# Morphodynamics and heavy metal accumulation in an artificially built near-natural river (Inde, Germany)

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## Abstract

Heavy metals in riverine sediments threaten fluvial ecosystems worldwide. Sediment cascades transporting the compounds downstream lead to pollution stress downstream from the original input source. In regulated rivers, artificially built reaches with re-activated morphodynamics and morphological structures may become typical sink areas for contaminants. Therefore, a thorough understanding of transport mechanisms and accumulation dynamics is the key to managing enhanced heavy metal concentrations in alluvial sediments. In this study, we investigate a morphologically diverse 12 km-long river reach of the Inde River in Germany, that was relocated in 2005 due to an open-pit lignite mine. As the Inde catchment is a former industrial hotspot (beginning in the Iron Age; golden age at the end of the nineteenth century), the floodplain sediments that accumulated since the construction of the Neue Inde are enriched in heavy metals. The structures and sediments of the relocation are recycled repeatedly, causing the mixing of contaminated and uncontaminated sediments. The Neue Inde is an important sediment trap, especially due to the river's intense regulation immediately upstream. Thereby, the input of sediments enriched in heavy metals into the receiving waters, the Rur River, is limited. So far, it is unclear whether there is a threshold of sediment storage that, if exceeded, turns the Neue Inde from a sink to a source. The morphodynamical development of artificially built river reaches mainly depends on the restoration design in terms of initially built morphological structures and the width of the river corridor.

**Keywords** River relocation · River morphodynamics · Flood events · Sediment trap · Heavy metal source/pollution

## Abbreviations

| | |
|---|---|
| XRF | X-ray fluorescence |
| Rkm | River kilometer counted from the mouth (rkm 0) to source |
| SSC | Suspended sediment concentration |
| LMI | Lateral mobility index |
| CSI | Channel sinuosity index |
| PEC | Potential effect concentration |
| EU-WFD | European union water framework directive |
| Q | Total daily discharge |
| Ys | Total suspended sediment yield |

## 1 Introduction

The enrichment of contaminants in fluvial systems is a big challenge in river management. Worldwide, many river catchments are influenced by the heavy metal emissions of former and ongoing mining and other industrial activities (*Global:* Byrne et al., 2012; Debnath et al., 2021; Macklin et al., 2023; *Europe:* Brännvall et al., 1999; Žák et al., 2009; Resongles et al., 2014a, b; Dhivert et al., 2016; Hahn et al., 2021; *Asia:* Sundaray et al., 2011; Zhang, et al., 2015; Yang rt al. 2018; *America:* Axtmann & Luoma, 1991; Lecce & Pavlowsky, 2014; Tobin et al., 2000; *Australia:* Birch et al., 2000). Even if industrial transformation has caused changes in the composition of industrial sectors, their legacies still affect fluvial systems. Trace elements adsorb to fine sediments, which act as carriers in water courses (Jacoub &

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Westrich, 2007). Especially heavy metals, which are non-degradable and persistent, therefore tend to accumulate in floodplains, which then become long-term sinks until they eventually are eroded during a flood event and turn into pollution sources themselves (Ciszewski, 2001; Clark et al., 2014; Clement et al., 2017; Colica et al., 2019; Foulds et al., 2014; Hudson-Edwards, 2003; Matys Grygar et al., 2016; Resongles et al., 2014a, b; Žák et al., 2009). Marron (1989), for example, found mine tailings eroded by the river to contaminate floodplain sediments of the Belle Fourche River in South Dakota over a large area. Therefore, studies of sediment transport in river catchments, which provide valuable insights into the transport of particle-bound contaminants, are needed (Coulthard & Macklin, 2003; Debnath et al., 2021; Foulds et al., 2014; Le Gall et al., 2018; Szabó et al., 2020; Walling et al., 2003).

In the context of heavy metal enrichment, near-natural and restored river reaches with high morphological diversity provide valuable storage capacities. If floodplains are overflown, and sedimentation occurs, a part of the polluted sediments is trapped. Even comparably small structurally diverse river reaches may retain as much as 30% of a river's sediment (Ahilan et al., 2016). Thereby, they act as sinks for sediment-bound pollutants as the decreasing flow velocity allows for the sediment to settle (Schulz-Zunkel, 2014). Hence, the capacity for holding back pollutants is directly linked to the river's structure (Wohl et al., 2015). Rebuilding near-natural river reaches can improve the water quality of the receiving waters (Ahilan et al., 2016; McMillan et al., 2017). However, this also raises the risk of the restored river reaches becoming pollution hotspots (Brettschneider et al., 2023).

The European Union Water Framework Directive (EU-WFD) requires achieving good ecological potential, good chemical conditions of water courses, species abundance, and biodiversity for all European surface waters until 2027 (WFD, 2000). Despite extensive investment in countless river restoration projects within this framework, this goal is often not fully attained (UBA, 2022), and the stated aims are rarely achieved (see, e.g., Palmer et al., 2010; Nilsson et al., 2015; Johnson et al., 2020). One of the many reasons for failure is the insufficient understanding of the interactions of multiple processes within river catchments (Brierley & Fryirs, 2022; Johnson et al., 2020). Insufficient knowledge and understanding of sediment dynamics in rivers and the lack of methods to estimate sediment dynamics are current crucial limitations to the optimal design of river restorations (Wohl et al., 2015).

The progression of open-pit mines has a severe impact on its surrounding landscape. It may even require the relocation of rivers (Hardie et al., 2000; Flatley et al., 2018; Gerwin et al., 2023).

Anthropogenic alterations to river courses often result in short, steep channels aimed at cost reduction, resulting in excessive erosion, sedimentation, and disrupted sediment balance in both the upper and lower reaches (Brookes, 1985; Flatley et al., 2018). A particularly drastic intervention becomes necessary when river sections have to be completely relocated due to the progression of open-pit mines (Hardie et al., 2000; Flatley et al., 2018; Gerwin et al., 2023). This kind of river sections close to open-pit mines requires high flood protection, often realized by high discharge capacity provided by morphologically inactive river reaches to channel floodwaters (Lehmkuhl & Stauch, 2023; McCullough, 2015; Mutz, 1998; Pacina & Popelka, 2014; Vujić et al., 2020). However, an alternative concept for river relocations can be the construction of a more natural river course and the creation of a more ecologically attractive floodplain that co-acts as a retention area for flood waters. For previously straightened and enclosed rivers, relocation can, therefore, also mean renaturation.

The study of Maaß et al. (2018) concludes that the Neue Inde has successfully evolved according to its pre-defined guiding principle, achieving the status of a natural river with the potential to establish a dynamic morphological equilibrium. In this study, the relocation of the Inde River (hereinafter referred to as Neue Inde) in the Rhenish lignite mining area acts as a case study for a large-scale artificial river reach that aims to meet the requirements of the EU-WFD.

### 1.1 Aim of this study

Due to past mining and industrial activities, the floodplains of the Inde River are known for their elevated levels of heavy metals (Esser et al., 2020; Gottschalk et al., 2011; Maaß et al., 2018). However, the role of the Neue Inde (translating to New Inde) in the sediment cascade into the Rur River is currently unclear. Therefore, this study investigates whether restoration (as seen at the Neue Inde) affects the trapping of potential risk elements (specifically heavy metals) and the transfer toward downstream reaches (in our case the Rur River).

Trace-element analyses are performed to investigate sediment-bound heavy metal transport dynamics. As the material used for building the river bed and corridor is made from excavation material from the lignite mine, which is not enriched with heavy metals, a clear differentiation from recent flood sediments transported into the Neue Inde area from upstream is possible (c.f. Schulte et al., 2022). The analysis of floodplain deposits is complemented by channel bed and suspended load sediments.

Furthermore, different geomorphological indicators based on orthophoto analysis are tested for their suitability to assess the lateral and structural development of the river.

## 2 Regional setting

The Inde River, located in western Germany, is a gravel-rich lowland river (Fig. 1). The Inde River flows 54 km until joining the Rur River near the city of Jülich with a catchment area of 344 km$^2$. In the upper reaches, sedimentary rocks are predominant. However, the Inde River is incised here into Pleistocene sediments such as loess and periglacial cover beds (debris in clayey, silty matrix) that thinly cover the area. The middle reaches are characterized by Carboniferous claystone and siltstone, while the lower reaches are located in the Lower Rhine Embayment with Cenozoic loess and sand (Fig. 1B; Ribbert, 1992; Schmidt-Wygasch, 2011).

The Inde River has a pluvio-nival discharge regime with high flows in winter and low flows in summer (Fig. 1 C). However, flood events regularly occur in summer due to heavy rainfall. Winter floods are also likely when rainfall and snowmelting co-occur. The highest discharge documented occurred in July 2021 (an equivalent maximum flood wave discharge of 270 m$^3$/s was estimated for July 15th; Weber et al., 2023), when an extreme flood event due to continuous rainfall combined with heavy rain led to a flood crisis in the whole region with discharges in many locations exceeding estimated 100-yr recurrence peak discharge (Lehmkuhl et al., 2022; Weber et al., 2023).

The Inde River catchment has a long history of anthropogenic exploitation. The occurrence of Fe-, Pb-, and Zn-ore and coal deposits in the middle and upper reaches
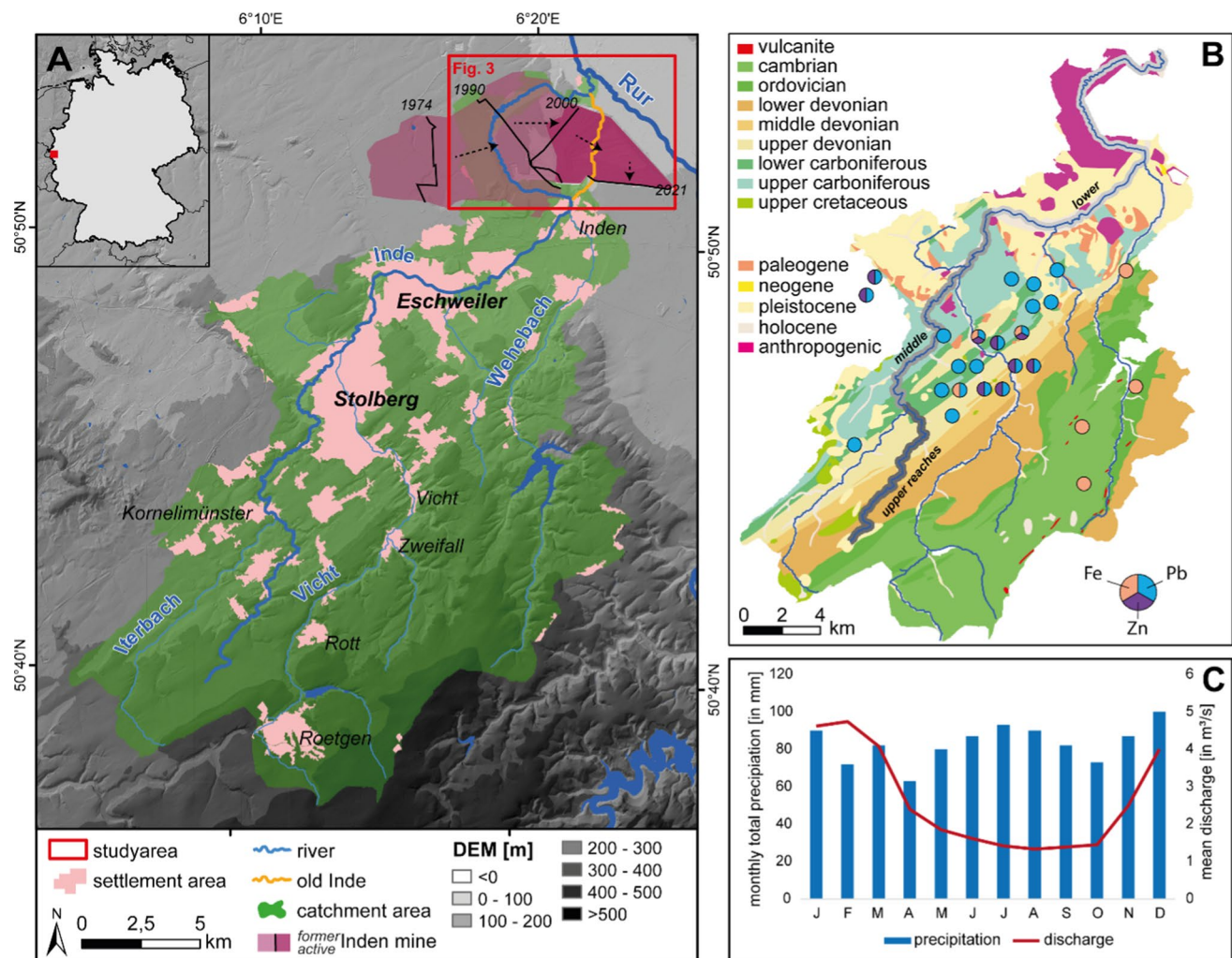


**Fig. 1 A** Overview of the study area and location of the Inde River in Germany (LANUV NRW, 2022a, 2022b, 2022cA). **B** Geology in the Inde catchment (BGR 2022), **C**: monthly mean discharge at the Gauge station Eschweiler from 1991 to 2020 (LANUV NRW, 2022a, 2022b, 2022cB) and monthly total precipitation in the upper catchment (LANUV NRW, 2022a, 2022b, 2022cC)

of the Inde catchment (Fig. 1B) led to the establishment of mining and related industries, mainly in Eschweiler and Stolberg, already since the iron age with its golden age at the end of the nineteenth century (Hiersekorn, 1989; Holtz, 2020; Schneider, 1982; Sindern et al., 2016). Industrialization led to a widespread enrichment of heavy metals in the Inde catchment (Esser et al., 2020; Schneider, 1982), especially along the rivers, as waterpower was one of the drivers of industrial growth (Esser, 2020; Hiersekorn, 1989). The river's planform morphology was further reshaped in the twentieth century when the middle and lower reaches were widely regulated (Paul, 1994). Today, the Inde River is characterized by various hydraulic constructions like bed drops, bed slides, and bottom ramps (Maaß et al., 2018). Therefore, the naturally dominating process of bedload transport is hindered, and the sediment transport is dominated by suspension load. In recent decades, large-scale open-pit mining of lignite has dramatically affected the lower catchment and required the diversion of the lower Inde River into a new artificial reach (Oster, 2003). A 5 km-long section of the Inde River was cut off, and the

river was redirected into a new river channel of 12 km in length, the Neue Inde (translating to New Inde). The Neue Inde was built in a recultivated area, which used to be part of the open-pit mining (Fig. 1). The land recultivation plans aimed at restoring the natural characteristics of the area as much as possible (Kulik & Hennemann, 2012). Thereby, the relocation also acts as a form of river restoration where the ecological and morphodynamic states of the river are intended to improve compared to the formerly degraded channel.

The substrate of the Neue Inde consists of an artificial ocher-colored mixture of local loess, gravel, and sand of the Pleistocene terraces, applied by the mining company, called "Forstkies" (Schumacher et al., 2014), which translates to "forest gravel" (Fig. 2b, c) (Schulte et al., 2022). To promote morphodynamic development, the relocated channel was additionally equipped with gravel with a grain size corresponding to its stream type. The flood protection measures in the transition area from the old Inde to the Neue Inde are designed to cover an HQ100 event (+1 m freeboard) (personal communication by the local water authority); the 2021



**Fig. 2** Impressions from the Neue Inde: (**a**) The Neue Inde and the open-pit lignite mine, (**b**) "Forstkies" structures caused by stacker (a large machine handling bulk material to piles related to open-pit mines), because leveling was not conducted to prevent soil compac-tion, (**c**) "Forstkies" profile, (**d**) river, (**e**) erosion on a cut bank, (**f**) bank erosion, (**g**) natural grading on a slip-off slope, (**h**) in-channel morphological structures and cut bank erosion, and (**i**) island formed between 2010 and 2013

flood event exceeded this magnitude, causing the Inde River overflowing a levee right at the beginning of the relocated reach and flowing into the open-pit mine (Lehmkuhl et al., 2022). Due to the catchment's history, the sediment deposition on the floodplains of the Neue Inde is inevitably linked to an input of heavy metals into the newly formed system (Maaß et al., 2018).

## 3 Materials and methods

### 3.1 Analysis of orthophotos to assess fluvial morphodynamics

The course of the relocated river reach was digitized based on orthophotos taken in 2007 and 2016 with a spatial resolution of 30 and 10 cm, respectively. To evaluate the morphodynamic activity, two approaches were applied:

(1) The lateral mobility (LM) of the river channel was evaluated using the lateral mobility index (LMI) after Richard et al. (2005)

$$LMI_{Channel,Time1-2} = \frac{Area\,of\,Abandoned\,Channel_{Time1} + Area\,of\,New\,Channel_{Time2}}{Area\,of\,Channel_{Time1}}. \tag{1}$$

Values close to 1 describe more pronounced lateral shifts in the channel bed (Esfandiary & Rahimi, 2019; Richard et al., 2005). In contrast, an LMI < < 1 indicates a somewhat stable riverbed.

(2) The channel sinuosity index (CSI; Fernandes et al., 2020) defined as the ratio of channel length to air length was determined for the Neue Inde. For this purpose, the Neue Inde was divided into five sections with diverse initial (i.e., in 2007) morphological structure. The CSI was compared between 2007 and 2016 to identify differences in morphological development between the five sections.

### 3.2 Sediment sampling

The locations of different sampling sites are shown in Fig. 3. River kilometers (rkm) are counted from the mouth (rkm 0) to the source (rkm 54.1). Five different types of sediments were investigated.

From the riverbed, *surface samples* of the first centimeters and *composite samples* of the uppermost 20 cm were collected during conditions characterized by low water
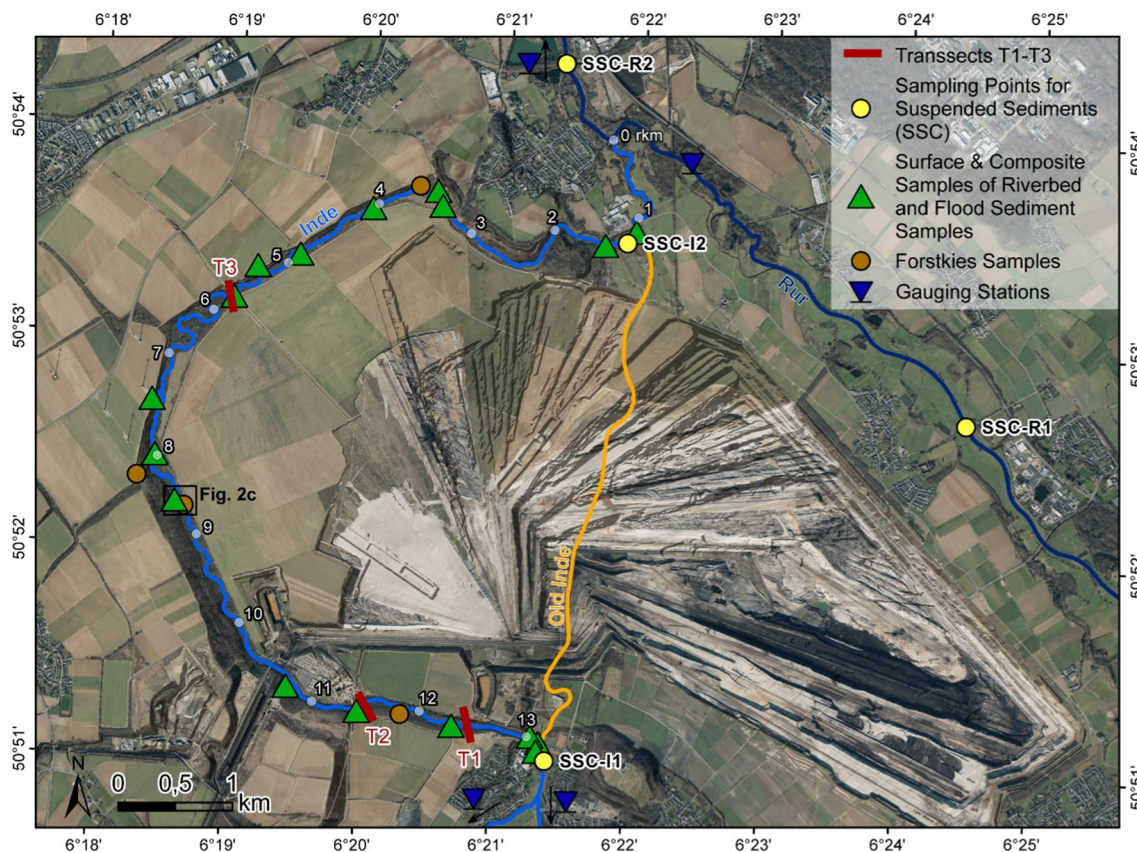


**Fig. 3** Location of sampling sites sorted by sampling methods. Source of the orthophoto: Bezirksregierung Köln (2021)

discharge. From the floodplains, freshly deposited overbank sediments were taken after flood events (here referred to as *flood sediments*). The number of samples taken in these three categories is listed in Table 1. During three flood events (event A: 9th of December 2018; event B: 24th of December 2018; event C: 29 th of January 2021), the *suspended sediment load* was sampled at the in Fig. 3 marked locations (yellow dots). Furthermore, eight *vertical soil profiles* were investigated along three transects (red bars). The results of the individual sample series are summarized in Fig. 6.

### 3.3 Laboratory analysis

Suspended sediment samples were placed in cans and left to settle. After 1 week, the water was pumped off using a water jet pump. The remaining material was air-dried. Samples of all sediment types were sieved to $< 63$ µm and dried at 105° C for 12 h. Then, 8 g of the sieved sample was mixed and homogenized with 2 g of wax (Fluxana Cereox) and pressed into a pellet with a pressure of 19.2 MPa for 120 s. Element concentrations of the sample pellets were measured using an energy-dispersive polarized Spectro Xepos X-ray fluorescence (XRF) device. Each pellet was analyzed twice, and mean values were calculated. Further information on detection limits and the accuracy of measurements are provided in SPECTRO (2007). For investigating heavy metal dynamics in the Neue Inde, we focused on Cu, Pb, and Zn, as they are among the key anthropogenically enriched metals (Hurley et al., 2017) and are particularly relevant in the Inde catchment due to the mining activities and brass industry (Esser et al., 2020). To evaluate the impact on organisms, the threshold values of the potential effect concentration (PEC) after MacDonald et al. (2000) were used for Cu, Zn, and Pb. Exceedance of PECs in the samples indicates toxic effects on sediment-dwelling organisms (MacDonald et al., 2000).

To evaluate a potential vertical relocation of heavy metals in the depth profiles, pH values were measured with the "Labor-pH-Meter 766 "(Company Knick). For this analysis, 10 g of sediment from each sample was mixed with 25 ml of CaCl$_2$-solution.

Particle size was measured with a Laser Diffraction Particle Size Analyzer (Beckman Coulter LS 13 320). For it,

all samples were dried at 35 °C, homogenized, and sieved ($> 2$ mm). Treatment with 0.70 ml 30% $H_2O_2$ at 70 °C for several hours was conducted to remove organic matter. To keep particles in dispersion, treatment with 1.25 ml $Na_4P_2O_7$ for 12 h on an overhead shaker was necessary (DIN ISO 11277, 2002; Pye & Blott, 2004). The Laser Diffraction Particle Size Analyzer calculates the size frequency (percentage) of 116 classes. With an error of 2%, the detectable sizes range between 0.04 and 2000 µm. To increase accuracy, the samples were measured four times in two different aliquots (Schulte et al., 2016).

Color measurements of the samples were measured using a spectrophotometer (Konica Minolta CM-5). The device detects the reflection of the samples in the visible spectral range (360–740 nm). The reflected wavelengths are measured, allocated to color characteristics, and exported as color codes of different systems (Eckmeier & Gerlach, 2012).

The sediment load of the water samples was determined by vacuum filtration over a glass fiber filter with a retention of 0.6 µm using a pump. The filter was weighed before the filtration and subsequently after being dried at 100° C for 24 h. The suspended sediment concentration (SSC) was calculated by dividing the sediment weight by the water sample volume. The average was calculated from the two samples taken at each sampling event. Based on the SSC and the corresponding total daily discharge (Q), the total suspended sediment yield (Ys) is calculated.

## 4 Results

### 4.1 Morphodynamic development based on remote-sensing data

In this chapter, a comprehensive investigation of morphodynamic development is conducted based on remote-sensing data. The results of two different approaches are compared. The results of the LMI analysis are displayed in detail in Fig. 4.

The results of the river length and CSI analysis for the five sections of the Neue Inde are shown in Fig. 5. In Sects. 1

**Table 1** Number of Surface & Composite Samples of the Riverbed and Flood Sediment Samples (green triangels in Fig. 3) along the Neue Inde. The Surface & Composite Samples of the Riverbed were collected during a field campaign in 08/2017 characterized by low water discharge. Flood Sediment Samples were taken after flood events in 03/2018, 06/2018, 01/2019, and 03/2019
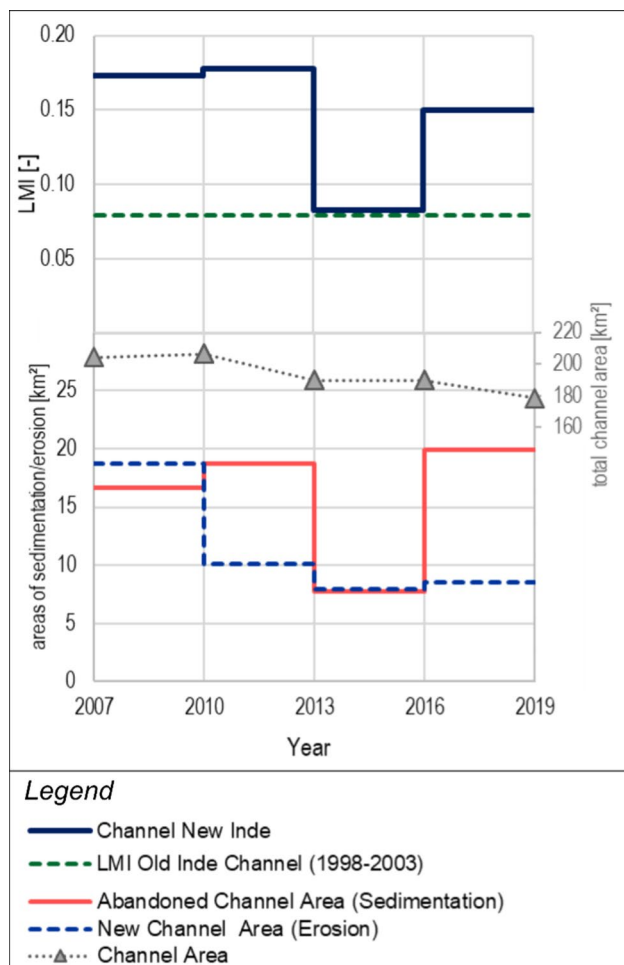
|  |  | Sampling site (rkm) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | 1.15 | 1.40 | 3.40 | 3.50 | 4.10 | 4.85 | 5.30 | 5.68 | 7.50 | 8.10 | 8.40 | 10.81 | 11.35 | 12.40 | 13 |
| Sampling method | Surface samples riverbed | 1 |  | 1 | 1 |  |  | 1 |  | 1 |  | 1 |  | 1 |  |  |
|  | Composite samples riverbed | 1 |  | 1 | 1 |  | 1 |  | 1 |  |  |  | 1 |  | 1 | 1 |
|  | Flood sediment samples |  | 4 | 4 |  | 1 | 3 | 1 | 4 | 3 | 4 | 4 | 1 | 4 | 4 | 5 |

**Fig. 4** Lateral mobility of the Neue Inde channel (dark blue) over time in comparison to the lateral mobility of the old channel (green). Additionally, the components of the Lateral Mobility Index (LMI) of the Neue Inde are displayed

and 5, only slight changes in total length occurred. The same applies to the CSI (Channel Sinuosity Index), which has a constant low value of 1.03. Similarly, small changes have occurred in Sect. 3. However, there is a notable shift in the river bed at rkm 7.4, which has a strong effect on both parameters, section length and sinuosity (Fig. 5 Sect. 3). Sections 2 and 4 exhibit the most remarkable changes in length. This lenghtening is accompanied by an increase in CSI from 1.20 to 1.25 and from 1.54 to 1.59, respectively. Both sections already had the highest sinuosity values in the base year of 2007.

## 4.2 Sediment analyses in the Neue Inde

### 4.2.1 Geochemical longitudinal profile

To characterize the longitudinal profile of heavy metal concentrations in the Neue Inde, Cu, Zn, and Pb

concentrations of different sediment sample types are shown in Fig. 3.

Along the Neue Inde, the contents of the considered elements decrease discontinuously (Fig. 6). The comparison of the different sediment sample types generally indicates the highest heavy metal concentrations in flood sediments and suspended load sediments. Lower values characterize both riverbed sediment types. The suspended sediment samples from events A (9th of December 2018) and B (24th of December 2018) taken at rkm 13.3 show heavy metal concentrations comparable to the maxima of the sampled flood sediments at rkm 13. The suspended sediment samples from Events A and B taken at rkm 1.4 exceed the measured heavy metal concentrations of the other samples in this river section.

Only four composite river bed samples (rkm 12.4, 5.6, 3.5, and 3.4) show Cu, Zn, and Pb concentrations that are comparably low to the background concentrations of the "Forstkies" samples. All other samples exceed background concentrations. Almost all samples exceed the PEC threshold value in the case of Zn concentration; for Cu and Pb, the PEC values are exceeded by considerably fewer samples (Fig. 6).

### 4.2.2 Depth profiles in transects of floodplains

The Zn concentrations in the vertical floodplain soil profiles and surface sediment are shown in Fig. 7. The corresponding results for Cu and Pb are presented in Figs. A.1 and A.2 in the supplementary material.

Profiles 7, 13, 14, and 18 show similar variability with depth in terms of heavy metal concentrations, soil color characteristics, and median grain size. Zn, Cu, and Pb concentrations decrease with depth, while the median grain size increases. The color changes from dark brown to ochre (see Fig. 7, Figs. A.1, and A.2). Thus, all three parameters approximate the values of the landscape construction material ("Forstkies").

The characteristics of profiles 3, 5, 9, and 20 differ from the aforementioned profiles. Profile 3 is probably disturbed by animal burrows observed here. Although the samples were taken at a distance above the animal tunnel system, an influence of bioturbation is likely. Profile 5 is located on an island within the river channel. The values of the heavy metals Zn, Cu, and Pb are clearly above the "Forstkies" background values in the entire profile. Profile 9 was created on a small hill of "Forstkies" (Fig. 2c)). In this profile, the heavy metal concentrations in all samples are as low as the background values of the "Forstkies" (Fig. 7). In profile 20, the background values of the "Forstkies" for Cu, Zn, and Pb are found at a depth of 30 cm. However, these changes are not accompanied by a significant increase in grain size. At
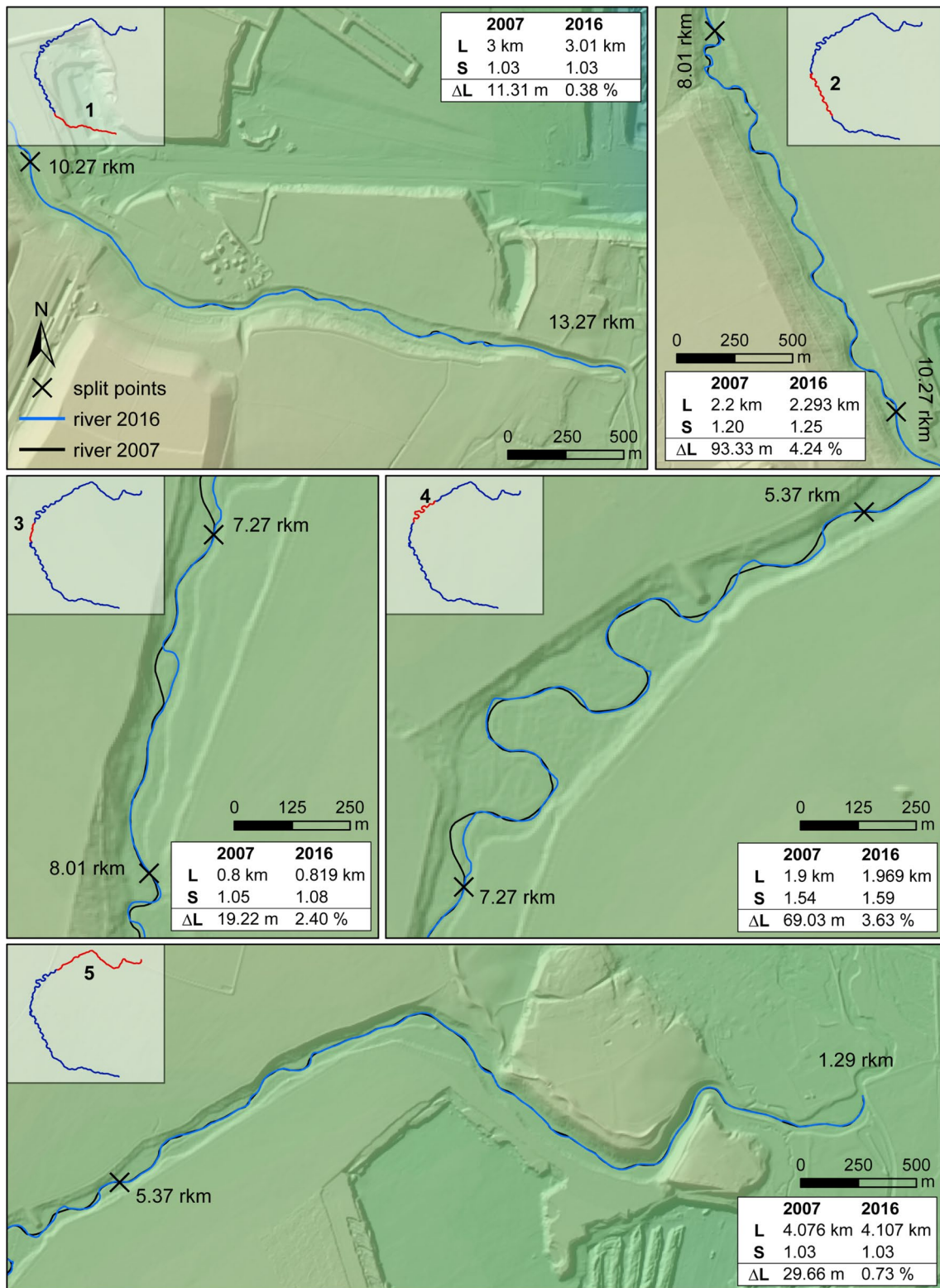
**Fig. 5** Comparison of the river course from 2007 to 2016. Preceded by the partitioning of the river course into 5 sections based on morphodynamic changes expressed by the change in river length and sinuosity. Sections 2, 3, and 4 exhibit marked deviations of the river course for the compared timesteps
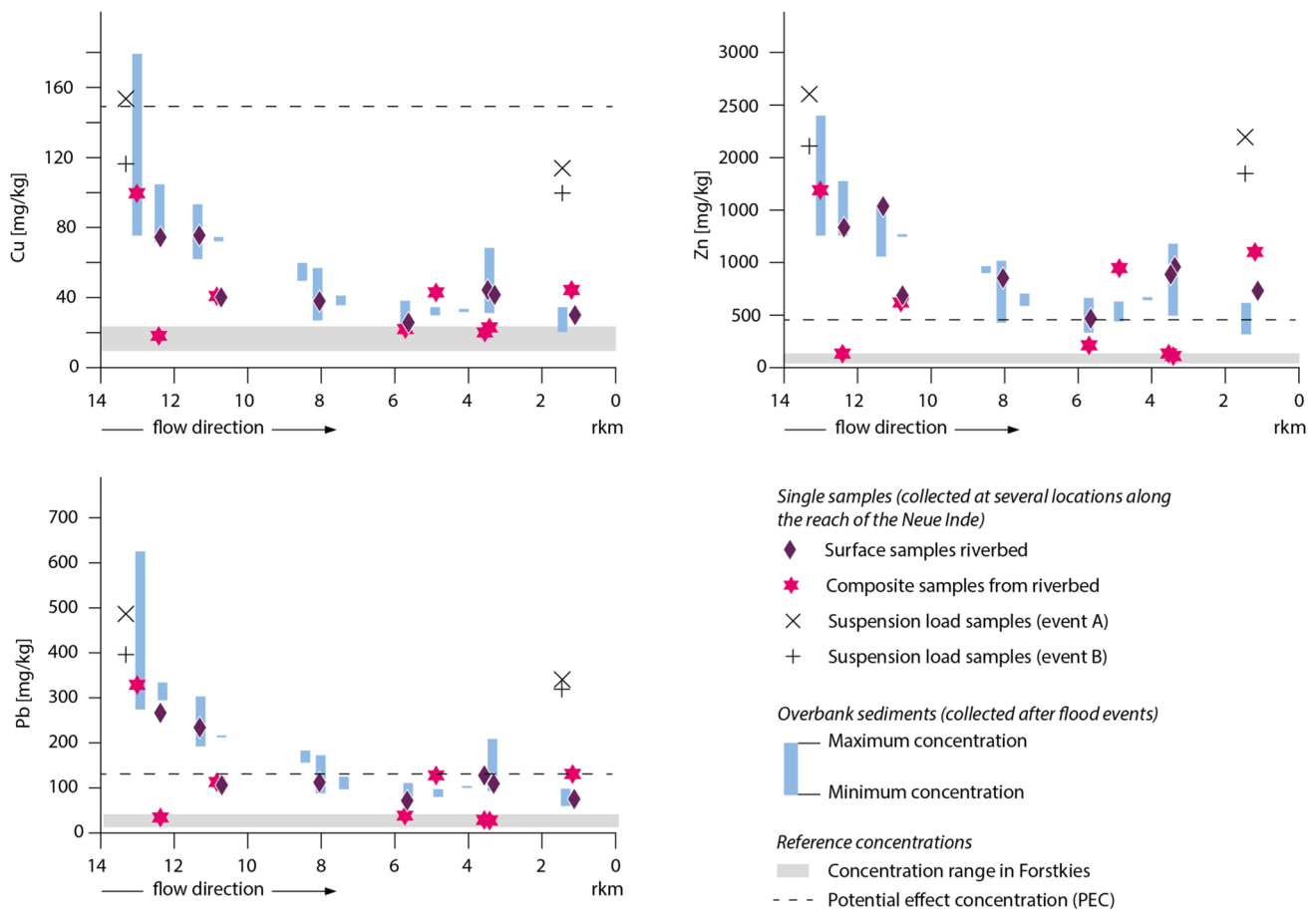
**Fig. 6** Longitudinal profile of heavy metal concentrations in the Neue Inde conducted with different sediment sample types. The values of flood sediments represent the maximum and the minimum of each sampling site calculated from four flood events. Event A was sampled on the 9th of December 2018 during bankfull discharge; Event B occurred on the 24th of December 2018, where flooding took place in the Neue Inde. PEC is the potential effect concentration after MacDonald et al. (2000)

the profile 20 site, the original "Forstkies" was not reached before the trench was filled with groundwater.

### 4.3 Floodplain surface sediments

Surface samples 1, 2, 4, 6, 8, and 10 along transect 1, as well as samples 11, 12, and 15 along transect 2, and samples 17 and 21 along transect 3 show enrichment of heavy metals, resulting in higher concentrations than the Forstkies background (Fig. 7). The heavy metal concentrations of sample 16 (transect 2) and sample 22 (transect 3) are as low as the "Forstkies" background. Sample 19 (transect 3) is also characterized by background values, despite its location near the river (Fig. 7).

### 4.4 Transport of suspended sediment

The suspended sediment samples from the Neue Inde River (SSC-I1 and -I2) collected during the two flood events (A, B) show discharge-dependent differences and

a reduction in Ys caused by the Neue Inde (Fig. 9). Event A, characterized as bankfull discharge, and Event B, in which floodplains were flooded, also differ in terms of SSC, with significantly higher concentrations during Event B. However, for both events, SSC decreases between sampling points SSC-I1 and SSC-I2. In addition to SSC and Q, Fig. 9 shows the daily suspended sediment yields indicating a net mass loss of 14,000 kg/d and 55,000 kg/d between SSC-I1 and SSC-I2 for Events A and B, respectively. These values of the net mass loss represent the sum of deposited and resuspended sediments within the section of the Neue Inde. If these values are combined with the metal concentrations for the sampling points SSC-I1 and SSC-I2 shown in Fig. 3, an estimate of 17,700 to 20,900 kg and 112,300 to 194,100 kg of sediment deposited in the area of the Neue Inde is obtained. The basic assumption is that deposited material has the concentration measured at SSC-I1 and eroded material has the corresponding concentration of Forstkies. The range of the estimated accumulation values results from
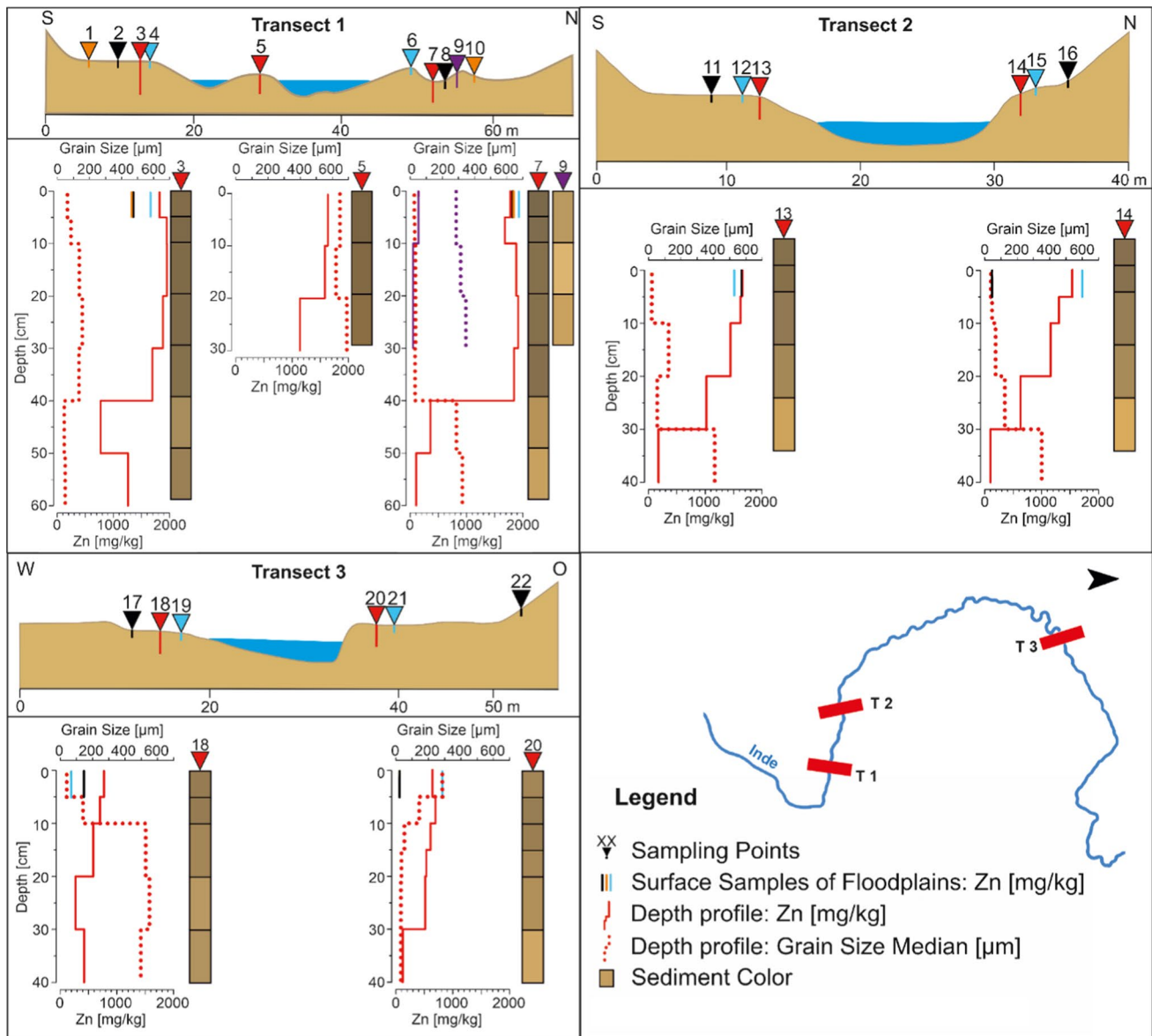
**Fig. 7** Results of XRF analyses for Zn as well as grain size and color analyses of depth profiles and surface samples of the three transects. Transects 1, 2, and 3 are located at rkm 12.4, 11.35, and 5.6, respectively. Sampling points in red and purple are trenches with depths of 30–60 cm. Sampling points in turquoise, black, and orange are surface samples of the upper 5 cm. The colors of the sampling points coincide with the graphs shown below the transects

the approximation of a sediment budget for each measured metal (Cu, Pb and Zn).

Assuming an even deposition over the floodplains, these accumulation values would equal an aggradation of 0.07 mm and 0.65 mm in the maximum for Event A and B, respectively.

The SSC values, measured at the sampling points at the Rur River, show a significant increase downstream of

the confluence point with the Neue Inde. Combining this with the observed discharge, the Neue Inde contributes almost half of the total suspended sediment yield to the Rur River during Event C.

# 5 Discussion

## 5.1 Morphodynamic development of the Neue Inde

The Neue Inde was provided with a sufficiently wide corridor to allow lateral changes in the river course, enabling the development of a near-natural state (Maaß et al., 2018).

The LMI of approximately 0.15 (Fig. 4) indicates low rates of bank erosion and only slight lateral shifts, which is common for gravel-dominated lowland rivers, such as the Inde River (UBA, 2014). The Neue Inde is characterized by several islands that were mostly part of the initially built artificial river structure, resulting in a bisection of the river into two distinct channels. Whenever one of those pre-defined river channels is abandoned, the LMI peaks. However, it would be erroneous to link this to the lateral activity of the river. Therefore, the LMI needs to be evaluated cautiously.

While the LMI summarizes the lateral mobility of the entire Neue Inde (under the restriction of previously described error), the CSI identifies individual sections where increased lateral erosion and channel modifications have occurred. The sections that are morphologically active based on the CSI coincide with the reaches that were initially built with a higher degree of sinuosity. This shows that building structurally diverse rivers speeds up their morphological activity.

## 5.2 Heavy metal enrichment in the Neue Inde

The level of sediment reworking and the effectiveness of fluvial morphological processes are confirmed by sediment analysis, as chemical tracers with a limited area of emission can be used as tracers for sediment transport (Esser et al., 2020). In the Inde catchment, the former industrial area of Stolberg, with widespread enrichment of Pb, Zn, and Cu, is a source of identifiable sediments (Dongmann et al., 1987; Paul, 1994; Ewers et al., 1996; LABO, 2017; Esser et al., 2020; Weber et al., 2023). The heavy metal enrichment within the Neue Inde proves the recent accumulation of fluvial sediments and the formation of longitudinal bars through fluvial morphodynamic processes.

The general morphological structure of the Inde River supports the input of heavy metal-enriched sediments into the Neue Inde: To achieve a high level of flood protection, the Inde River upstream from the Neue Inde is straightened, and the banks are fixed, resulting in higher flow velocities. This immediately changes when the Inde River enters the Neue Inde, where the floodplain widens, and the river course starts meandering. This widening causes a significant decrease in flow velocity, resulting in a reduced transport capacity and accumulation of sediments. One aim of the Neue Inde project design was to ensure frequent flooding of the constructed floodplains (Schumacher et al., 2014). The strong enrichment of heavy metals in the floodplains of the Neue Inde and the aggradation of all sampled areas of the river corridor, except samples 16 and 22 (see Fig. 7), show that this aim was achieved. The "artificial" floodplains are connected to the river catchment and fulfill their natural retention function (similar observations were made by Hupp et al., 2008; Noe & Hupp, 2009; Hoffmann et al., 2010).

The spatial variability of heavy metal concentrations in the floodplain is caused by mixing sediment from different sources (i.e., the upper catchment and the Neue Inde itself), local fluvial morphodynamics, and individual flood characteristics. Similar results from other case studies are provided by Ten Brinke et al. (1998), Heaven (2000), Notebaert et al. (2011), Foulds et al. (2014), and Buchty-Lemke (2018). For the Neue Inde, mixing with "Forstkies" sediments is the main driver of variability: In transect 1, evenly distributed high heavy metal concentrations, color, and grain size characteristics indicate the exclusive accumulation of flood sediments originating upstream from the Neue Inde (Fig. 7). For example, profile 5, situated on an island in the river channel, shows strongly elevated heavy metal values (relative to the Forstkies) throughout the whole profile, suggesting a recent formation of the island. In contrast, transect 2 shows a stepwise bottom-up increase in Cu, Zn, and Pb concentrations (Fig. 7, Fig. A.1, and A.2), which indicates that over the years, the accumulated sediment gradually changed from sediments mobilized from surrounding hillsides and the artificial floodplain itself to material dominated by sediment originating upstream from the Neue Inde. Transect 3 indicates synsedimentary input of both materials eroded within the Neue Inde area and flood sediments from the upstream areas of the Inde. This observation corresponds well with the situation at transect 3 immediately downstream of the most morphodynamic active river section (Fig. 7), where Forstkies material is continuously eroded at the cutbanks. In all profiles, the pH values range between 6.1 and 7.6, which indicates that post-depositional vertical dislocation of heavy metals is unlikely.

This mixing of heavy metal-enriched sediments with Forstkies is consistent with the estimated sediment budget based on the measured SSC, Ys, Q (Fig. 8), and the corresponding heavy metal concentration (Fig. 6), which decreases within the Neue Inde. Based on the assumptions made (Chapter 4.3.), the calculated deposited sediment volumes represent the maximum possible accumulation and the highest retention of contaminated sediments. However, the estimated sediment budgets (as deduced from the concentrations of Pb, Zn, and Cu) indicate that suspended material at the end of the Neue Inde is a mixture of Forstkies and resuspended floodplain sediments with higher enrichment
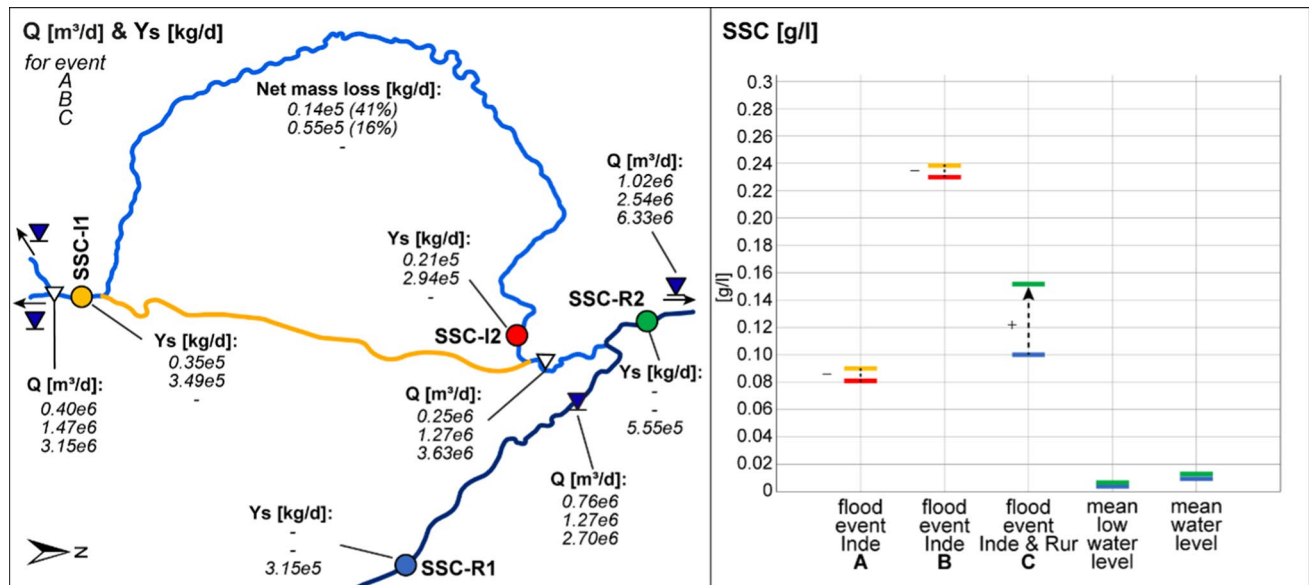
**Fig. 8** Right panel: Measured suspended sediment concentration in the Neue Inde (SSC-I1 and SSC_I2) and in the Rur River (SSC-R1 and SSC-R2). While sampling sites SSC-I1 and SSC-I2 measure the effect of the Neue Inde itself, sampling sites SSC-R1 and SSC-R2 represent the differences in the Rur River upstream and downstream of the confluence with the Neue Inde. Left Panel: Q: observed (blue-colored gauging stations) and estimated (white colored triangles) total daily discharge. Ys: estimated total suspended sediment yield based on the measured SSC and the corresponding Q. The net mass loss (sum of deposition and resuspension) calculated as difference between the Ys values for SSC-I1 and SSC-I2 in kg per day as well as relative share to the Ys at SSC-I1

in heavy metals. Predictions on future trends of this effect need long-term monitoring.

This trend is of serious concern, because at the beginning of the Neue Inde, especially for Zn and Pb, PEC threshold values are already exceeded, which means that sediments might be toxic to sediment-dwelling organisms (MacDonald et al., 2000). The trend of a decreasing number of samples exceeding the PEC is observed only for Pb. Zn surpasses the PEC in almost all sampling points. For Cu, the heavy metal concentration is at no critical state yet (Fig. 6). The mining and processing history of Zn and Pb in the Inde catchment is reflected in the considerably higher concentrations compared to Cu. The copper concentrations are lower, because copper had to be imported for the brass industry in Stolberg (Schneider, 1982).

This sediment transport and its negative consequences for the Neue Inde, e.g., clogging of the riverbed, are discussed and explained by high riverbed degradation by Maaß et al. (2018). It was concluded that the input of heavy-metal-enriched suspended sediment into the Rur River will decrease over time (Maaß et al., 2018). The retention can be confirmed for low and mean water levels when the Neue Inde buffers suspended sediment almost entirely. However, during flooding, we found higher suspended sediment loads at the Rur River downstream of the confluence point with the Inde River (Fig. 8). Therefore, during flood events, the Neue Inde might become a source itself due to more intense erosion of its contaminated banks. Alternatively, there is a certain discharge threshold above which the filtering of fine sediments becomes relatively less efficient. The second theory is supported by the comparison of SSC-I1 with SSC-R1 and SSC-R2, which shows that the upper Inde River itself delivers high sediment loads (Fig. 8).

The influence of the Inde River inevitably also includes the transport of heavy metals into the Rur River. Along the Neue Inde, the heavy metal concentrations in the suspension load decrease (SSC-I1, SSC-I2), which indicates a dilution effect by uncontaminated Forstkies material (Fig. 8). However, the metal concentrations in these SSC samples still exceed the PEC limits and thus represent a potential risk for the ecosystems of the Inde River and the receiving Rur River.

### 5.3 Near-natural river structures acting as sinks or sources for heavy metal-enriched sediment

The intention to restore fluvial morphodynamics and to achieve the EU-WFD's objective of good ecological status and good chemical conditions of watercourses results in a conflict with anthropogenic contamination. The fluvial transport over long distances and the persistence of heavy metals in floodplains can make the construction of new river development corridors in such secondarily contaminated floodplains hazardous.

This study proves that after only 16 years, the Neue Inde is already strongly enriched by heavy metals in its riverbed and floodplain sediments. This is the result of (1) erodible remnants of historical industry and mining sites close to the river entering the fluvial system, (2) the fluvial morphodynamics within the Neue Inde, and (3) the sediment connectivity between these two areas caused by the removal of transverse structures (barrier across the width of a river) within the active river bed. To achieve the goals of geomorphological and ecological improvement of a river system, such a catchment-wide sediment connectivity is necessary. However, on the catchment scale, the remediation of all heavy metal-contaminated river sites—both sources and accumulation zones—is impossible. Thus, a thorough pollution risk assessment is particularly important for measures in catchments with mining and industrial legacies (Lair et al., 2009).

Further problems arise if the restoration is built from contaminated sediments: The sediments enriched with potentially toxic trace elements return to the system through newly achieved near-natural morphodynamic processes, which were previously restrained by stream regulations (Howard et al., 2017; Matys Grygar et al., 2022). The exchange of sediment-bound pollutants between the water column and the hyporheic zone, which takes place in near-natural rivers in contrast to regulated rivers, is not considered sufficiently in restoration projects (Wohl et al., 2015).

Potential negative impacts on downstream areas may be reduced by providing retention capacity for pollutants along upstream river reaches. The increasing accumulation of sediment-bound heavy metals in the area of the Neue Inde is associated with a simultaneous decrease of contaminant input into the receiving water Rur (Fig. 8). Yet, in the light of hydrological changes due to climate change, future ecosystem services might change: Floodplains could lose their natural filtering function for pollutants and episodically become a source of pollutants that were originally bound (Schulz-Zunkel, 2014). Due to more dynamics and lateral erosion in the artificial river sections as well as in the upstream and downstream areas, old alluvial deposits, whose heavy metal inventory is completely unknown in most cases, are increasingly remobilized. This may become problematic in the future, particularly in connection with the increasing frequency of heavy runoff events (Blöschl et al., 2019; Milly et al., 2002).

## 6 Conclusions

The Neue Inde is a rare example of a river relocation project that aimed at creating a near-natural river corridor from a geomorphological and ecological point of view. However, in catchments with a long history of mining and industrial activities, the ubiquitous enrichment of sediment-bound heavy metals is inevitable, especially in the floodplains.

We found mining history and related pollution sources, availability of fine sediments, and the status of the morphodynamical system, as influenced by river engineering, and the catchment's geomorphology, to be important parameters to be accounted for when designing river relocations or restorations.

To further evaluate the success of artificial river constructions that are typically only a few km in length, the intensity of erosion processes and changes in channel structures need to be quantified. We tested different approaches, of which only the Channel Sinuosity Index (CSI) provided meaningful results. The Lateral Mobility Index (LMI) is not sufficiently sensitive to detect small-scale changes in only slightly meandering gravel-rich rivers.

The enrichment of heavy metals in-channel structures points to high sediment connectivity to the reaches upstream, and fluvial morphodynamic activity within the New Inde, which causes repeated recycling and mixing of contaminated and uncontaminated sediments.

This shows that artificially built near-natural river sections that increase the structural heterogeneity are prone to become sinks for sediment-bound pollution. While this might seem worrying, it also minimizes the possible negative effects on downstream reaches or receiving water. However, extreme events with high discharge may erode these sediments, and the sinks become new sources, ultimately enhancing the load of contaminants transported by the flood wave.

## Declarations

**Competing interests** The authors declare no competing interests.

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