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

Methods

In this study, large-scale morphological changes over the last 200 years are determined based on historic maps and up-to-date orthophotos. The indicators 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 does increase especially during the industrial revolution, even without direct hydraulic channelization, which applies not only to the study area but also to further examples worldwide. The period and grade of river straightening has a direct morphodynamic impact on today’s river restorations. Since the Rur River is a typical upland to lowland river, the results show additional impact of geo-factors, like landform configurations.

Conclusions

The morphodynamic development is correlated with five historic periods between 1801 and 2019 of industrial development up to the introduction of the EU - Water Framework Directive (EU-WFD). Each period shows different influence on the watercourse which is connected with human intervention. Even if worldwide comparisons show that the five historical phases differ slightly in time 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

Since the beginning of the Holocene, the influence of humans on the environment has continuously increased [1–3], hence many fluvial systems have been negatively and profoundly influenced worldwide by human actions for centuries [4–9]. While geomorphologic changes up to 2250 BC are mainly attributed to climatic factors [2], the establishment of agriculture and large-scale deforestation in the Neolithic period led to a tipping point [10, 11].

Most of the European rivers have experienced extensive channel changes, whereby human impact is an important key driver [12]. The first hydraulic engineering measures were carried out in the form of river straightening, dam and weir constructions and the construction of mill canals and ponds [13]. In the Middle Ages, being the main energy source, the establishment of water mills boomed [14].

Various studies investigate the human impact on river systems worldwide in different times [8, 9, 15, 16]. Gibling evaluates the human influence using worldwide examples and creates a timeline, divided into six phases, from the late Pleistocene to the Holocene [15]. He emphasizes that in many studies 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).

Over the last two centuries, changes in land use, industry, flood protection, drinking water supply and hydroelectric power measures as well as shipping caused further morphodynamic impact on fluvial systems [10, 17, 18]. Especially the development of automatized production and steel industry caused a higher demand of hydroelectric power, process water and transportation routes provided by waterways [19–22].Therefore, the timeframe from the Middle Ages up to modern times is considered to have the biggest impact on lateral channel movement due to hydraulic structures [23].

With the increasing need of energy supply for industrialization, anthropogenic impact on rivers rose worldwide [19, 21] and was connected with river pollution [24]. Today, industries are still dependent on water supply and hydroelectric power [25] and it is expected that anthropogenic influence on rivers will even increase [26]. Apart from that, in the last decades, a rethinking took place towards the protection of fluvial systems. Especially in Europe sustainable development of water bodies became a common goal with the legislative basis of the EU-WFD [27].

Hence, the culture of river management changed a several times within the last 200 years. Focusing on the history of industrial development, five eras of river management in the last 200 years can be summed up for the Rur River (cf. Figure 2). The Eras are to be understood as cultural epochs and the time divisions were worked out using the example of the Rur Catchment. Cultural epochs are generally variable in time and space [28, 29].

Interventions in water bodies in favor of industry started in the Pre-Industrial Era in the 18th century. In the Industrial Era, rivers were primarily used in favor of a water demanding industry. The Industrial Era is superseded by Agricultural Era after WW I, where large area structural changes for food production and a shift from water power to electricity took place. From 1980 on water quality and the environment are focused. Today we are in the second management cycle of the EU-WFD (Water Framework-Directive) [30] (cf. Figure 2), but industries are still a large stakeholder in water management.

In this context the increased use of water resources as well as flood protection are often connected with river bed regulations [19, 31], but does industrialization really straighten a river?

Despite the massive anthropogenic influences, geo-factors of riverine landscapes are still affecting the morphology and hydrology of rivers and their floodplains today, as they have always been [32]. 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 [33, 34].

Human Influence of Morphodynamic Structures

Sinuosity, oxbows, braided and anastomosis structures

Oxbow often develop from meander cutoffs [35, 36] and therefore are a sign of river straightening. Generally, a low degree of sinuosity indicates anthropogenic disturbance [37]. According to Gibling, human impact causes changes from meandering to braided planforms and from multichannel to single channel riverbeds [15]. With a decreasing main channel sinuosity a change from anastomosis to braided river structures is common [38]. Braided streams are generally characterized by low sinuosities [39]. Therefore, braiding is a general indicator for river straightening. When sinuosity decreases and braiding increases, the development often is accompanied by higher peak flows and higher monthly discharge variability [39]. Those changes in discharge are commonly caused by human activities, such as deforestation, mining and agriculture [40]. If a channel is anastomosing or braided, depends on the sediment supply from upstream [41]. Braided rivers have a high supply rate but low transport capacity, which leads to the deposition of material [42]. Downstream of artificial river straightening higher river bank erosion occurs due to bed load deficits [37, 43], which explains changes from an anastomosing to a braided river. Anastomosis structures are more common for lower slopes and non-confining thalforms [35]. The main sediment transport is suspendedload [35]. Anastomosis river structures have a relatively low ability to erode and transport sediment [42] and are therefore seen as development towards a natural equilibrium.

Side arms and Islands

A marker of a natural and unspoilt river bedload balance is a high morphological development capacity leading to formation of islands and side channels [37]. Usually hydraulic forces in channelized river sections are too high for island formation [44]. Islands reestablish when river channelization is dismantled [44] and are therefore a sign for increasing structural diversity. The dynamic equilibrium of a river is shown in small scale changes, like island formations [45]. Side arms vanished during times of a high sediment input due to siltation and are today restored through river management actions [46]. Therefore, they increase structural diversity of the river.

Scope of Present Study

The aim of this study is to assess the correlation between river management of the last 200 years and the changes in river courses by means of historic maps and digital orthophotos on the example of the Rur River. Comparable studies showed that these data type represents valuable source for information on river channel changes and that the period of analysis should be at least 100 years [47]. Therefore, large-scale morphological changes over the last 200 years are determined using the indicators river length, sinuosity, oxbow structures, sidearms and the number of islands. Due to the importance of the Technological Era after Gibling [15], this period is subclassified into different river management phases. Understanding the interaction between human influence and changes in fluvial systems from the past is the key to a sustainable river management in the future.

There historic periods of hydraulic development of the study area, the Rur River catchment (North Rhine-Westphalia, Germany), are compiled from literature, including industrialization (cf. Figure 2). Afterwards different historic maps and morphodynamic indicators are used to access if those periods lead to specific morphodynamic changes of the river. Differences between low mountain regions and lowlands are also considered in order to address the impact of geo-factors. Concluding, the transferability of the results to river systems worldwide is discussed.

Regional settings

To investigate long-term effects of anthropogenic influences on fluvial systems, especially during the industrialization, the Rur catchment (North Rhine-Westphalia, Germany) was chosen. Changes in smaller catchment have direct effects on the fluvial system and morphological investigations are possible with higher spatial resolution [9, 48]. Hence, the Rur River catchment is particularly suited since it is of a moderate size with 2,361 km^2 [49]. It also extends from the mid mountainous area of the northern Eifel Mountains in the upper reach to the lowland of the Lower Rhine Embayment in its lower reach [50]. 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 [49]. In the Dutch city Roermond the Rur river flows into the Meuse at an elevation of 30 m above sea level [49]. About 6.7% of the Rur catchment are located in Belgium, about 4.6 % are on Dutch territory and almost 90% are located in Germany [51]. The catchment area of the Rur River makes 7% of the Meuse catchment area, but it is the only river in the catchment significantly regulated by dams, which balance out water levels [50].

After around 10 river km in Belgium the Rur River flows in its upper reach through the German low mountain range of the Eifel [52]. The Eifel is one of the most rural areas in Germany [53]. The catchment is area-wide anthropogenic marked by forestry in the highlands and grass- and farmland on plateaus [50]. The Lower Rhine Embayment is marked by agriculture and lignite open cast mining [50]. 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 [50, 59]. Precipitation in the Eifel mountain region is significantly higher than in the northern lowlands [50]. Due to its source region in the Eifel, the year-round aquiferous and dam-regulated Rur River has a rain and snow influenced discharge regime and is affected by the snowmelt from the low mountain range [60].

In the last 200 years the northern Eifel has been characterized by urbanization as well as grassland cover of arable land in the low mountain ranges and in the foothills as well as by reforestation measures in the Eifel forests [61]. Today, the Rur River is strongly anthropogenically influenced. Private companies, especially the paper industry, are still the largest water consumer in the Rur-Eifel region up to today [59, 62]. Most days of the year various reservoirs in the upper catchment cause a minimum water withdrawal which is morphodynamically ineffective [62]. The largest settlement at 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 German river type 9, which stands for silicate, low mountain range river rich in fine to coarse material [52]. Today's river course in the upper catchment is partly similar to the ecological mission statement, stretched to slightly sinuous, natural sections are existing with numerous characteristic longitudinal benches, sliding slopes and riffle pool sequences [63, 64]. Side channels would be characteristic, but are missing [64]. In the lowland, the Rur River is categorized as German river type 17, gravel-embossed lowland river [52]. Immense hydraulic engineering between 1940s and 70s led to a completely embossed straightened channel with strong incision [63]. Also, the flow is regulated by dams and a large number of transverse structures restricts the continuity [63]. Nevertheless, near-natural sections can be found in the lowlands between Schophoven and Kirchberg and between Jülich and Linnich (cf. Figure 4 f)) [63].

Methods

In order 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).

Focus Regions

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

Focus region A is located upstream from the dams starting at the end of the village Monschau. In the low mountain range of the Eifel 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. The 20 km long focus region B covers a typical agricultural area. In this focus region the city of Düren plays an important role for industrial development in the Rur catchment. Being a transshipment point for rafted wood in the Middle Age, it later became the main location for 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.

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 the digitalization were introduced in order to make the length of the digitalized river courses comparable. The accuracy of a line object can be identified by its amounts 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. A 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 structure 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 river bed, which are not part of a braided river section, are digitalized. Anastomosis river structures are multi-bed channels, in which the outflow is divided into a multitude of watercourses [39]. Braided river structures are characterized by intertwined blurred shorelines and variable bedload deposits in the river bed [39]. Oxbows or ox bows are constantly or temporarily flowed through former watercourse [66]. Oxbows are permanently connected to the watercourse on one side, ox bows are separated former river sections [66]. Side arms are permanently flowed side waters, whose start and beginning attached to main course.

Hand sketched historic maps in a low resolution and vegetation in digital orthophotos lead to difficulties in digitalization, as also recognized by Roccati et al. [68]. Therefore, some structure elements are digitalized with a possible alternative. For the analysis, the first choice for the type of structure element is considered with a weight of 0.8 and the alternative with a weight of 0.2. From the digitalized channels and its structure element indicators are computed for each time slice according to Table 1. Inaccuracies up to 20 m in historical maps of the 19th century, lead to a variation of results of less than 0.2%. Focus regions are not affected by sheet lines or map-edges. Therefore, results can be specified without an error range.

For 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 according length from the historic map or orthophoto. 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 among each other besides covering unequal long river sections.

In order to calculate the river sinuosity, the thalweg for each focus region is computed using a DEM25. By using a relatively coarse DEM it is ensured that the thalweg and not the river coarse is computed (e.g. [69]).

Table 1: Morphologic indicators for channel changes and their meaning

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 of river length is a sign for artificial straightening [70]
SINUOSITY	Total river length of the Rur River in a focus region divided by the thalweg [71–75], computed with the DEM 25	Reduced sinuosity often is a sign for river straightening [33, 76], an increase is a sign for tending towards a new equilibrium [70] but can also occur when the flow velocity increases [35].
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 of channel structures is a reaction to changes in the sediment household and/or changes in the river slope [70] often due to straightening [77]
- ANASTOMOSIS RIVER	… for anastomosis river structures	Anastomosing river structures develop after periods of high floodplain flow [42] and require low valley floor slope, fine bottom substrate or high organic content to form [37]
- BRAIDED RIVER	… for braided river structures	Sign for excess bed load, coarse bottom substrate and high valley bottom slope [37, 78], instable state [79]
- SIDE ARM	… for side arms	Occur at flood events as a reaction to hydraulic stress, today side arms are preserved as habitats [80]
RELATIVE NUMBER OF OXBOWS	Number of oxbows and ox bows in a focus region divided by the river length in km	Oxbows as channel cut offs are a sign for river course shortening [35]
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 [35]

Indicators are used to evaluate the development of river straightening (Eq. I). Additionally, it is evaluated if the rivers structural diversity is increasing (Eq. II). If structural development is driven by fluvial processes it is very likely self-sustaining [81].

The increase of 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 [33, 38, 76]

$\Delta_{Braiding}$ Change in length of braided river structures between two time slices; indicator for river straightening according to [38, 42, 78]

Δ_{Oxbows} Change in number of oxbows between two time slices; indicator for river straightening according to [35]

The increase of 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 [80]

$\Delta_{Anastomosing}$ Change in length of anastomosis river structures between two time slices; indicator for river straightening according to [42]

$\Delta_{Islands}$ Change in number of islands between two time slices; indicator for river straightening according to [35]

Results

First, changes in river length and sinuosity in the three focus regions are evaluated. In focus region A, the river course was 2.5% shorter in the early 19th century compared to today, meaning that a small river elongation has taken place (cf. Figure 9). In focus region B, a river course shortening of approximately 20% has taken place during the same time period. Similar to focus region A the length remains about the same since the 21st century. In focus region C, the largest river course shortening with about 43% has taken place since the early 19th century.

Unlike in focus regions A and B the development is not continuously but the river course elongates between WW I and WW II. Since the 21st century, the length of the river courses is remaining 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 gravel-embossed lowland river.

The sinuosity in focus region A is slightly increasing from 1.11 to 1.14 over the last 200 years (cf. Figure 9). According to the criteria of Brice [71], the Rur River in focus region A is classified as sinuous over all five eras. 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 and Agricultural Eras. With a sinuosity smaller than 1.06 the Rur River in focus region B has been straight since the last 200 years [71]. 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 [71]. Since the early 21st century, the river sinuosities are stabilizing with a very slight tendency to increase.

Braided river structures only occur in small dimensions, whereby anastomosis river structures can be found more often (cf. Figure 10 a)). In the Pre-Industrial Era, the length of anastomosis river structures increased from 1.5% of the total river length in focus region A to 3.5%. During the Industrial Era anastomosis river structures almost vanished, but some braided river structures occurred. Since the Era of EU-WFD anastomosis structures are expanding again. In focus region B anastomosis river structures were of significant length during the Pre-Industrial Era. During the Industrial Era up to WW II they declined. Since the Agricultural Era anastomosis river structures are expanding, and since the early 21st century braided river structures are disappearing again.

Side arms are rarely present in focus region A, which can be explained by the steep thalweg (cf. Figure 10 b)). In focus region C, side arms were of significant length during the Industrial Era. In focus region B, the total length of side arms also increased during this Era.

In focus region A, oxbows rarely occur with less than one oxbow per river km, however they increased since the middle of the 20th century (cf. Figure 10 c)). In focus region B, oxbows occur more often. After the Industrial Era, the number of oxbows per km dropped from approximately 2.0 to 0.5 with a decreasing tendency up to today. In focus region C, the number of oxbows per km was at its peak during the Industrial Era. Afterwards numbers are declining up to today.

Overall, the number of islands per river km has decreased in the last 200 years in focus region A (cf. Figure 10 d)). In focus region B, the average number of islands per river km varies heavily. After a decrease of islands during the Pre-Industrial Era in focus region C, a slight increase since the beginning of the 21st century can be detected.

The greatest changes in river sinuosity occur at the Rur River in focus region C during the Industrial Era and the Agricultural Era (cf. Figure 11). In focus region B, the decrease in river sinuosity is almost as significant as in focus region C. The largest changes in braided and anastomosis river structures occur in focus region B. During the Pre-Industrial Era and the Industrial Era anastomosis river structures decreased and braided river structures increased. During the Agricultural Era both, braided and anastomosis river structures as well as the sinuosity of the Rur River decreased in focus region B. The number of oxbows and ox bows greatly varied during the Pre-Industrial Era, the Industrial Era and the Agricultural Era 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 Era can be observed. Since the general focus shifted towards improving the water quality and sustainability in river management, the number of oxbows and ox bows slightly decreased and the number of islands slightly increased in focus region B, whereas both small scale indicators decreased in focus region C.

With those indicators (cf. Figure 11), using equation I and equation II, the development of river straightening and structural diversity over the five eras of river management can be evaluated (cf. Figure 12). In contrast to the other two focus regions, no river straightening is observed in in focus region A. Also, changes in structural diversity are very little in focus region A. In the Pre-Industrial Era river straightening and structural diversity decreased in focus region B and increased in focus Region A. During the Industrial Era both, river straightening and structural diversity, increased in focus region B and C, which are both located in the lowlands of the Rur catchment. During the Agricultural Era, developments were similar to the Pre-Industrial Era, except structural diversity decreased further. Since the 1980s (Era of Ecological Improvement and Era of EU-WFD) river straightening is decreasing, but structural diversity is only increasing for focus region B.

Discussion

Results show the development of river length, sinuosity and morphodynamic indicators over five eras over river management during the last 200 years. River length and sinuosity are direct indicators for river straightening. However, the validity of indicators derived from morphodynamic structure elements need to be discussed, since they are dependent on geological and climatic factors and the river type.

River development in the Rur catchment

River straightening

In comparison to focus region A in the low mountain area, focus regions B and C in the lowlands experienced significant 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 [70], as it is the case in the low mountain area of focus region A. In addition, the very 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.

Changes of sinuosity from 1.02 to 0.85 in focus region B, which is characterized by farmland, indicates that the river has experienced artificial straightening. During the Pre-Industrial Era, the river length in focus region B significantly decreased. This leads to the theory, that intense agricultural activities during this era lead to river straightening to make fertile floodplains usable and reduce flooding. Besides agriculture, local river bed straightening around bridges is common [82], which means that an expanding infrastructure leads to river straightening. With a considerable expanding of industrial and urban settlements in focus region B (cf. Figure 7), this is another explanation for river straightening in this area.

With a decreasing sinuosity and assuming an increase in ox bow, oxbow and braided river structures being signs for river straightening, the Industrial Era did straighten the river. In addition, large-area structural changes for agriculture led to river straightening in the lowlands.

Structural Diversity

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. Intense agricultural use and deforestation lead to an increased sedimentation which is prone to cause siltation of mill ponds [83]. In addition, the land use change, which was connected with land reclamation, explains the decrease in side arms and oxbows during the Agricultural Era in focus regions B and C (cf. Figure 13). The significant drop in islands during Agricultural Era in focus regions B and C can be explained by the dam constructions in the 20th century and the resulting regulation of the discharge in the Rur River. Especially the systems of three dams, as it is installed in the Rur River, can trap nearly all sediments of the inflow [84]. Before that, the number of islands increased, which can be explained by a higher sediment yield due to land clearance and deforestation for uprising industries. Regarding the Agricultural Era within the Technological Era according to [15] one needs to keep in mind, that in the early Anthropocene led consumption for farming was considerably higher [85]. Hence, morphodynamic changes in the Agricultural Era according to this study very likely occurred intensified during the early Anthropocene.

In the 20th century the reduction of base flow levels due to installation of hydroelectric power plants in many rivers led to siltation of many side arms [86]. In addition, the increasing urbanization from the 20th century onwards also leads to increased sediment inputs into the waters at the beginning of urbanization. If the urban structures are largely developed, the sediment input is reduced again, but the hydrological retention of the area is greatly reduced [76]. At the end of the 20th century restoring of side arms began in order to create habitats [86].

<u>European transferability of the concept of five Eras of river management</u>

In order to transfer the findings to further river systems, the transferability of the five eras 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 more and less strong industrial development in the last 200 years. Further, findings from recent GIS-based studies of the anthropogenic influenced development on rivers in the Technological Era are compared to this study in order to find general statements.

Generally the period from the late eighteenth century to World War I is declared as a phase of European industrialization but the growth rate varied greatly between different countries [87]. Around the fourth to fifth decades of the nineteenth century the phase of economic preparation was completed for countries in mid Europe and their industrial development sped up [87]. River straightening and the increase of 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 [88], being roughly 100 years behind the development in the Rur catchment. The landscape of the Vistula catchment is influenced since the 13th century through water mills and settlements [14]. Over the last 200 years, landscape changes, differences in use of process water and drainage as well as construction of infrastructure had an impact on the development of the Vistula River [14]. Since the early 20th century river, channeling and straightening for shipping intensified in Poland [89]. Just like in the Rur catchment, after World War II the number of watermills declined due to the replacement of water power by electricity [14]. After World War II the industrial development in Poland sped up, so that the last 75 years can be seen as main phase of the Industrial Era [88]. Also the demand for process water was still growing 25 years ago [90]. Open-cast mining increased in the late 20th century [91] and up to today mostly mining and quarrying products, i.e. coal, are transported by waterways [89]. In Poland industrial development is accompanied by the construction of small water mills as local and independent energy source up to today [92]. After intense river straightening on river systems in northern Poland in the last century the water quality decreased [93]. Since the early 21st century the situation improved due to oxbow and old arm restoration and its maintenance [93]. This development is comparable to the Era of Ecological Improvement and the Era 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 until 2016 were evaluated to explain the human impact on the river [94]. As the Rur River in its upper reach, the Skawa River is a gravel embossed river [94]. 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 [94]. Although indicators and proceeding slightly differ from the present study, 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 [94]. Between 1864 and 1911 islands reduced and the bed narrowed, meaning that anastomosis structures decreased [94]. 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 [94]. Since the 21st century more anabranching structures occurred and sinuosity increases again after removal of riverbank protections on the Skawa River [94]. The channel width is increasing again since the late 1970s. These developments overlap with the Era of Ecological Improvement and the Era of EU-WFD at the Rur River.

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

Worldwide international context

Common anthropogenic drivers for morphological change of rivers worldwide are land cover and land use changes, dam construction, bank protection and instream mining [95]. In the early days of Industrial Era small-scale water mills were an important energy source [96]. In its high time rivers played a great role for transportation which led to the building of various canals [97–99]. Over the past 150 years the Mississippi river was straightened mostly for navigation [45, 100]. At the same time navigable canals in France extended [38]. In England in the early 19th century canals expanded providing a cheap way to transport coal [101]. The Rhine, the Rhône and the Danube River were also channelized in the 19th century [102]. Swedish hydropower developed after World War I for industrial sakes, which led to river regulation [103].

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

Large river course structures such as anastomosis structures are not dependent on a certain climate type [42], so it can be assumed that river straightening during an industrial era happens 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 anastomosis sections and islands.

Conclusion

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 periods between 1801 and 2019 of industrial development can be distinguished:

1. Pre- Industrial Era (Mid18th - mid19th century)
2. Industrial Era (Mid19th century - WW I)
3. Agricultural Era (After WWI - 1980s)
4. Era of Ecological Improvement (1980s - 2000)
5. Era of EU-WFD (From 2000 on)

These periods correlate with changes of the river course, which can be explained by corresponding human interventions. The changes are detected by means of the morphodynamic indicators sinuosity, anastomosis and braided river structures, side arms, oxbows and islands.

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 stronger characterized by changes over the last 200 years compared to focus region in the low mountain area. In this context the indicators sinuosity or river braiding, show that the mountainous valley configurations lead to a more stable river morphology.

The Industrial Era, in contrast to the Pre- Industrial Era, was characterized by intense river straightening, indicated by decreasing sinuosity and increasing numbers of ox bows, oxbows and braided river structures. The Agricultural Era led to river straightening in the lowlands due to land reclamation. Both, the Era of Ecological Improvement and the Era 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 five river management phases – concept. Since the different periods are to be understood as cultural epochs, their starting and ending points may vary in time and region, depending on factors like wealth disparities or legislation. Therefore, they are still applicable on 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 are needed. The key to a sustainable river management in the future is understanding the interaction between fluvial systems and human intervention from 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 on specific aspects of the manuscript. All authors read and approved the final manuscript.

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The authors declare that they have no competing interests.

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Figure captions

Figure 1: a) Tipping pints of human development, b) Classification of five phases of river management in the Rur River catchment into phases of human impact on river courses world-wide; Source: Own illustration modified after [15]

Figure 2: Five eras of river management in the Rur catchment over the last 200 years, definition and characteristics; Source: Own illustration, data according to [1, 26, 29, 35, 39, 46, 57, 70, 85, 86, 90, 96, 102, 107, 115]

Figure 3: Overview of the Rur-Catchment and its location in Europe. Source: Own Illustration; DEM: [54]; river system: [55, 56]; cities: [57]; country boarders: [58]

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

Figure 5: Focus Region; Source: Own illustration; DEM: [54]; River system and catchment area: [55, 56]; cities: [57]; country boarders: [58]; German river type: [50]

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

Figure 7: Development of industry and land use in the Rur catchment from 1850 until today; Source: Own illustration; River system and catchment area: [55, 56]; cities: [57] Corine Land Use data: [61, 65]

Figure 8: Objects of digitalized river courses; Source: Own illustration; Criteria according to [39, 66, 67]

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

Figure 10: Change of indicators over the five eras of river management in the last 200 years in the three focus regions of the Rur River, a) changes in the length of anastomosis and braided river structures in comparison to the total river length, b) changes in the length side arms in comparison to the total river length, c) changes in the average no. of oxbows per river km, d) changes in the average no. 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 five Eras of water management in the last 200 years; Source: Own illustration

Figure 12: Qualitative development of summed indicators for river straightening and natural morphological activity after the five historical phases of the last 200 years: Pre-Industrial Era, Industrial Era, large-area structural change; Source: Own illustration

Figure 13: Changes in river courses in the three focus regions of the Rur River over five Eras 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 eras of water management, d) amendment of the German Federal Water Act, e) river course development of a representative section of the focus regions; Source: Own illustration