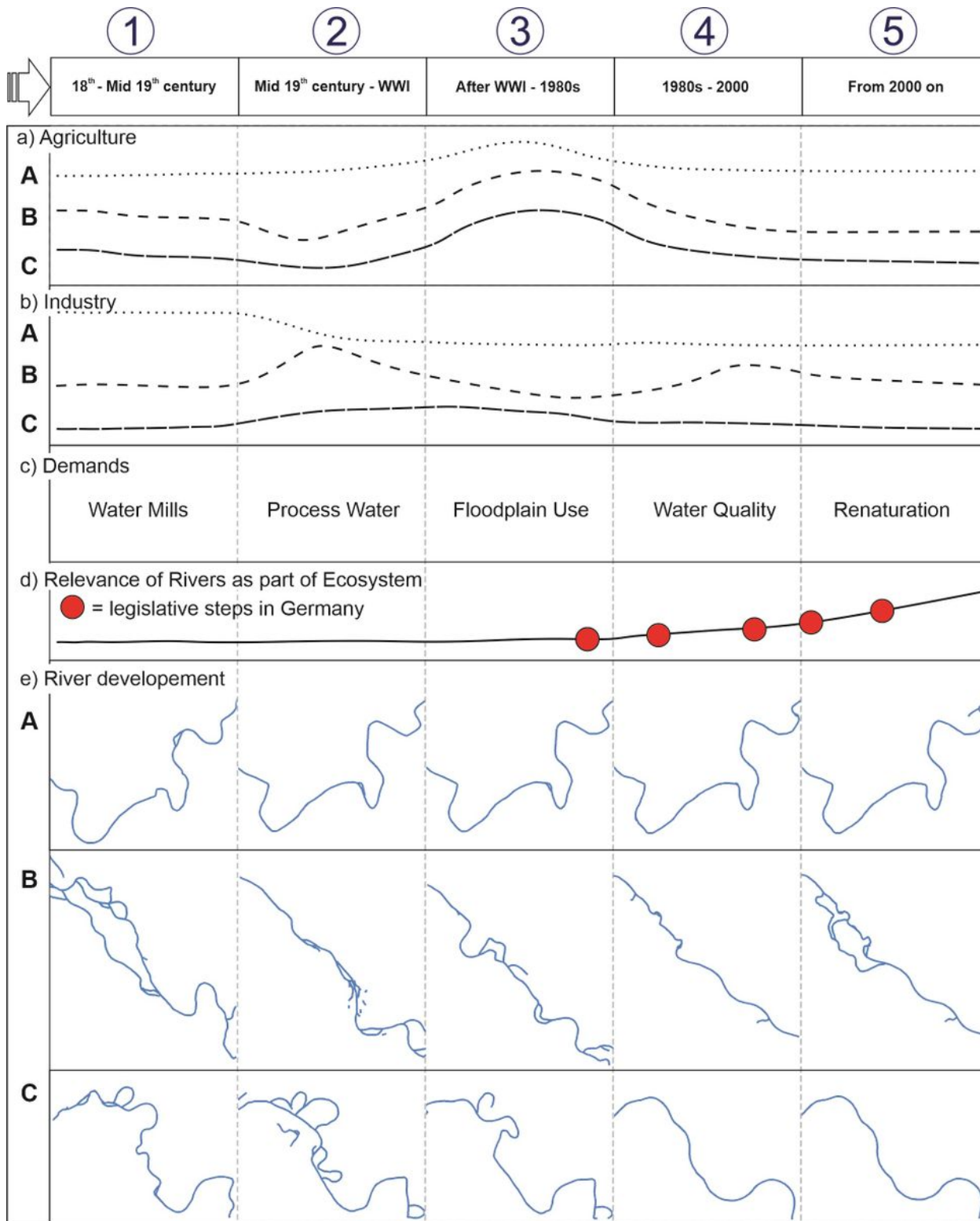


Figure 13

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