PHYSICAL AND CHEMICAL PROPERTIES OF THE SEDIMENT IN NATURAL AND ARTIFICIAL RIVER BARS IN THE ELBE

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ABSTRACT

Physical and chemical properties of natural river bars in the lower reaches of Elbe in the Czech Republic were studied and compared with those of artificial river bars. Most of the chemical properties of the sediment are not correlated with the texture of the sediment but are affected by the organic matter content. The highest content and most of the chemicals were recorded in the central parts of a bar and close to the shore and terrestrial habitats. Artificial bars significantly differ from natural ones in their chemical properties. There were higher levels of phosphorus and other nutrients in artificial bars.

Keywords: Elbe; chemistry; habitat; river bars; texture

Introduction

River bars are habitats formed by the accumulation of sediments in a part of a river when the sediment supply exceeds the transport capacity. River bars are shaped by a continuous deposition and erosion of sediments. This results in a very dynamic environment with frequent disturbances, which harbours a very specific biota (Bendix and Stella 2013). This is particularly true of river bars in the lower reaches of the Elbe in the Czech Republic (Juříček 2013; Bejček and Volfová 2019; Havlíček et al. 2023). Although the flora and fauna on these bars has been intensively studied, especially in terms of indicative umbrella species, such as *Corrigiola litoralis* (Juříček 2013; Bejček and Volfová 2019; Havlíček et al. 2023), little is known about the nutrient distribution in these habitats and whether it is major driving factor. Understanding these patterns is essential for more effective protection of river bars or even for targeted intervention aimed at restoring bar habitats. Bar restoration is a complex process that must consider many hydrological and ecological aspects (Eekhout et al. 2013; González et al. 2015; Li et al. 2023), of which differences in the nutrient dynamics of natural and artificial river bars are among the least studied.

In this study, the nutrient distribution in relation to the distribution of organic matter and sediment texture in natural river bars is compared with that in artificial bars mainly in terms of the level of nutrients and other key elements.

Material and Methods

Study sites and sampling design

This study was carried out on periodically flooded gravel river bars in the Elbe River between Ústí nad Labem and the Czech-German border (Fig. 1). The appearance of gravel bars above water depends on the flow of water, with the largest area exposed occurring in summer. However, in wet years gravel bars can remain underwater all year round. In addition, fluctuations in river level during a year are significantly influenced by the dams

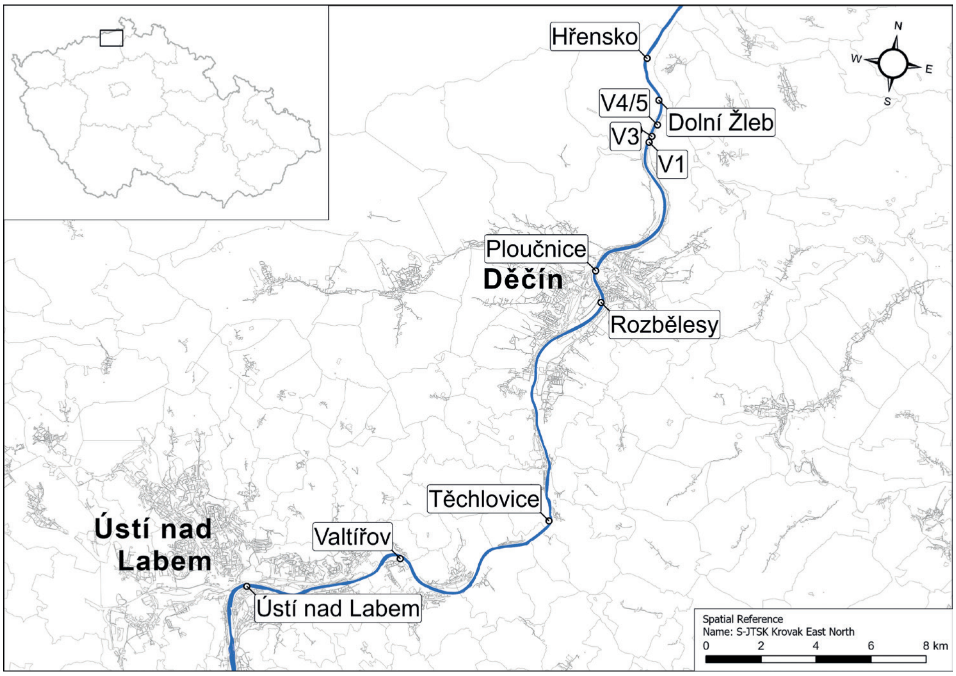


Fig. 1 Maps showing the locations of the sites studied on the Elbe between Ústí nad Labem and the Czech-Germany border. Artificial bars are indicated by the letter V. Map based on orthophoto ČÚZK 2019.

Frouz, J., Borovec, J.: Physical and chemical properties of the sediment in natural and artificial river bars in the Elbe
European Journal of Environmental Sciences, Vol. 15, No. 1, pp. 5–11
https://doi.org/10.14712/23361964.2025.1

Table 1 Location and details of the sites studied, with those selected for more detailed study marked with an asterix *.

Site	Type	Width (m)	Length (m)	Slope	Latitude (N)	Longitude (E)
Valtířov*	natural – ruderal plants	22	280	steep	50.676	14.127
Ploučnice	natural – ruderal plants	10	40	moderate	50.778	14.206
Hřensko*	natural – typical	19	400	moderate	50.849	14.217
Dolní Žleb*	natural – typical	16	450	moderate	50.836	14.226
Rozbělesy	natural	17	220	moderate	50.768	14.211
Těchlovice*	natural	8	200	moderate	50.695	14.200
Ústí nad Labem	natural – ruderal plants	12	50	moderate	50.660	14.051
V4/5	artificial	24	240	moderate	50.828	14.227
V3	artificial	28	100	uneven	50.824	14.225
V1	artificial	6	60	uneven	50.822	14.224

on the Vltava River and the Střekov weir. It follows a natural seasonal pattern, but the maximum discharge during floods used to be higher and summer minimums during dry periods were lower, when there were no dams. Also, the river ceased to freeze over in winter and early spring after the reservoirs were built.

To characterize the differences in grain size and distribution, and chemical composition of the deposited material, seven sites with the largest and best developed gravel bars and three artificial sites designed to provide an alternative habitat for riparian vegetation were selected (Table 1).

Sediments were sampled next to the 60 permanent 1 × 1 m plots that were arranged in transects across and parallel to the river; the five largest localities had nine plots (i.e. three parallel and three across) and five smaller localities had three plots (i.e. one across in the central part of the locality). Parallel transects were used to determine differences in the composition of deposited material at the front, middle and rear of gravel bars that reflect the typical decrease in flow velocity of the river (Fig. 2). Each transect across a bar started at the point determined by when the water recorded at the water level gauge in Děčín was 150 cm and ended in front of where the terrestrial vegetation started (Fig. 2).

Texture and chemistry of the sediment in the river bars

Texture of the top 5 cm of the substrate collected from a 20 × 20 cm area near the 1 × 1 m permanent plots was measured. The weight of the fresh sample and the sample after drying at 60 °C were used to calculate the water content. Texture was analysed using the whole dry sample, when fractions >200 mm, 200–50 mm, and 50–20 mm were separated manually; fractions 20–5 mm, 5–2 mm, 2–0.5 mm by dry sieving and the particles below 0.5 mm were analysed in the suspension using MasterSizer 2000 MU (Malvern Instruments, England). The finest fraction of particles below 0.5 mm was used for loss on ignition (550 °C for 2 hrs.) and all other chemical analyses.

For the determination of plant-accessible nutrients and selected metals (P, K, Ca, Mg, Fe, Mn, Al, Cr, As), Mehlich III extraction solution (Mehlich 1984) was used, where 1 g of sample was extracted using 10 ml of solution for 5 min. The samples were centrifuged and filtered (0.4 μm GF filters) before analyses using an ICP-QQQ (Agilent, Japan). A semi-micro modification of perchloric acid digestion method for the determination of total P in soils, sediments and organic materials (Kopáček et al. 2001) was used to analyse the composition of the particles smaller than 0.5 mm. Samples were digested for 30 minutes in nitric acid at 115 °C and then for 2 hours with

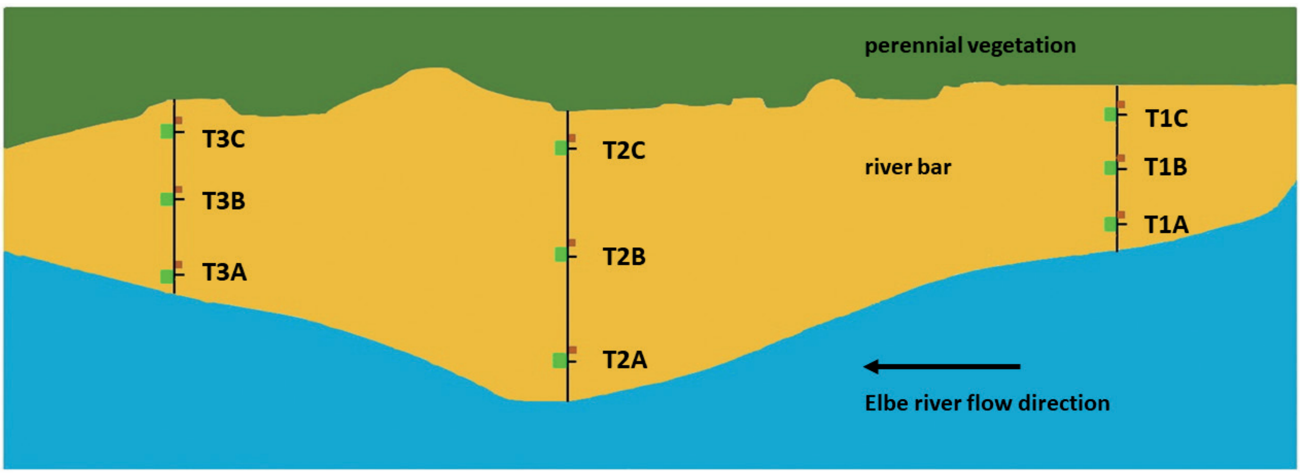


Fig. 2 Positions along and across the plots sampled (green dots) at each site.

perchloric acid at 170 °C in an aluminum heating block before analyses using an ICP-QQQ (Agilent, Japan).

Data processing

Linear regression coefficients and Pearson's correlation coefficients were used to describe the relationships between the physical and chemical properties of the substrate and their position on the gravel bar (the position on the bars was entered categorically). Due to the large number of variables studied, only those coefficients that were significant at $p < 0.05$, when the Bonferroni correction was applied, were used. To test whether the chemical properties of the natural gravel bars are similar to those of artificial bars, only samples from the leading edge of the bars were collected as bars were relatively short in the downstream direction no comparable samples were available downstream. Natural and artificial gravel bars were compared using a two-way ANOVA done in Statistica 13.0, in which habitat, i.e., natural or artificial, and the distance of the source of the sample from the shore were explanatory variables.

Results and Discussion

Natural river bars

The distribution of grain size is associated with position on the bar, with the proportion of fine grains, i.e. those 63–250 µm and below 0.5 mm, is correlated significantly with downstream locations (r = 0.407 and 0.435). The ANOVA also indicates significantly higher proportions of fine grains (<125 µm and >63 µm) in the most downstream location on the bars (Fig. 3A, Table 2; data shown only for one grain size, but all fractions vary significantly along the bars and have the same pattern). This distribution is consistent with the grain size distribution observed in river bars in other river systems (Rice and Church 1998; Purkait 2006), which is due to the decreasing velocity of water flowing over the bar, which results in sedimentation of coarser particles mainly upstream and finer particles downstream. In contrast to the findings of Sin et al. (2015), no significant correlations were recorded with the location of the site or the content of individual nutrients, in the current study. In addition, significant

Table 2 Mean values (±SD) of individual parameters recorded on natural river bars and effect of upstream and downstream and flow across bars (from river to adjacent land) on the parameters evaluated by two-way ANOVA, p values for effect of across and position along a bar are shown, ns = not significant.

	Parameter	Along bar	Across bar	Mean value ± SD
Total content	K	0.0069	ns	10.28 ± 3.43
mg g^{-1}	Al	0.0228	ns	0.74 ± 0.25
	P	ns	ns	4.30 ± 1.52
	Ca	0.0173	ns	0.03 ± 0.01
	Cr	0.0113	ns	0.92 ± 0.45
	Mn	0.0046	ns	15.35 ± 4.54
	Fe	0.0008	0.0363	0.01 ± 0.01
	As	ns	ns	2.58 ± 0.80
	Mg	0.0178	ns	0.11 ± 0.04
Available	K	0.0227	ns	379.85 ± 108.20
mg kg^{-1}	Al	ns	ns	74.10 ± 16.90
	P	ns	ns	1,922.92 ± 646.17
	Ca	ns	ns	0.30 ± 0.05
	Cr	ns	ns	151.53 ± 46.03
	Mn	0.0157	ns	305.32 ± 75.61
	Fe	ns	0.0025	0.69 ± 0.11
	As	ns	0.0331	187.16 ± 72.02
	Mg	ns	ns	32,621.09 ± 20,954.28
Texture	>50 mm	ns	ns	32.06 ± 11.76
%	20–50mm	ns	ns	14.87 ± 8.42
	5–20 mm	ns	ns	5.22 ± 3.55
	2–5 mm	ns	ns	10.27 ± 5.34
	0.5–2 mm	ns	ns	1.63 ± 1.10
	250–500 µm	ns	ns	0.90 ± 0.55
	125–250 µm	0.0069	ns	0.72 ± 0.45
	63–125 µm	0.0331	ns	0.75 ± 0.50
	<63 µm	0.0154	ns	4.03 ± 1.55
Organic matter %		ns	ns	4.79 ± 2.93

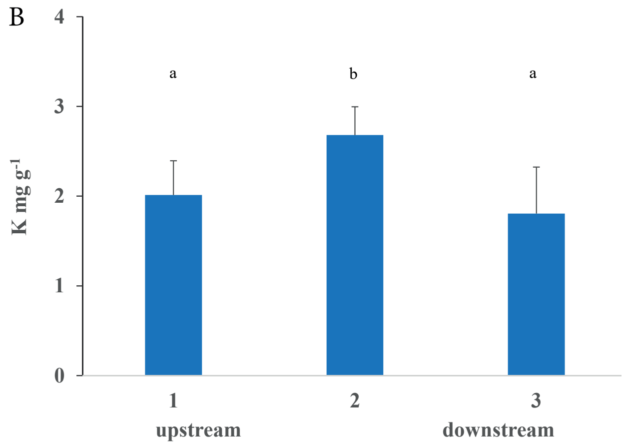
correlations between nutrient contents and the proportion of individual grain sizes in sediments are rare (Table 3), although other authors (Steiger and Gurnell 2003; Turner et al. 2007) report an increase in nutrients with increase in the proportion of fine sediment. There is no correlation between individual elements and position on the bar. However, the ANOVAs of the positions of elements along and across bars (depicted in Fig. 2) revealed significant effect of position along bars for total K, Al, Ca, Cr, Mn, Fe, Mg and available K and Mg, and significant effect across bars on total Fe and available Fa and As (Table 2, Figs 3B–C). For all elements with significant associations with position along bars the values in the central part of the bars were significantly higher than those for the most downstream and upstream locations (Fig. 3B). For elements with significant associations with positions across bars the highest values were for the positions closest to the land (Fig. 3C). Interestingly, the distribution of total phosphorus, which is an important plant nutrient is not affected by the position on the natural bars. In contrast to grain size, most elements, including the key nutrients, are barely significantly correlated with the organic content in the sediment (Table 3).

This indicates that the nutrient status of river bars is not primarily determined by the granular properties of the sediments, but with complex interactions with river flow and erosion of material from the adjacent land possibly supplying the nutrients. Similar complex nutrient dynamics are also reported by Claret et al. (1997) and Maazouzi et al. (2013).

Table 3 Correlation between the content of nutrients, grain size of the substrate and the content of organic matter: A available nutrients, T total nutrient content, data presented in units of length refer to grain sizes. Only correlation coefficients that are statistically significant at p<0.05 when applying the Bonferroni correction are listed.

	Na – T	K – T	Al – T	P – T	Ca – T	Cr – T	Mn – T	Fe – T	As – T	Mg – T	K – A	Al – A	P – A	Ca – A	Cr – A	Mn – A	Fe – A	As – A	Mg – A
Na – T	1.00																		
K – T	0.42	1.00																	
Al – T	0.45	0.96	1.00																
P – T	0.43	0.86	0.94	1.00															
Ca – T	0.47	0.89	0.86	0.76	1.00														
Cr – T		0.84	0.85	0.75	0.77	1.00													
Mn – T	0.41	0.88	0.85	0.78	0.83	0.79	1.00												
Fe – T	0.54	0.88	0.89	0.76	0.83	0.88	0.82	1.00											
As – T		0.00	0.41	0.00				0.52	1.00										
Mg – T	0.53	0.89	0.93	0.85	0.83	0.79	0.80	0.84		1.00									
K – A		0.77	0.79	0.72	0.69	0.62	0.72	0.67		0.79	1.00								
Al – A		0.68	0.79	0.73	0.63	0.73	0.69	0.77		0.75	0.77	1.00							
P -A		0.68	0.62	0.53	0.65	0.53	0.67	0.61		0.61	0.67	0.52	1.00						
Ca – A		0.74	0.74	0.65	0.81	0.61	0.70	0.64		0.71	0.81	0.73	0.71	1.00					
Cr – A															1.00				
Mn – A		0.58	0.48		0.59	0.45	0.78	0.56		0.50	0.54	0.40	0.66	0.48		1.00			
Fe – A		0.49	0.40		0.47	0.45	0.59	0.58		0.43		0.46	0.69			0.73	1.00		
As – A		0.49	0.43		0.49	0.50	0.49	0.64		0.44		0.50	0.67	0.45	0.44	0.55	0.85	1.00	
Mg – A		0.65	0.76	0.78	0.63	0.55	0.59	0.59		0.75	0.78	0.78	0.48	0.80					1.00
>50 mm																			
20–50 mm																0.42			
5–20 mm																			−0.47
25 mm																			
0.5–2 mm													−0.42						−0.56
250–500 µm										−0.46	−0.44			−0.49					−0.51
125–250 µm																			−0.44
63–125 µm																			−0.46
<63 µm																			−0.45
Org. matter.		0.68	0.72	0.70	0.54	0.54	0.55	0.57	0.00	0.65	0.63	0.59	0.56	0.61					0.64
<0.5mm																			

Significant correlations were recorded between nutrients, indicating that they are all associated with the same environmental gradient (Table 3). This indicates that nutrient content is not associated with the sorption properties of the sediment but is most likely determined by the flux of nutrients from the riparian ecosystem into the river. This flux can be further influenced by biotic interactions at upwellings and on the surfaces of the sediment, which can influence both the total supply and the availability of nutrients determined by mobilization and immobilization, both of which are influenced by redox conditions.



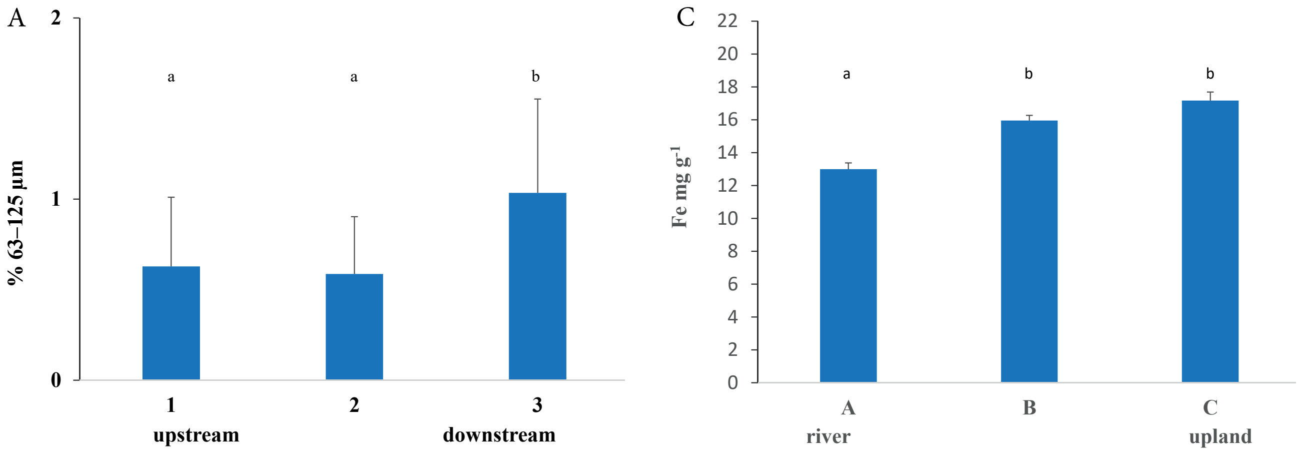


Fig. 3 Examples of the distribution of material of different grain sizes and selected elements along and across natural river bars A) fraction 125–63µm B) K content along profile and C) Fe content across profile.

Comparison of natural and artificial river bars

Comparison of artificially created and natural river bars revealed statistically significant differences in the content of total nutrients (K, Al, P, Ca, Cr, Mn, Fe, Mg) and available nutrients (K, Al, Ca, Mg) as well as organic matter. In addition, there are significant differences in the granular composition of the sediment (Table 4 and Fig. 4).

As described above and reported by other authors (Claret et al. 1997; Maazouzi et al. 2013), the factors that determine the spatial distribution of nutrients and other elements on a bar are complex. This can be further affected by the development of vegetation, which can affect sedimentation (Steiger et al. 2003) and trigger additional effects (Frouz 2024), such as the formation of microbial growth, which in turn can influence the mobilization and immobilization of nutrients. These complex interactions may be one of the reasons why it is technically difficult to imitate natural river bars and why technically restored river bars differ in nutrient status from naturally formed bars (Table 4). In particular, artificial river bars have significantly higher P and organic matter content and a strong gradient across the bar, with it being much higher near the adjacent land and decreases towards the river. Thus, artificial bars retain organic matter and associated nutrients brought in either by the river or from the surrounding land. Although this has not been studied, it is likely that higher nutrient status promotes fast-growing vegetation that recycles nutrients faster and triggers a number of other processes that increase the nutrient differences between natural and artificial bars (Frouz 2024).

Conclusion

The results show that naturally formed river bars differ from artificial ones in their nutrient status. Detailed records of the nutrient distribution in natural river bars indicate that it is associated with the distribution of organic matter, but the final pattern is a consequence of a complex interplay of several factors. The complexity of these factors is the most likely reason why the nutrient distribution in natural river bars hosting *Corrigiola litoralis* is difficult to mimic technically.

Acknowledgements

This study was funded by the Technology Agency of the Czech Republic, grant number SS03010279 (Management optimization of the Elbe lower reach with respect

Table 4 The effect of natural or artificial origin of gravel bars and distance from shoreline determined using two-way ANOVA, numbers are p values for individual factors and their interactions with only p values <0.05 presented. Only the upstream part of natural bars was considered for comparison.

		Natural bars mean value ± SD	**Artificial bars mean value ± SD**	**Position (distance from shoreline)**	**Natural vs. artificial bars**	**Interactions**
Tolal content	K	2.02 ± 0.58	2.50 ± 0.83	0.0048	0.0421	ns
mg g^{-1}	Al	9.87 ± 2.81	14.01 ± 4.45	0.0069	0.0014	ns
	P	0.72 ± 0.20	1.03 ± 0.30	ns	0.0021	ns
	Ca	4.09 ± 1.47	5.53 ± 1.60	ns	0.0219	ns
	Cr	0.02 ± 0.01	0.03 ± 0.01	0.0115	0.0174	ns
	Mn	0.88 ± 0.40	1.26 ± 0.48	ns	0.0338	ns
	Fe	14.94 ± 3.95	20.66 ± 7.58	0.0032	0.0029	ns
	As	0.01 ± 0.01	0.01 ± 0.01	0.018	0.0641	ns
	Mg	2.52 ± 0.72	3.46 ± 0.82	ns	0.0035	ns
Available content	K	110.69 ± 37.44	145.60 ± 44.54	ns	0.0359	ns
mg kg^{-1}	Al	382.03 ± 111.90	610.11 ± 243.75	0.0379	0.0004	ns
	P	74.31 ± 16.47	80.582 ± 10.03	ns	ns	ns
	Ca	1 891.21 ± 570.46	2,481.97 ± 867.92	ns	0.0285	ns
	Cr	0.30 ± 0.10	0.30 ± 0.10	ns	ns	ns
	Mn	144.95 ± 43.55	159.66 ± 309.88	ns	ns	ns
	Fe	303.51 ± 70.34	353.63 ± 108.48	0.0061	0.0881	ns
	As	0.70 ± 0.10	77.10 ± 20.80	0.0006	ns	ns
	Mg	187.20 ± 51.17	299.42 ± 104.56	ns	0.0002	ns
Texture %	>50 mm	37.54 ± 20.08	40.38 ± 17.62	ns	ns	ns
	20–50mm	31.67 ± 11.10	32.71 ± 12.75	ns	ns	ns
	5–20 mm	12.76 ± 6.06	11.24 ± 4.92	ns	ns	ns
	2–5 mm	4.56 ± 2.60	5.83 ± 2.96	ns	ns	ns
	0.5–2 mm	9.04 ± 3.53	6.37 ± 2.63	ns	ns	ns
	250–500 µm	1.51 ± 0.97	1.03 ± 0.48	ns	ns	ns
	125–250 µm	0.83 ± 0.52	0.74 ± 0.46	ns	ns	ns
	63–125 µm	0.62 ± 0.38	0.55 ± 0.32	ns	ns	ns
	<63 µm	0.67 ± 0.45	0.64 ± 0.35	ns	ns	ns
Organic matter %		4.01 ± 1.47	5.32 ± 2.18	0.0028	0.0296	0.0367

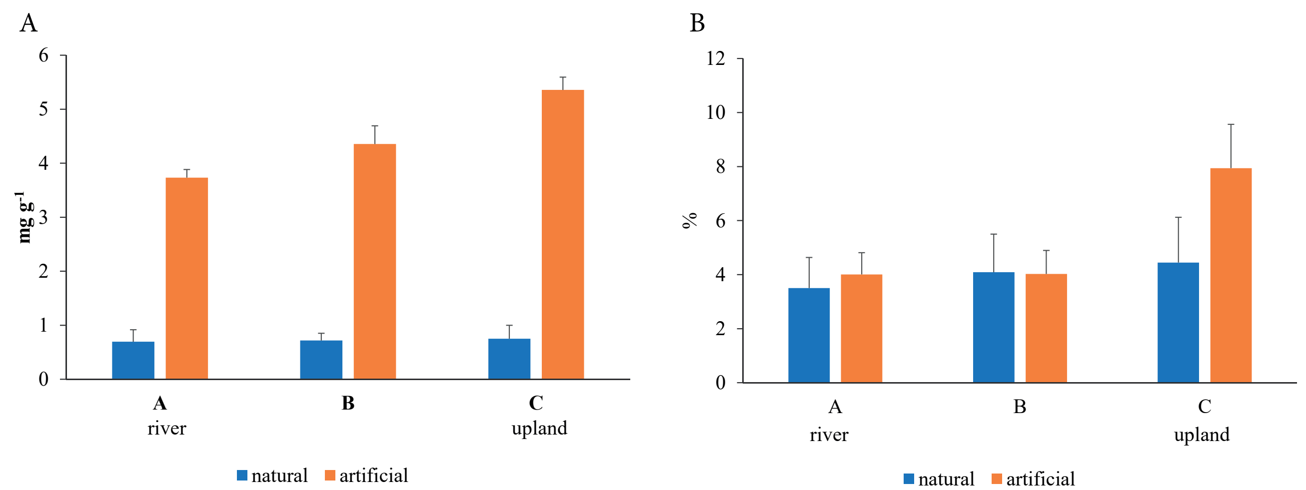


Fig. 4 Distribution of phosphorus A) and organic matter B) along the gradient depicted in Fig. 2 from river to adjacent terrestrial habitat compared on the upstream part of natural bars with that on artificial bars.

to the presence of 3270 biotope and improvement of the hydro morphological state as based on an interdisciplinary study).

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