Short-term geomorphic adjustments of bars in the Elbe, a large regulated river in Czechia

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ABSTRACT

Gravel and sandy bars constitute critical components of river channel morphology, yet their morphodynamics in large, heavily regulated rivers during periods without significant flows remain poorly understood. This study investigates changes in surface heterogeneity and sediment sizes through a two-year field monitoring program, focusing on the frontal, central, and distal sections of four bars along the Elbe River in Czechia. Despite the absence of high-flow events reaching at least a one-year recurrence interval, observable changes in surface heterogeneity and sediment sizes were noted across all bars. However, the changes did not follow a uniform pattern; individual bars and their sections exhibited varying degrees of surface sediment coarsening or fining, alongside increases or decreases in surface heterogeneity. These findings highlight the necessity for site-specific management strategies for individual bars within such human-impacted rivers, recognizing their value as ecological hotspots. Furthermore, the methodology presented in this study may serve as a blueprint for the cost-effective monitoring of bar dynamics in channelized river sections.

KEYWORDS

regulated river; bar; river morphodynamics; the Elbe

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1. Introduction

Channel depositional forms are a key element in the natural evolution of river channels (Bridge 1993; Lewin 1976). These deposits can be represented by gravel or sandy bars formed from fluvial sediments settled either along the banks (such as lateral or point bars) or within the central channel (such as transverse, mid-channel, or diagonal bars). They are shaped through the deposition and reworking of loose sedimentary material transported by the water flow to locations where there is a local decrease in transport capacity. This process is typically associated with the channel geometry, with deposits most often found on the inner banks of bends, in areas of local channel widening, or in zones with flow obstacles that allow for the dispersion of the flow energy (e.g., downstream transversal structures like check dams and weirs or behind stable large wood) (Abbe and Montgomery 1996; Hey et al. 1982; Jaballah et al. 2015; Škarpich et al. 2019). These bars are typically described as “forced” due to their formation process, in contrast to “periodic bars”, which are large sediment deposits formed as a result of morphodynamic instability (Duró et al. 2016).

The ratio of channel width to flow depth is a critical parameter for the formation of the bars (Cordier et al. 2020; Duró et al. 2016; Redolfi et al. 2020). In cases of periodic lateral bars, which can be observed in straight channel reaches, their relative height above the level of common flows is proportional to the depth of the channel (Tubino et al. 1999). In general, the bars are highest in their central sections and the elevation above water surface correlates with flow characteristics related to the river transport capacity, where higher flows usually lead to the formation of relatively lower deposits (Redolfi et al. 2020). The bars also often exhibit specific characteristics in terms of grain size distribution. Typically, bars are made up of finer sediments than those found in the permanently submerged parts of the channel (Smith 1974). It has been frequently observed in natural channels that the surface layer of bars becomes finer in downstream direction, with the coarsest material present in the frontal (i.e., upstream) bar segment and the finest sediments found in the distal (i.e., downstream) segment (Ashworth and Ferguson 1986; Li et al. 2014; Smith 1974). Additionally, there is usually a gradual fining of sediments from the water level to the outer edge of the bar as the depth and flow velocity decrease during bar flooding (Parker and Andrews 1985). Surface layer armoring on bars can also occur, meaning that the sediments beneath this layer contain finer grain-size fractions (Hey et al. 1982; Smith 1974). However, all these morphological or sedimentological trends can be disrupted by the presence of vegetated patches on the bars, which acts as a hydraulic roughness element facilitating the deposition of particularly fine sediments (Corenblit et al. 2015; Edwards et al. 1999). Similarly, bars in human-impacted, channelized channel reaches (Holušová and Galia 2020), or those directly affected by sediment dredging (Zawiejska et al. 2015), can exhibit significant differences in sedimentary structure and morphology.

The formation and morphodynamics of bars depends on the availability of a sufficient quantity of fluvial sediment, whose characteristics (volume, grain-size, and the frequency and intensity of its movement) are influenced not only by natural conditions (e.g., lithology, energy of relief, and hydrological regime) but also by various types of direct and indirect anthropogenic interventions that are quite typical for European cultural landscapes and human-impacted fluvial systems. Examples of such interventions include bank reinforcements that prevent the delivery of sediments to the channel through bank erosion, the construction of longitudinal barriers that slow down or prevent the downstream movement of sediments, or changes in land use, such as afforestation, which stabilizes sediment sources across the entire catchment area (Syvitski et al. 2005). Another important factor is the presence of vegetation in the river channel, which can stabilize the banks or bars through root systems and reduce flow velocity due to increased hydraulic roughness (Corenblit et al. 2015). In this regard, a variable hydrological regime and the regular occurrence of flows capable of transporting sediments, and thus actively reshaping these bars, are crucial for the occurrence and sustainability of bars. Low variability in flows (e.g., due to the presence of valley dams regulating peak discharges or water abstraction), with the absence of transport-efficient flows, can lead to complete colonization of the bars by vegetation and their integration into the floodplain, resulting in a reduction of both the width and flow capacity of the channel (Adami et al. 2016; Crosato and Mosselman 2020).

From the ecological point of view, bars provide an environment essential for certain plant species that require periodic flooding (Gilvear and Willby 2006; Zeng et al. 2015). The presence of bars also influences water temperature variability and nutrient deposition in the streambed (Claret et al. 1997; Ock et al. 2015). However, as suggested, bars are sensitive to human interventions in channels and anthropogenic influence on flows. The recent decades have seen trends of decreased frequency or loss of bars due to channelization leading to increase of river transport capacity, construction of valley reservoirs, and gravel and sand extraction from rivers (Arróspide et al. 2018; Kondolf 1997). In this context, obtaining information on the current morphodynamics of bars in regulated rivers is crucial to direct management efforts towards preserving these valuable components of river channels that are subject to significant anthropogenic pressure and climate change.

Interannual changes in surface sediment sizes and bar morphology in large regulated rivers during periods without high flow events have not been thoroughly investigated. Furthermore, some water authorities debate the stability of these bars, their overgrowth by vegetation, and their formation as obstacles to flow during floods. To assess the current morphodynamics of these bars with potential implications for enhancing current management practices in relation to the sustainability of these habitats, we conducted a two-year (September 2021 – September 2023) geomorphic monitoring of four bars in the Elbe River near the border between Czechia and Germany. We utilized a comprehensive approach, including repeated geodetic measurements, observations of scour chains, and repeated grain-size sampling, to gather field evidence of potential recent activity of geomorphic processes.

2. Materials and Methods

2.1 Study area

The Elbe River, one of Europe's longest rivers, spans 1,094 km and encompasses a catchment area of 148,268 km^2. It originates in the Giant Mountains in Czechia and flows into the North Sea near Hamburg, Germany. Characterized by a pluvio-nival flow regime within a temperate climate, the Elbe experiences its highest discharges during the spring months due to melting snow and rainfall, while the lowest water levels are observed in summer period.

Our study investigates four bars located in the Czech portion of the Elbe River, near the state boundary between Germany and Czechia. These bars approximately extend from 760 to 730 river km, with distances measured upstream from the Elbe outflow into the North Sea (contributing catchment area ca. 48,500–51,000 km^2). This reach traverses terrain uplifted by tectonic activity. During the Neogene and Quaternary periods, significant river erosion occurred, resulting in the formation of a predominantly confined channel, incised 200–300 m into the surrounding terrain and characterized by narrow floodplain strips (Balatka and Kalvoda 1995). From the perspective of the channel's planform shape, the Elbe River in the studied reach is characterized by a single-thread river pattern (sinuosity = 1.21) with the occurrence of lateral bars composed of gravel-sand material. Bars typically form along the inner banks of river bends as relatively narrow, elongated strips of exposed sediment. Their formation is sometimes influenced by the artificial addition of material from channel dredging intended for ship navigation. Additionally, bars infrequently develop at confluence points with streams draining the adjacent hilly terrain. This part of the river, like much of its length, is subject to significant modifications due to ship navigation, including bank stabilization efforts and above mentioned maintenance of the shipping channel through dredging. Outer banks of bends and channel segments within the intravilane are stabilized using riprap. As the result, local channel width varies between 110 and 150 m and flow depth between 2–3 m during base flow conditions. The natural flow regime is affected by large dams in the Vltava River (the main tributary in Czechia) and the presence of weirs with navigation locks. At the same time, the studied reach is under environmental protection as part of a site of European significance. It is adjacent to the České Švýcarsko National Park and the České Středohoří protected area.

The studied bars show some variations in their planform morphology and can be classified as forced bars sensu Duró et al. (2016) due to their location on the inner bank of a distinctly curved river bend (Fig. 1). Hre and Dzb are characterized as relatively long and flat lateral bars (Tab. 1). In contrast, Val shows characteristics of a point bar morphology, attributed to its location in a pronounced river bend and the noticeable difference in elevation between the water surface and the outer edge of the bar. The fourth bar, Tech, is a lateral bar but is considerably shorter than both Hre and Dzb. All bars are recently covered with patchy herbaceous vegetation and their surface and sub-surface layers are composed of gravel-size fractions, with varying amounts of sand and mud. Gravel-size fraction dominates the surface sediments, comprising 71–94% of the mass sample. However, at the distal part of Hre, this proportion decreases to 59% due to its local flat, low surface characterized by an abundant presence of sand and mud (Hradecký et al. 2024).

Our monitoring of bar dynamics and their sediment composition spanned from September 2021 to September 2023. The nearby gauging station in Děčín (located between Tec and Dzb bars at 740.5 river km)

Tab. 1 Positions and morphometric parameters of the studied bars; morphometric parameters are related to a bar surface delineated by base flow (approximately 130–150 m^3/s) and bounded externally by continuous vegetation during the 2023 inventory.

Bar	Geographical position	River (km)	Length (m)	Maximal width (m)	Elevation over water surface (m)
Val	50.6762N, 14.1272E	759	250	20	1.4
Tech	50.6953N, 14.2001E	752	100	10	0.5
Dzb	50.8363N, 14.2261E	733	790	16	0.8
Hre	50.8496N, 14.2172E	731	730	25	1.1

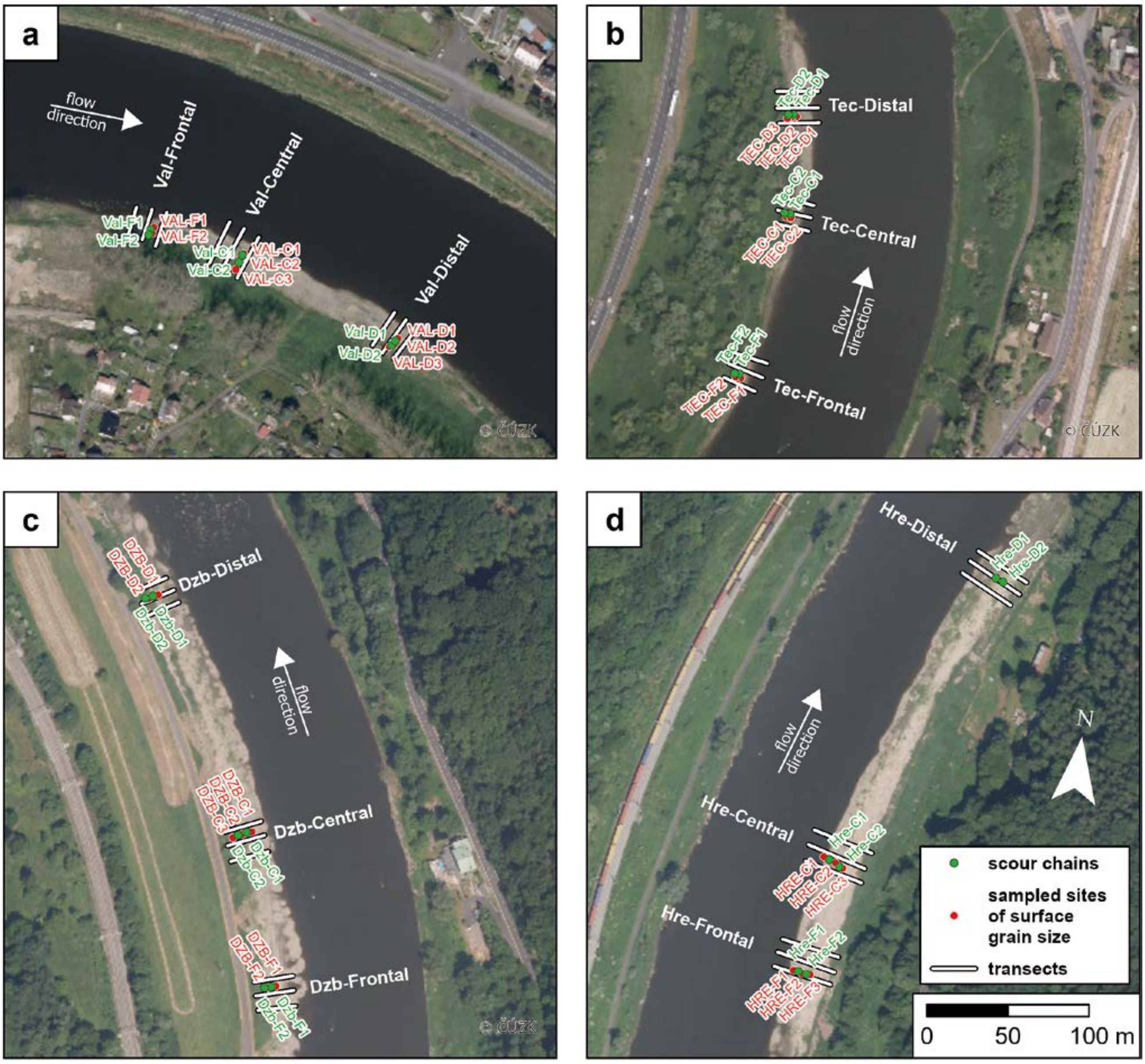

Fig. 1 Studied bars in the Elbe River: a – Val, b – Tec, c – Dzb, d – Hre; data source: Czech Office for Surveying, Mapping and Cadastre. The positions of the monitored cross-sectional transects, scour chains and surface grain-sizes are indicated.

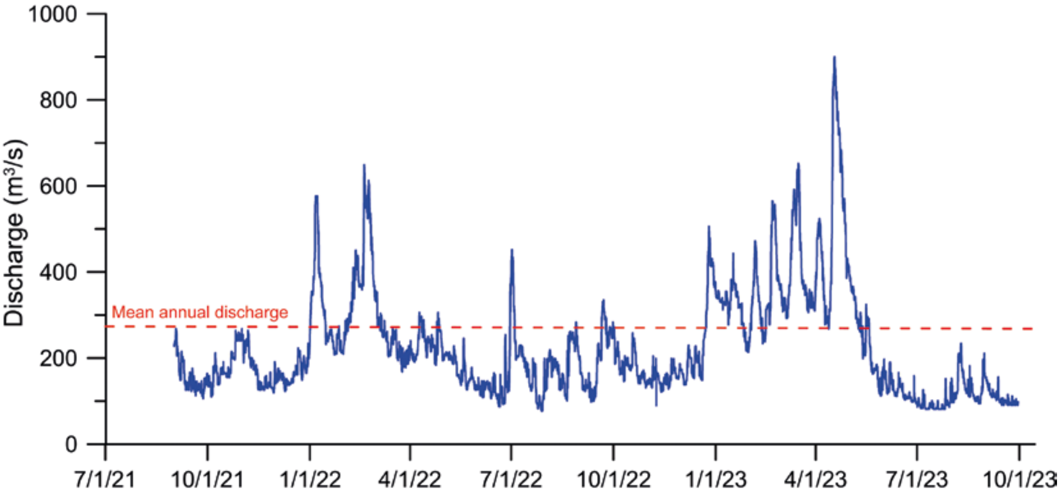

Fig. 2 Hydrograph of hourly discharges from Děčín gauging station for the studied period 9/2021–9/2023 (data source: Czech Hydrometeorological Institute).

Tab. 2 Flow characteristics of Děčín gauging station (data source: Czech Hydrometeorological Institute).

Flow recurrence interval	Discharge
Mean annual discharge	287 m^3/s
1-year	1300 m^3/s
2-year	1720 m^3/s
5-year	2300 m^3/s
20-year	3240 m^3/s
100-year	4290 m^3/s

recorded no significant flood events during this period. The highest discharge recorded was on April 17, 2023, at 900 m^3/s (Fig. 2). This high flow event did not even reach 1-year discharge (Tab. 2), indicating that the bars' morphology and sediment dynamics during the study period were not influenced by extreme flooding events.

2.2 Monitoring of cross-sectional transects

We monitored transects arranged perpendicularly to the flow direction across three sections (frontal, central, and distal) of each studied bar. In each section, we established three parallel transects, spaced 5 meters apart. These transects were geodetically surveyed using a total station, with measurements taken at 1-meter intervals along each transect in September 2021 and again in September 2023. We meticulously recorded the coordinates by GNSS station at both the start and end of each transect. Due to slight fluctuations in water levels between our two measurement periods, which affected the starting points of the transects in relation to the water surface, we standardized the length of the transects for direct comparisons between the years of survey.

Due to little variations in individual measurements of relative elevation at 1-m intervals – attributable to factors such as the presence of coarse material or the resolving power of the total station, which can introduce errors up to several centimeters – it was challenging to precisely compare potential morphological changes along a pair of transects. These changes could be of a similar scale as the potential measurement error. Consequently, we focused our comparisons on the differences in concavity across the frontal, central, and distal sections of the studied bars. The concavity parameter is defined by the elevation difference between two consecutive points along a transect (Laub et al. 2012):

$$Conc = \Sigma(|x_2 - x_1| + |x_3 - x_2| + \ldots + |x_{n-1} - x_n|) \qquad (1)$$

By computing the average concavity *Conc* for each transect (that is, by averaging the relative elevation changes between points x_1, x_2, ... x_n, which are spaced 1 meter apart, from the water surface to the outer edge of the sampled transect), we obtained insights into potential variations in the surface heterogeneity of the bars. Specifically, lower concavity values imply a relatively flat and homogeneous surface between successive points along the transect, whereas higher concavity values point to a more irregular or heterogeneous surface. This implies that we did not assess absolute vertical changes across the transects; instead, we focused on examining the changes in morphological heterogeneity within the transects.

2.3 Monitoring of scour chains

In September 2021, we placed 24 scour chains across the monitored bars to observe the dynamics of the surface sediment layer. For each bar, we positioned two chains in the frontal, central, and distal sections, respectively, near the monitored cross-sectional transects. This setup necessitated excavating around 0.5 meters into the bar's surface, altering its sedimentary structure. The burial depth of the 1-meter-long scour chains was 50 cm, with the remaining

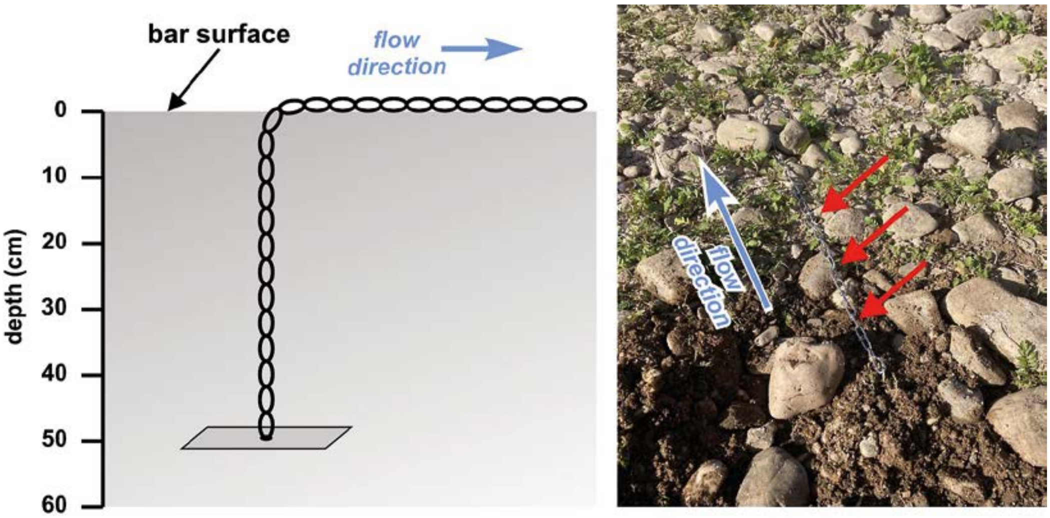

Fig. 3 Photograph and schematic illustration of scour chain installation in bar sediments.

protruding part oriented in alignment with the expected flow direction (Fig. 3). To assess changes in sediment dynamics – particularly regarding the burial or exposure of the chains – we conducted analyses over two distinct intervals: September 2021 to September 2022 and September 2022 to September 2023. We then disregarded data from the first period to reduce the influence of sediment settling on our findings related to chain burial or exposure. Therefore, our reported results reflect observations from only the latter one-year period, capturing data through the highest recorded discharge on April 17, 2023, which was 900 m^3/s.

2.4 Monitoring of bar sediments

In the frontal, central, and distal sections of each bar studied, we evaluated the surface grain size for particles equal to or larger than 8 mm. In September 2021, we set up 2–3 parallel rectangular areas (each measuring 1 m by 0.75 m) in each section, depending on the width of the bar (the minimal distance between the areas should be ca. 5 meters). These areas were meticulously cleared of litter and sparse vegetation, and their coordinates were recorded using a total station and GNSS. We captured orthogonal photographs of each area, which were later analyzed with the PebbleCounts software (Purinton and Bookhagen 2019). This software facilitates the automatic identification of individual grains. Following this preprocessing step, we selected accurately detected particles in each photograph. Utilizing the b-axis values generated by PebbleCounts, we randomly selected 150 values. Subsequently, we constructed a grain-size distribution curve and calculated the median grain-size value (D_{50}). In September 2023, we replicated the entire procedure in the same designated areas to assess temporal changes. To do this, we calculated the changes in median particle diameter by determining the ratio of median sizes obtained in 2021 to those in 2023.

2.5 Potential uncertainties in the used methods

Potential uncertainties related to geodetic measurements, such as the precision of geodetic total stations and the influence of pebbles on the bar surface, or issues with automated grain-size analysis (where incorrectly identified clasts were excluded from the final automated measurements), should be recognized. Additionally, the use of scour chains introduces certain uncertainties due to their susceptibility to errors in capturing multiple phases of erosion and deposition. Furthermore, the establishment of a small terrestrial vegetation patch near the scour chain burial site may influence the stability of the bar surface or the deposition of fine sediments, due to flow roughness induced by the vegetation. Nonetheless, it is unlikely that these factors significantly altered the general observed trend of changes between the 2021 and 2023 datasets.

3. Results

Despite the occurrence of relatively low flows that did not reach the level of a 1-year recurrence interval during the monitoring period – suggesting an expected low level of morphological activity on the studied bars – we observed measurable changes in both bar morphology and surface grain sizes. This indicates that even under conditions of low hydrological activity,

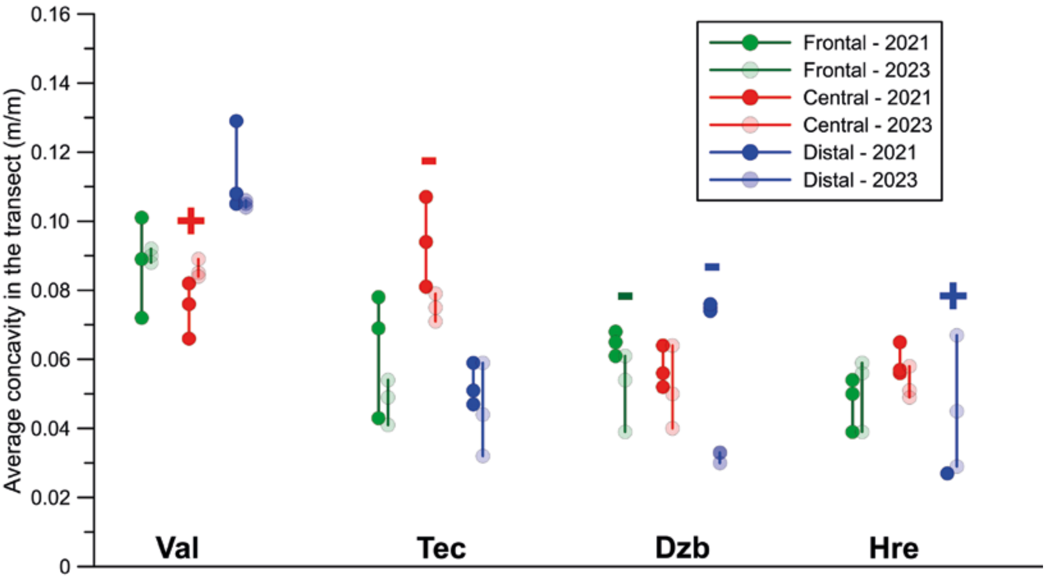

Fig. 4 Visualization of average concavities recorded along individual transects from field measurements in 2021 and 2023; the symbols "+" and "–" indicate significant changes, with all concavities in a section being higher or lower in 2023 compared to 2021, respectively.

Tab. 3 Changes in surface relative elevation (in cm) based on variations in scour chain length above the bar surface between September 2022 and September 2023. Positive values indicate erosion, negative values indicate deposition, an asterisk (*) denotes additional deposition on top of a scour chain lying on the surface, and NR signifies "not recovered", likely due to vandalism.

Bar	F1	F2	C1	C2	D1	D2
Val	−1*	−1	4*	−1	−1	−1
Tec	NR	1	NR	NR	1*	−1
Dzb	0	2*	−4	−15	NR	NR
Hre	0	1	0*	−1*	1*	2

significant alterations to the bars' physical characteristics can still occur.

3.1 Changes in cross-sectional transects

Overall, the average concavities (i.e., relative elevation changes per 1 m length) typically ranged between 3 to 10 cm, with the highest values observed for the Val bar, which exhibits a morphology closely resembling that of a point bar (Fig. 4). The different average concavity values observed between 2021 and 2023 indicated frequent alterations in the heterogeneity of the bar surfaces. However, these alterations did not follow a consistent pattern across the different bars or their respective sections, as illustrated in Fig. 4. Specifically, Val displayed an increase in average concavity, particularly in its central section, while Tec exhibited a decrease in concavity in the same section. Hre showed an increase in concavity in its distal section, whereas Dzb experienced a decrease in concavity in both its distal and frontal sections. These variations suggest that the responses of the bar surfaces to environmental factors are highly variable, influenced by the specific morphology of each bar, as well as potentially by local vegetation succession.

3.2 Recorded erosion/deposition by scour chains

Observations of scour chain burial dynamics across all monitored bars from 2022 to 2023 revealed variations, although several chains (three in Tec and two in Dzb) were not retrieved, likely due to vandalism (Tab. 3). Variations in the length of exposed chain were generally minor and within the anticipated margin of measurement error for most locations. It is important to note that some chains experienced additional sediment deposition, with exposed scour chains becoming slightly buried under sediment layers of 1–3 cm. This suggests multiple phases of sediment erosion and deposition during the 2022–2023 period, or more specifically, sediment deposition following an erosion event (i.e., erosion during the rise of high flow and deposition during its recession phase). Dzb demonstrated the most significant morphodynamics, with erosion of up to 15 cm observed in its middle section. Nonetheless, geodetically measured concavities exhibited minimal variance when compared to its distal or frontal sections (Fig. 4).

3.3 Changes in median grain-sizes

Firstly, none of the bars exhibited a coarser D_{50} grain size in their frontal sections, while the two upstream

Tab. 4 D_{50} surface grain-size percentiles displayed in mm and the 2023/2021 ratio of D_{50} values for sampled sites in 2021 and 2023 (colors indicate whether the ratio is positive or negative); F = frontal, C = central, and D = distal sections of the bar, with numbers denoting the position from the water surface to the outer edge of the bar; NS = not sampled.

Bar/year	F1	F2	F3	C1	C2	C3	D1	D2	D3
Val									
2021	40	36	NS	46	43	36	30	29	33
2023	32	35	NS	41	34	32	35	25	27
Change	0.80	0.97	NS	0.89	0.79	0.89	1.17	0.86	0.82
Tec									
2021	39	38	NS	46	38	NS	32	33	26
2023	34	34	NS	41	36	NS	35	30	25
Change	0.87	0.89	NS	0.89	0.95	NS	1.09	0.91	0.96
Dzb									
2021	33	35	NS	29	34	30	24	33	NS
2023	32	30	NS	33	36	39	36	27	NS
Change	0.97	0.86	NS	1.14	1.06	1.30	1.50	0.81	NS
Hre									
2021	33	24	23	25	24	27	NS	NS	NS
2023	29	23	21	38	30	23	NS	NS	NS
Change	0.88	0.96	0.91	1.52	1.25	0.85	NS	NS	NS

bars (Val and Tec) displayed noticeably larger D_{50} in their middle sections. However, finer D_{50} are typically observed in the distal sections of all the bars studied (Tab. 4 and Fig. 5). During the monitoring period, a significant number of grain-size samples exhibited substantial shifts in their median values, with 19 out of 28 samples showing an increase or decrease in D_{50} of more than 10%. We noted a somewhat contradictory trend between the upstream bars (Val and Tec) and the downstream bars (Dzb and Hre) regarding changes in median grain size on their surfaces. As indicated in Tab. 4, with the exception of a single measurement in the distal section, the upstream bars exhibited a degree of fining in their D_{50} values, most notably in the central section of Val, where the D_{50} 2021 to D_{50} 2023 ratio reached as high as 0.79. Conversely, the central sections of Dzb and Hre, in particular, showed signs of surface sediment coarsening, with the ratio climbing up to 1.52. This variation suggests differing responses of the bars over the two-year period, without a consistent trend in median grain size evolution. Additionally, we were unable to process any samples from the distal section of Hre during both 2021 and 2023 field campaigns, as the dominance of silt to sand-sized particles prevented their automated analysis by the PebbleCount software.

4. Discussion

All three geomorphic methods used in our study suggest that gravel bars with some content of finer grain-size fractions in a large regulated river are prone to changes in their morphological and sedimentological characteristics, such as variations in surface morphology or median grain sizes, even during periods of low flow that do not reach the level of a one-year recurrence interval. However, it is important to note that our observations are based on a two-year period only, and thus we cannot predict the future evolutionary trajectory of the investigated bars. Future changes over the coming decades will depend on ongoing climate changes and the approaches to local water management, including water abstraction or

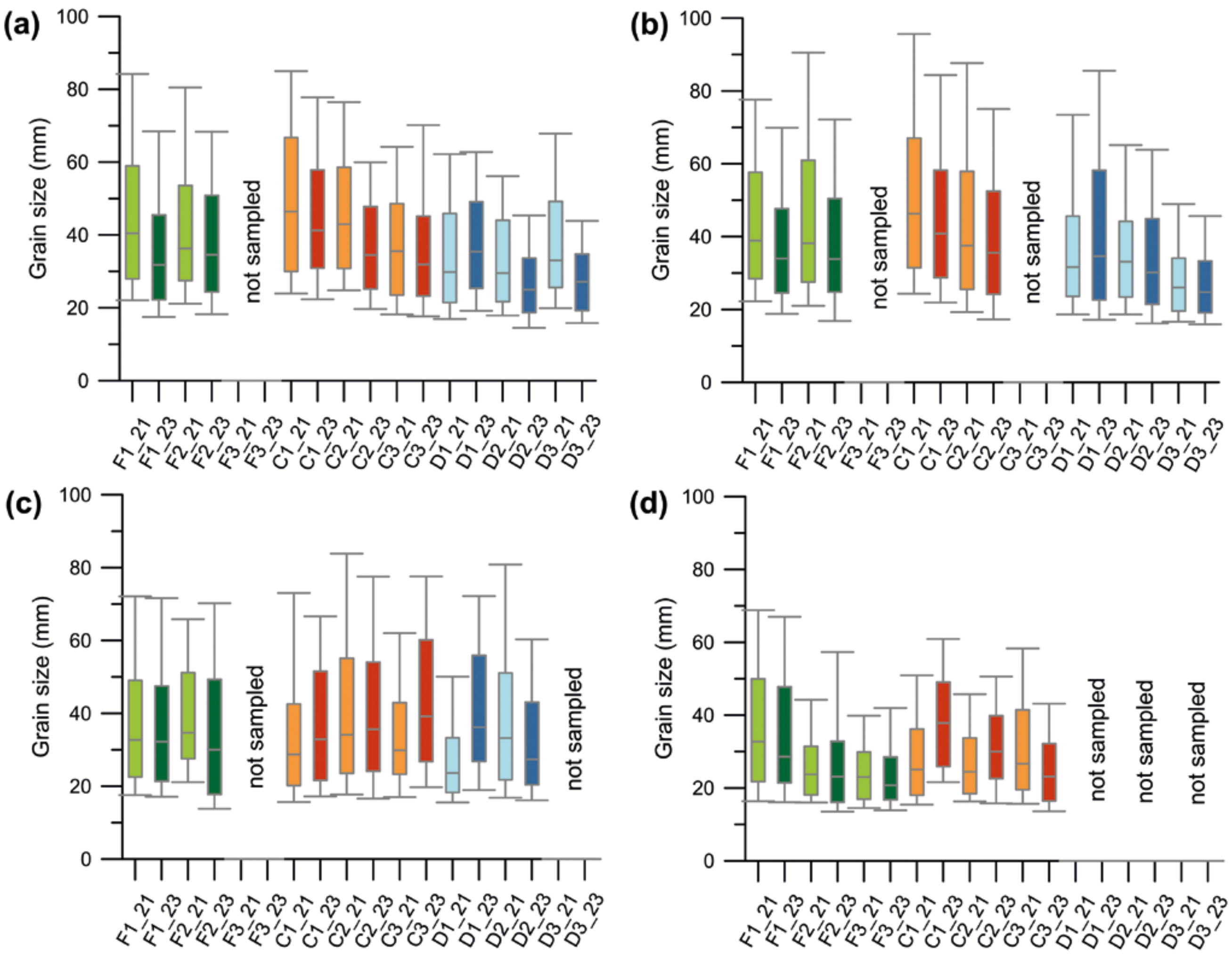

Fig. 5 Grain-size distribution of all sampled sites: (a) – Val, (b) – Tec, (c) – Dzb, (d) – Hre; whiskers show 10th and 90th grain-size percentile, F = frontal, C = central, and D = distal sections of the bar, with numbers denoting the position from the water surface to the outer edge of the bar (_21 and _23 represents the years of the sampling).

discharge regulation by dams in the upstream parts of the Elbe catchment. It should be noted that the potential impact of changing climate on the morphodynamic trajectories of rivers and their components, like gravel or sandy bars, is still largely unexplored (Redolfi et al. 2023).

During the two-year study period, we observed a variety of responses from the bars, which prevented us from identifying a consistent trend in bar evolution or morphodynamics in the studied reach of the Elbe River, subject to significant anthropogenic pressure. Despite their differences in morphology and size, the upstream bars (Val and Tec) exhibited larger median grain sizes in their central sections and showed some tendencies towards fining of the surface sediment layer between 2021 and 2023. Concurrently, their central sections exhibited contrasting morphodynamics, with an increase in concavity in Val and a decrease in Tec. A completely different scenario was observed in the downstream bars (Dzb and Hre), which tended towards sediment coarsening in their central sections. However, these bars also showed notable differences in concavity trends between 2021 and 2023. This clearly highlights the uniqueness of individual bars, despite their presence in a regulated river reach with a homogeneous planform. Our study is exploratory in nature, which necessitates caution when attributing specific factors to the observed variations within a single two-year period. For example, the coarsening observed in the central sections of bars located downstream of Děčín city (Dzb and Hre) may be due to the more confined nature of the local valley. This area lacks floodplain segments, potentially increasing transport capacity and sediment supply from adjacent steep catchments, even during low flows. However, to ascertain reliable factors, a longer monitoring period that includes high flow events is recommended.

In the context of short-term monitoring, our findings align intriguingly with those of (Kibler et al. 2011), who observed the evolution of median grain size (D_{50}) on gravel bars following dam removal. They noted a rapid increase in D_{50} size immediately downstream of the removed dam, underscoring the rapid response of sediment characteristics to such environmental changes. However, they also highlighted the variability of D_{50} and the challenges in ascribing significant meaning to downstream D_{50} changes. This perspective resonates with our observations, suggesting a parallel in the characterization of D_{50}. Furthermore, their work underscores the notable inter-annual variability in grain size, reinforcing the importance of linking grain size changes to flow magnitude. This connection becomes particularly relevant for bar surfaces prone to frequent flooding, where signs of morphological change are observable at flow events with one- to two-year recurrence intervals, as indicated by Haschenburger and Wilcock (2003). They documented the surface activity of grains across four monitoring phases, each associated with a distinct flow magnitude, affecting different active zones of the channel. Our data lead to a comparable insight, emphasizing that not just the flood magnitude and active grain size matter, but also the position within the channel, such as relative elevation or flow direction, plays a critical role in shaping sediment dynamics. In this context, based on our observations of scour chains, we anticipate not only suspended sediment transport but also a degree of bedload transport during periods of relatively low flow, as evidenced by the partial burial of some chains by fine gravels.

Short-term (year-to-year) detailed examinations of the grain size and morphological development of bars in large regulated "stable" rivers are almost absent in field research, especially when compared to studies on freely meandering or braided rivers. This scarcity of data makes it difficult to directly compare our results with those from other rivers affected by intensive human activities. Jaballah et al. (2015) observed swift alterations in bar dynamics – ranging from several months to a few years – due to engineering constructions and damming in a previously wandering Alpine gravel-bed channel. These interventions resulted in a decrease in the number of bars and an elongation of their lengths. However, details regarding variations in their grain sizes or surface heterogeneity were not disclosed. The recent disruption in the natural development of bars in the Elbe, relative to rivers in a more natural state, is highlighted by the absence of the coarsest sediment fractions in the frontal sections of the bars. Conversely, the finest median grain sizes were observed in the distal sections of the studied bars, aligning with the natural development processes of bars as documented by researchers like (Ashworth and Ferguson 1986; Smith 1974). Two of the bars examined in our study, Val and Tec, exhibited the highest D_{50} values in their central sections. This observation suggests a similarity with alternate sand-gravel bars in the middle Loire River, which has also been influenced by various river training works, such as embankments, groyne construction, and sediment extraction (Cordier et al. 2020). Some long-term (decadal-scale) studies have focused on the biogeomorphic interactions between bar morphodynamics and vegetation in channelized river reaches. Although our study did not explore the development or composition of vegetation, the influence of vegetation in trapping sediments or stabilizing bars is undeniable. Projected climate changes, which influence the timing and frequency of floods linked to the development of vegetation as demonstrated in numerical simulations of alpine channelized river reaches (Jaballah et al. 2015; Jourdain et al. 2020), suggest a potential future transformation of bars. Over the past decade, relatively low flows in the Elbe River have likely encouraged the establishment and spread of vegetation on exposed bar surfaces, a phenomenon recently also observed in another central-European river, the Odra, across both channelized and meandering sections

(Holušová et al. 2023). Conversely, the maintenance of the Elbe reach, associated with ship navigation and irregular dredging of sediments from the channel bottom to banks or bar surfaces, may somewhat replicate the disturbance effects typically caused by high flows.

Our methodology could serve as a template for cost-effective monitoring of the dynamics of bars in channelized river segments. Bars in such settings often manifest as extended strips along the inner parts of river bends and are generally accessible and temporally quite stable (e.g., Adami et al. 2016), in contrast to the more dynamically changing natural channels like wandering or braided rivers. The use of unmanned aerial vehicles (UAVs) and airborne LiDAR systems has the potential to accelerate data collection and facilitate the monitoring of more extensive areas of bar surfaces or a larger number of bars. Nonetheless, it is crucial to address and reduce the impact of vegetation on the generated digital elevation models (e.g., Caponi et al. 2019; Langhammer and Vacková 2018; Rusnák et al. 2018). Field data are essential for precisely characterizing the habitats of fauna and flora inhabiting these boundary zones between aquatic and terrestrial environments, and this information is crucial for improving their management in the context of sustainable river usage (Brierley and Fryirs 2016). Our study exemplifies the need for tailored management approaches for bars in large regulated rivers, as their characteristics and morphodynamic trajectories can differ markedly across individual locations. For instance, Hre bar exhibited a relatively flat and muddy distal section that precluded the processing of grain-size samples via photogrammetry, a situation not encountered in the other three bars studied.

5. Conclusions

Our study comprehensively examines the morphological and sedimentological dynamics of bars within a regulated reach of the Elbe River over a two-year period, highlighting the susceptibility of these geomorphic features to changes despite low flow conditions. The utilization of three classic geomorphic methods revealed significant variability in surface heterogeneity, median grain sizes, and morphodynamic trends among the studied bars, underscoring the complexity of bar evolution in regulated rivers. Particularly notable were the observed divergent trends in sediment coarsening and fining, as well as variations in concavity across different studied bars. This study also underscores the need for detailed, site-specific research to understand the impacts of regulation and climate change on river morphology. Moreover, our methodology offers a blueprint for cost-effective monitoring of morphodynamic changes in channelized river segments, providing essential data for the sustainable management of river habitats.

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