Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Lithological Controls on Riverbank Retreat: Four-Year Monitoring Using Erosion Pins and Terrestrial Laser Scanning

Karol Augustowski

karol.augustowski@uken.krakow.pl

University of the National Education Commission

Article

Keywords: riverbank retreat, bank erosion, lithology, erosion pins, terrestrial laser scanning, Western Carpathians

Posted Date: October 29th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11251350/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Riverbank retreat reflects interactions between bank-material properties and variable erosional forcing, but the extent to which lithological contrasts persist in multi-year retreat patterns remains unclear. We monitored six riverbanks in the Podhale region of the Western Carpathians, Poland, representing fine-grained alluvium (Type A), gravel-dominated sediments (Type B), and consolidated flysch bedrock or cemented Neogene gravels (Type C). Retreat was measured from 2019 to 2022 using erosion pins and terrestrial laser scanning (TLS). Mean annual retreat over the four-year period ranged from 39.2 to 81.4 cm for erosion pins and from 42.2 to 81.0 cm for TLS. Type B sites showed the lowest retreat, whereas higher values occurred at Type A sites and at the single Type C site, indicating that greater consolidation did not correspond consistently to lower retreat. Substantial interannual variability occurred at all sites. Despite larger differences in individual years, erosion pins and TLS identified broadly consistent multi-year spatial patterns. Lithological differences were therefore evident, but they did not account for retreat magnitude on their own. The four-year record also shows the value of combining point measurements with spatial surveys when interpreting variable riverbank erosion.

Introduction

Riverbank retreat is a dynamic and multifactorial geomorphological process resulting from the interaction of fluvial erosion, gravitational mass movements, and subaerial processes such as drying, wetting, and freeze–thaw cycles [1, 2, 3, 4]. The relative importance of these mechanisms varies according to local hydrological, climatic, geological, and geomorphological conditions, as well as human modifications of river channels [5, 6, 7, 8, 9]. Consequently, rates of bank retreat may differ considerably not only between river systems but also between individual reaches of the same river.

Among the factors controlling riverbank retreat, the lithological composition and physical characteristics of bank material are particularly important because they determine the resistance of the bank to both hydraulic and subaerial erosion [10, 11, 7, 12]. Grain size, degree of consolidation, sediment cohesion, moisture conditions, and the internal structure of the bank influence its susceptibility to particle detachment, undercutting, mass failure, and weathering. Weakly consolidated sediments may be readily removed once exposed to hydraulic forces, whereas more consolidated materials generally provide greater resistance to erosion. However, the response of a riverbank cannot be explained by lithology alone, because the resistance of bank material interacts with temporally variable external forcing, particularly flow conditions, precipitation, temperature fluctuations, and seasonal changes in moisture. Recent studies have further emphasized that bank retreat results from interactions among material erodibility, hydraulic forcing, pore-water conditions, and bank stability rather than from any single controlling factor [13, 14, 15]. Changes in moisture and groundwater conditions may substantially modify bank-material strength, while hydraulic erosion and fluctuations in river stage can alter both toe erosion and the probability of subsequent mass failure.

This interaction may be especially important in mountain and foothill river environments, where heterogeneous sedimentary sequences occur over relatively short distances and are exposed to pronounced seasonal hydroclimatic variability. Previous studies in the Carpathians have demonstrated that frost-related processes, particularly repeated freeze–thaw cycles, can contribute substantially to bank degradation during the cold season [16, 17, 7]. Frost-induced loosening and disintegration of bank material may increase its susceptibility to subsequent removal, although the magnitude of this effect varies according to sediment grain size, moisture content, and structural properties [11, 18, 19]. During warmer periods, fluvial processes such as lateral erosion and basal scouring become increasingly important, particularly during high-flow events [20, 21, 22, 14]. Lithology can therefore be regarded as an important control on how riverbanks respond to changing erosional forcing rather than as an isolated driver of bank retreat.

Quantifying lithological controls on riverbank retreat requires monitoring approaches capable of detecting changes over sufficiently long periods to account for both spatial differences among bank materials and temporal variability in erosional conditions. Erosion pins are widely used in fluvial geomorphology as a simple and cost-effective technique for measuring local changes in bank position [10, 23, 24]. Their repeated measurement enables relatively high-frequency observations and can capture short-term and seasonal variations in erosion. However, erosion pins provide point-based measurements and may not fully represent spatially heterogeneous processes such as localized undercutting, bank collapse, or sediment accumulation.

Terrestrial laser scanning (TLS), in contrast, provides high-resolution, spatially continuous information on bank morphology and enables three-dimensional detection of surface changes over larger areas [25, 26, 27]. The method is therefore particularly useful for monitoring complex or heterogeneous bank profiles. Combining point-based erosion-pin measurements with TLS offers an opportunity to assess riverbank retreat at complementary spatial and temporal scales. More importantly, the application of both techniques to banks composed of contrasting materials makes it possible to determine whether lithology-dependent patterns of retreat remain consistent irrespective of the monitoring approach used. Comparative applications of erosion pins and TLS under conditions of pronounced lithological variability remain relatively limited [28, 22]. Repeated TLS surveys have proved particularly useful for identifying spatially heterogeneous erosion and deposition patterns that cannot be adequately represented by point-based measurements alone. In mountain environments, TLS has also been successfully applied to relate bank-surface changes to seasonal hydrometeorological conditions and freeze–thaw processes.

The Podhale region of the Western Carpathians provides a suitable setting for examining these relationships because riverbanks within relatively small catchments are composed of markedly different materials, ranging from fine-grained alluvial deposits through gravel-dominated sediments to consolidated substrates. At the same time, these banks are exposed to seasonal freeze-thaw activity, high-flow events, and other processes capable of producing substantial temporal variability in erosion. Long-term monitoring of contrasting bank types can therefore provide insight into the extent to which

differences in lithological properties are reflected in riverbank retreat despite changing environmental conditions.

This study investigates riverbank retreat at six sites located in the Podhale region of southern Poland, within the Czarny Dunajec, Molczy, Cichy, and Wielki Rogoźnik catchments. The sites represent contrasting bank materials and were monitored over a four-year period (2019–2022) using repeated erosion-pin measurements and terrestrial laser scanning. The primary objective of the study is to determine how contrasting bank lithology and degree of material consolidation are associated with the magnitude and temporal variability of riverbank retreat. Specifically, the study addresses whether (i) retreat rates differ systematically among contrasting lithological bank types, (ii) lithological differences in retreat persist despite interannual variability in erosion intensity, and (iii) erosion pins and TLS identify consistent spatial and temporal patterns of bank retreat. The analysis therefore focuses on whether material-related differences remain visible through time and on how consistently the two monitoring methods capture those differences.

Methods

Study sites

The study was conducted at six riverbank monitoring sites located along four rivers in the Podhale region of southern Poland: the Czarny Dunajec, Molczy, Cichy, and Wielki Rogoźnik (Fig. 1). These rivers represent typical Carpathian foothill streams, characterized by sinuous or wandering channels, moderate channel gradients ranging from approximately 3 to 12‰, and banks developed in alluvial or partially consolidated glacial and fluvial deposits [7, 12].

The monitoring sites were selected to represent contrasting lithological and material characteristics. Bank materials within the study area range from fine-grained alluvial deposits to gravel-dominated sediments and more consolidated substrates, including flysch bedrock and cemented deposits [8]. The sites were specifically selected to represent this variability in bank material, allowing differences in riverbank retreat to be examined under broadly comparable foothill-river conditions.

All monitoring sites were located within unregulated river reaches and were free from artificial bank protection and dense vegetation that could substantially interfere with the observation and measurement of natural bank-erosion processes. These selection criteria reduced the direct influence of engineering structures on bank-retreat measurements and facilitated the application of both erosion pins and terrestrial laser scanning (TLS). The selection of unregulated and unvegetated sections follows the original study design used to observe predominantly natural erosion processes.

The six sites differed in the dominant characteristics and degree of consolidation of the exposed bank material. These differences formed the basis for the lithological classification described in Section 2.4, in which the monitored banks were assigned to three general bank-material types. The spatial distribution of the monitoring sites is shown in Fig. 1.

Erosion pin method

The erosion pin technique was used as the primary point-based method for monitoring riverbank retreat throughout the four-year study period. This approach is widely applied in fluvial geomorphology to quantify local changes in bank position and enables repeated measurements at relatively high temporal resolution. Steel rods 100 cm in length and 6 mm in diameter were installed horizontally into the exposed bank profiles to a depth of 80 cm, leaving 20 cm exposed at the time of installation. At each study site, between 50 and 200 pins were installed in 10–50 vertical transects, depending on the spatial extent and heterogeneity of the bank material [7].

Measurements were conducted 6–8 times per year between 2019 and 2022, with surveys covering periods of enhanced geomorphological activity, including spring thaw, post-precipitation conditions, and periods following summer floods. Changes in the exposed length of each pin were used to quantify local bank retreat. After each measurement, the pins were reinserted to their original depth to maintain a consistent reference position throughout the monitoring period. Where local accumulation of bank material, such as scree or deposited sediment, occurred around individual pins, measurements were interpreted cautiously to distinguish actual bank retreat from temporary burial or surface accumulation [7].

The repeated erosion-pin measurements provided a temporally detailed record of bank changes at each site and enabled retreat rates to be compared among banks characterized by contrasting lithological properties. The method was particularly suitable for repeated field monitoring because of its relatively low cost, ease of application in remote terrain, and ability to detect centimetre-scale changes in bank position ([7], 2021).

Terrestrial laser scanning (TLS)

Terrestrial laser scanning (TLS) was used as a spatially continuous monitoring approach complementary to the point-based erosion-pin measurements. TLS surveys were conducted once or twice annually at each study site between 2019 and 2022, typically following periods of substantial geomorphological activity, such as high-flow events or seasonal thaw [12]. A long-range, high-resolution terrestrial laser scanner was used to acquire dense three-dimensional point clouds representing the morphology of the monitored riverbanks [28].

Scanning was performed from multiple ground stations to provide adequate coverage of the exposed bank surfaces and to minimize data gaps associated with complex bank morphology. Individual point clouds were aligned using standard point-cloud processing procedures and georeferenced using GNSS control points. Digital elevation models (DEMs) with a spatial resolution of 2.5–5 cm were subsequently generated, and successive surfaces were compared to quantify morphological changes and bank retreat [28].

The spatially continuous TLS data complemented the erosion-pin measurements by providing information on the distribution of morphological change across entire bank surfaces, including areas affected by localized undercutting, bank collapse, or heterogeneous erosion. The combined use of TLS and erosion pins therefore enabled riverbank retreat to be assessed at complementary spatial and temporal scales and allowed the consistency of retreat patterns among contrasting bank-material types to be examined using two independent monitoring approaches.

Lithological classification of bank material

The lithological characteristics of the monitored riverbanks were assessed to determine whether differences in bank material were associated with the magnitude and temporal variability of riverbank retreat. At each study site, bank material was characterized through field inspection, sediment sampling, and granulometric analysis using dry sieving ([7], 2021). Particular attention was given to the dominant grain-size characteristics, degree of material consolidation, and general structure of the exposed bank profiles.

Based on these characteristics, the monitored riverbanks were grouped into three general lithological types representing contrasting bank materials:

- Type A – fine-grained alluvial banks: predominantly composed of clay, silt, and fine sand. This group included Sites 1, 2, and 5 and represented weakly consolidated alluvial material within the investigated range of bank types.
- Type B – gravel-dominated banks: composed predominantly of medium- to coarse-grained gravel with a sandy matrix. This group included Sites 3 and 4 and represented coarser bank material than that observed at Type A sites.
- Type C – consolidated banks: represented by flysch bedrock or cemented Neogene gravels. This category included Site 6 and represented the most consolidated bank material within the adopted classification.

The classification was designed to represent the principal differences in bank material observed across the six monitoring sites rather than to establish a predefined hierarchy of erosion resistance. Consequently, lithological type was treated as a characteristic potentially controlling bank response to erosional forcing, while the observed retreat rates were allowed to vary independently among individual sites and years.

The three lithological types were subsequently used as a framework for interpreting spatial and temporal differences in riverbank retreat during the 2019–2022 monitoring period. Comparisons were performed both among individual monitoring sites and among the defined bank-material types. This approach allowed the influence of lithological characteristics to be evaluated while accounting for site-specific variability that could not be attributed solely to bank material.

The combined erosion-pin and TLS datasets were additionally used to determine whether spatial patterns of retreat associated with contrasting bank materials were consistently represented by the two monitoring approaches. Thus, the lithological classification provided a common framework for linking bank-material characteristics with observed retreat dynamics without assuming that lithology was the sole factor controlling erosion intensity.

Table 1 summarizes the lithological classification and general characteristics of bank material at each monitoring site, while Fig. 2 illustrates representative bank morphology and material characteristics across the monitored sites.

Table 1
Lithological classification and general characteristics of bank material at the monitored sites.

Site	Lithological type	Dominant bank material	General material characteristics
Site 1	A	Clay, silt, and fine sand	Fine-grained, weakly consolidated alluvium
Site 2	A	Clay, silt, and fine sand	Fine-grained, weakly consolidated alluvium
Site 3	B	Medium- to coarse-grained gravel with sandy matrix	Coarse-grained, gravel-dominated material
Site 4	B	Medium- to coarse-grained gravel with sandy matrix	Coarse-grained, gravel-dominated material
Site 5	A	Clay, silt, and fine sand	Fine-grained, weakly consolidated alluvium
Site 6	C	Flysch bedrock or cemented Neogene gravels	Consolidated material

Data analysis

Riverbank retreat data obtained from erosion pins and terrestrial laser scanning (TLS) were analyzed for each of the six monitoring sites over the four-year study period (2019–2022). Annual retreat rates were calculated separately for each monitoring method and site, and mean annual values for the four-year period were subsequently determined to characterize the overall magnitude of bank retreat.

The analysis was conducted at two complementary spatial levels. First, retreat rates were compared among individual monitoring sites to identify spatial differences and site-specific temporal variability. Second, the results were interpreted according to the three lithological types defined in Section 2.4 (Types A–C). This approach was used to examine whether sites characterized by similar bank materials exhibited comparable retreat patterns and whether differences in retreat could be related to contrasting lithological characteristics.

Because the lithological groups were represented by an unequal number of monitoring sites, with three sites classified as Type A, two as Type B, and only one as Type C, comparisons among lithological types were treated as descriptive rather than as statistically replicated tests of lithological effects. Consequently, the observed differences were interpreted as patterns associated with contrasting bank materials rather than as evidence of a direct causal relationship between lithological type and retreat rate.

Interannual variability was evaluated by comparing annual retreat rates within each monitoring site over the 2019–2022 period. Particular attention was given to the persistence or reversal of spatial patterns between consecutive years and to differences between annual and mean annual retreat rates over the four-year period. This approach allowed lithological characteristics to be considered in the context of temporal variability in erosional conditions. Lithology was therefore interpreted as a factor influencing bank susceptibility to erosion rather than as the sole determinant of retreat magnitude.

Agreement between erosion-pin and TLS measurements was evaluated independently of the lithological comparison. For each monitoring site and year, differences between TLS and erosion-pin measurements were expressed as relative percentage differences using the erosion-pin measurements as the reference:

Relative difference (%) = [(TLS – erosion pins) / erosion pins] × 100

Positive values indicate greater retreat measured by TLS, whereas negative values indicate greater retreat recorded by erosion pins. For each monitoring site, mean, minimum, and maximum relative differences were calculated to characterize the magnitude and range of disagreement between the two monitoring approaches over the four-year study period.

No predefined threshold was used to classify agreement between the two methods as acceptable or unacceptable. Instead, the magnitude and direction of the observed differences were interpreted descriptively, with particular attention given to cases showing substantial divergence between erosion-pin and TLS measurements. Where such differences occurred, they were considered in relation to the contrasting spatial characteristics of the two techniques and to field observations of localized processes, including sediment accumulation, bank undercutting, and bank collapse.

The combined analytical framework therefore addressed three complementary aspects of riverbank retreat: (i) spatial differences among monitoring sites and contrasting lithological bank types, (ii) interannual variability in retreat rates during the four-year monitoring period, and (iii) the magnitude and direction of differences between point-based erosion-pin measurements and spatially continuous TLS observations. This approach enabled lithology-dependent patterns of riverbank retreat to be examined while accounting for both site-specific variability and differences associated with the monitoring techniques.

Generative artificial intelligence tools were used only for language editing of the manuscript. They were not used to generate or analyse study data. The author reviewed all language revisions and takes full responsibility for the manuscript.

Results

Riverbank retreat measured between 2019 and 2022 showed substantial spatial and temporal variability across the six monitoring sites. Both erosion-pin and terrestrial laser scanning (TLS) measurements revealed marked differences in retreat magnitude among individual sites and among the three lithological bank types. However, the relationship between lithological classification and retreat rate was not monotonic, indicating that differences in bank material alone did not account for the full spatial variability observed during the monitoring period.

Annual retreat rates measured using both methods, together with mean annual values for the four-year period for each monitoring site, are presented in Table 2.

Table 2. Annual riverbank retreat rates and mean annual retreat over the four-year monitoring period measured using erosion pins and terrestrial laser scanning (TLS).

Site	Year	Pins	TLS
Site 1	2019	83,5	64
	2020	67,3	76,3
	2021	66,9	67,5
	2022	67,8	77
	2019-2022	71,4	71,2
Site 2	2019	84	88
	2020	79,7	92,9
	2021	75,9	68,1
	2022	86	66,2
	2019-2022	81,4	78,8
Site 3	2019	38,7	39,5
	2020	31,7	41,2
	2021	40	43,8
	2022	46,4	44,3
	2019-2022	39,2	42,2
Site 4	2019	45,9	49,1
	2020	65	60,8
	2021	62,1	63
	2022	55,9	59
	2019-2022	57,2	58
Site 5	2019	64,1	70,1
	2020	48,6	65
	2021	69,6	47,7
	2022	59,2	53,3
	2019-2022	60,4	59
Site 6	2019	70,3	77,8
	2020	89,2	75,7
	2021	82,2	81,9

	2022	60,8	88,7
	2019-2022	75,6	81

3.1. Riverbank Retreat Across Lithological Types

Mean annual retreat over the four-year period differed considerably among the six monitoring sites. Based on erosion-pin measurements, mean retreat ranged from 39.2 cm at Site 3 to 81.4 cm at Site 2. TLS measurements showed a comparable range, from 42.2 cm at Site 3 to 81.0 cm at Site 6 (Table 2).

Sites classified as Type A, representing fine-grained and weakly consolidated alluvial banks, showed relatively high but internally variable retreat rates. Mean annual erosion-pin measurements over the four-year period ranged from 60.4 cm at Site 5 to 81.4 cm at Site 2, while corresponding TLS values ranged from 59.0 to 78.8 cm. When averaged across the three Type A sites, mean annual retreat over the four-year period was approximately 71.1 cm based on erosion pins and 69.7 cm based on TLS.

Type B sites, characterized by medium- to coarse-grained gravel with a sandy matrix, showed consistently lower retreat rates than the Type A sites. At Site 3, mean annual retreat over the four-year period amounted to 39.2 cm based on erosion pins and 42.2 cm based on TLS, whereas at Site 4 the corresponding values were 57.2 and 58.0 cm. The average across the two Type B sites was therefore approximately 48.2 cm for erosion pins and 50.1 cm for TLS.

Site 6, the only site classified as Type C and characterized by consolidated material, displayed high retreat rates despite its contrasting lithological characteristics. Mean annual retreat over the four-year period reached 75.6 cm based on erosion-pin measurements and 81.0 cm based on TLS. Thus, retreat at Site 6 was substantially greater than at both Type B sites and was within the range observed for the fine-grained Type A sites.

Overall, the lithological groups exhibited distinct retreat patterns, with Type B sites showing the lowest multi-year retreat rates, while both Type A sites and the single Type C site showed substantially greater retreat. The results therefore did not indicate a simple progressive decrease in retreat with increasing material consolidation. Instead, considerable variability occurred both among lithological types and among individual sites within the same lithological category.

3.2. Interannual Variability in Riverbank Retreat

Annual retreat rates varied throughout the four-year monitoring period at all six sites (Table 2; Fig. 3). The magnitude of interannual variability differed among sites, and no single year was characterized by consistently high or low retreat across the entire study area.

At Site 1, erosion-pin measurements were highest in 2019 (83.5 cm) and remained relatively stable between 2020 and 2022, ranging from 66.9 to 67.8 cm. TLS measurements showed a different annual pattern, with the highest retreat recorded in 2022 (77.0 cm). Site 2 maintained relatively high retreat

throughout the monitoring period, with erosion-pin measurements ranging from 75.9 to 86.0 cm and TLS measurements ranging from 66.2 to 92.9 cm.

Site 3 consistently exhibited the lowest retreat rates among the monitored sites. Erosion-pin measurements ranged from 31.7 cm in 2020 to 46.4 cm in 2022, while TLS values ranged from 39.5 to 44.3 cm. Site 4 showed greater retreat than Site 3, with the highest values recorded in 2020–2021 by both monitoring approaches.

At Site 5, substantial differences occurred between individual years and between the two monitoring techniques. Erosion-pin measurements ranged from 48.6 cm in 2020 to 69.6 cm in 2021, whereas TLS measurements ranged from 47.7 cm in 2021 to 70.1 cm in 2019. Site 6 also displayed pronounced interannual variability. Erosion-pin measurements reached their maximum in 2020 (89.2 cm) and minimum in 2022 (60.8 cm), whereas TLS recorded its highest value in 2022 (88.7 cm).

Despite these annual fluctuations, several broader spatial patterns persisted over the four-year period. Site 3 remained characterized by comparatively low retreat, while Sites 1, 2, and 6 generally exhibited relatively high retreat rates. At the same time, differences in the timing and magnitude of annual maxima demonstrate that short-term variations were strongly site-specific.

Figure 3. Annual riverbank retreat rates measured using erosion pins and terrestrial laser scanning (TLS) at the six monitoring sites during 2019–2022.

Comparison of erosion-pin and TLS measurements

The two monitoring approaches generally produced similar mean annual retreat rates over the four-year period, although larger differences occurred in individual years. At the site level, mean relative differences between TLS and erosion-pin measurements ranged from −3.0% at Site 2 to +10.3% at Site 6 (Table 3). Sites 1, 4, and 5 showed particularly small differences in their multi-year mean values, indicating similar estimates of cumulative retreat despite occasional year-to-year discrepancies.

The magnitude of disagreement was substantially greater for individual annual measurements. Minimum relative differences ranged from −31.5% at Site 5 to −4.5% at Site 3, while maximum positive differences ranged from +7.0% at Site 4 to +45.9% at Site 6. The largest ranges between negative and positive relative differences occurred at Sites 5 and 6, indicating that the direction of the difference between the two methods varied between years.

Table 3. Mean, minimum, and maximum relative differences between TLS and erosion-pin measurements at the monitored sites.

Site	mean	min	max
Site 1	1.1	-23.4	13.6
Site 2	-3.0	-23.0	16.6
Site 3	9.3	-4.5	30.0
Site 4	1.8	-6.5	7.0
Site 5	0.4	-31.5	33.7
Site 6	10.3	-15.1	45.9

Although annual measurements occasionally diverged substantially, the mean annual retreat estimates over the four-year period obtained using erosion pins and TLS remained relatively similar at most sites. Importantly, both monitoring approaches identified the same broad spatial pattern: comparatively low retreat at the Type B sites and substantially greater retreat at several Type A sites and at the Type C site. Thus, differences between the two methods affected the magnitude of individual annual estimates more strongly than the overall spatial pattern observed over the full monitoring period.

Discussion

Riverbank retreat differed markedly among sites with contrasting bank materials, but the pattern was not a simple function of material consolidation. The two Type B sites, dominated by medium- to coarse-grained gravel with a sandy matrix, had the lowest mean annual retreat over the four-year period. Higher values occurred at the fine-grained Type A sites and at Site 6, which represented the consolidated Type C material. Lithology therefore appears to shape bank response without accounting for the full range of retreat observed among individual sites.

This pattern agrees with studies that describe bank retreat as the product of interacting material properties and external forcing rather than bank material alone [14,9]. Zhao et al. [14] emphasized the coupled roles of hydraulic, geotechnical, and subaerial mechanisms, whose relative importance changes through time. Hydrological conditions can also alter bank strength; Deng et al. [13], for example, documented reductions in bank-soil cohesion associated with groundwater-level changes. Even relatively resistant materials may therefore retreat rapidly when pore-water conditions, hydraulic forcing, or bank geometry favour instability.

The relatively high retreat at the Type A sites is consistent with the weakly consolidated character of their fine-grained alluvium. Banks dominated by clay, silt, and fine sand can be affected by both hydraulic erosion and subaerial processes, especially when repeated wetting and drying or freeze-thaw activity weakens exposed material [16,11,18,17,19,7]. Carpathian studies have shown that frost-related processes can loosen and disintegrate bank material and make it more susceptible to subsequent removal [16,17,7]. At Sites 1 and 2, the observed retreat is thus compatible with a combination of material susceptibility and temporally variable erosional forcing.

The Type B sites behaved differently. Site 3 had the lowest mean annual retreat in the dataset (39.2 cm from erosion pins and 42.2 cm from TLS), whereas Site 4 reached 57.2 and 58.0 cm, respectively. The difference between these two sites, despite their assignment to the same lithological category, shows that broad material classes do not produce uniform responses. Grain arrangement, matrix content, bank geometry, local hydraulics, and individual erosional events may all contribute to the observed variation.

Site 6 is especially informative in this respect. Although it represents the most consolidated material in the adopted classification, its mean annual retreat was high: 75.6 cm from erosion pins and 81.0 cm from TLS. These values exceeded those at both Type B sites and fell within the range recorded for Type A. In this dataset, greater consolidation was therefore not associated with systematically lower retreat.

The Site 6 result also separates material resistance from the retreat ultimately observed in the field. Lithological properties affect susceptibility to erosion, but displacement of the bank margin also depends on external forcing. Hydraulic erosion, river-stage fluctuations, pore-water conditions, and bank stability can interact to produce substantial retreat even where material resistance is relatively high [13,15]. Local bank geometry and basal undercutting may further promote mass failure once critical stability conditions are exceeded. The high value at Site 6 is therefore consistent with lithological resistance operating within a broader geomorphological and hydrological setting.

Taken together, the site comparisons point to a non-linear relationship between bank material and retreat. Lithology is relevant to the way a bank responds to erosional forcing, but local conditions remain important when the magnitude of retreat is considered.

Interannual variability was pronounced during the four-year monitoring period. Annual maxima did not occur at the same time at all sites, and the magnitude of change differed between consecutive years. The lack of temporal synchrony suggests that local responses to changing environmental conditions were important rather than a single regional control acting uniformly across all banks.

Seasonal and event-scale variability is particularly relevant in foothill river environments, where bank erosion may result from the combined effects of high flows, precipitation, freeze–thaw processes, and changes in bank moisture conditions [16,20,17,21,7,22,14]. Contemporary reviews emphasize that the relative importance of hydraulic erosion, subaerial weakening, and mass failure may change over time, resulting in episodic rather than uniform bank retreat (Zhao et al., 2022). The relative importance of these processes can vary among years and among sites. Consequently, a bank that experiences limited retreat during one year may undergo considerably greater morphological change during another year if local hydraulic or meteorological conditions favour undercutting, material weakening, or mass failure.

The results from Site 6 provide a particularly clear example of this temporal variability. Erosion-pin measurements ranged from 60.8 cm in 2022 to 89.2 cm in 2020, whereas TLS measurements ranged from 75.7 cm in 2020 to 88.7 cm in 2022. Similarly, substantial interannual differences were observed at Site 5, where the two monitoring techniques also identified different years of maximum retreat. Such

variability indicates that annual measurements should be interpreted cautiously when assessing relationships between bank material and erosion.

The four-year monitoring period therefore provides an important advantage over short-term observations. Individual erosion events may temporarily dominate the geomorphological response of a particular bank and obscure broader spatial patterns. Multi-year observations reduce the influence of individual events and provide a more representative basis for comparing sites characterized by different bank materials. In the present study, some spatial differences remained apparent despite considerable year-to-year variability, particularly the relatively low retreat recorded at Site 3 and the generally higher retreat observed at Sites 1, 2, and 6.

Lithological characteristics and temporal forcing are therefore best considered together. The same hydrological or climatic event may produce different morphological responses depending on the condition and properties of the bank, while similar materials may retreat at different rates under different local hydraulic conditions. The observed interannual variability is consistent with this interaction between persistent bank characteristics and changing erosional forcing.

Erosion pins and TLS provided broadly comparable estimates of riverbank retreat when considered over the complete four-year monitoring period. The similarity of multi-year mean values was particularly evident at Sites 1, 4, and 5, where the mean relative differences between the two approaches were small. At the same time, considerably larger discrepancies occurred for individual annual measurements, with relative differences ranging from −31.5% to +45.9% across the dataset.

Erosion pins record change at predefined points and can be measured frequently, making them useful for local and short-term observations [10,23,24]. They may, however, miss changes between measurement locations. TLS samples a much larger proportion of the bank surface in three dimensions [28,25,26,27], allowing localized undercutting, irregular retreat, and bank collapse to be captured. Its lower survey frequency means that several processes occurring between scans may be represented by a single surface change.

For this reason, disagreement between the methods should not automatically be treated as measurement error. A bank failure between erosion-pin positions can strongly affect a TLS-derived surface while producing a smaller signal in the point-based dataset. Conversely, a localized change around an individual pin may not represent the broader bank surface.

The larger annual discrepancies, compared with the relatively close four-year means, support this interpretation. Despite year-to-year differences, both methods reproduced the main spatial pattern: lower retreat at Type B sites and higher retreat at several Type A sites and at Site 6. The methods thus contribute different, complementary information rather than interchangeable measurements of exactly the same spatial and temporal signal.

From a practical perspective, erosion pins are inexpensive, straightforward to deploy, and suitable for frequent measurements at remote sites. TLS requires specialized equipment and processing but adds

detailed spatial information on morphological change. Using both methods combines temporal resolution with a more complete representation of bank-surface complexity.

Bank material helps explain spatial differences in retreat, but the high value recorded at the consolidated Type C site shows that lithological class alone cannot account for retreat magnitude. Local geomorphology and hydraulic conditions must also be considered.

Retreat also varied considerably from year to year. A single season could therefore give a different picture depending on when measurements were made. The four-year record made recurring spatial contrasts easier to distinguish from short-lived fluctuations.

Several limitations constrain the interpretation. The lithological categories were represented unequally: three Type A sites, two Type B sites, and only one Type C site. Site 6 therefore cannot be treated as representative of consolidated riverbanks in general, and comparisons among the three types remain descriptive rather than statistically replicated estimates of lithological effects.

The material classification is also broad. Field observations, sediment sampling, and granulometric analysis identified the principal differences among sites, but other properties relevant to bank stability were not quantified independently. Their individual contributions to retreat cannot therefore be separated with the present dataset.

A further limitation arises from the different spatial and temporal scales represented by erosion pins and TLS. Exact correspondence is not expected during localized collapse or heterogeneous surface change. At the same time, this difference is useful: when applied together, the methods reveal aspects of bank response that either technique alone may miss.

Future work would benefit from replicated sites within each lithological category and direct measurements of additional material, hydrological, and hydraulic properties. Such datasets would allow the respective roles of lithology, bank geometry, flow conditions, and event-scale forcing to be tested more explicitly.

Conclusions

Four-year monitoring at six sites showed marked spatial and interannual variability in riverbank retreat. Gravel-dominated Type B banks had the lowest multi-year retreat, whereas higher values occurred at the fine-grained Type A sites and at Site 6, the only consolidated Type C site. The Site 6 result shows that greater material consolidation does not necessarily correspond to lower retreat under field conditions.

Lithology should therefore be treated as one component of bank susceptibility and interpreted together with local geomorphological conditions and erosional forcing. Erosion pins and TLS identified broadly consistent multi-year spatial patterns, although individual annual estimates sometimes differed because the methods sample bank change at different spatial and temporal scales.

The unequal replication of lithological types, particularly the single Type C site, limits generalization beyond the monitored banks. Studies covering more sites within each lithological group, together with direct measurements of material properties and hydrological and hydraulic conditions, would allow the contribution of bank resistance to be separated more clearly from event-scale forcing.

Declarations

Funding: This research received institutional funding as part of the statutory research activities of the University of the National Education Commission, Krakow, Poland.

Author contributions: K.A. conceived and designed the study, conducted the fieldwork and data collection, performed the data analysis and interpretation, prepared the figures and tables, and wrote and revised the manuscript. K.A. read and approved the final manuscript.

Data availability: The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests: The author declares no competing interests.

References

1. Thorne, C. R. Processes and mechanisms of river bank erosion. In Gravel-Bed Rivers (eds. Hey, R. D., Bathurst, J. C. & Thorne, C. R.), 227–272 (Wiley, 1982).
2. Lawler, D. M., Thorne, C. R. & Hooke, J. M. Bank erosion and instability. In Applied Fluvial Geomorphology for River Engineering and Management (eds. Thorne, C. R., Hey, R. D. & Newson, M. D.), 137–172 (Wiley, 1997).
3. Abernethy, B. & Rutherfurd, I. D. Where along a river's length will vegetation most effectively stabilise stream banks? *Geomorphology* **23**, 55–75 https://doi.org/10.1016/S0169-555X(97)00089-5 (1998).
4. Couper, P. R. & Maddock, I. P. Subaerial river bank erosion processes and their interaction with other bank erosion mechanisms on the River Arrow, Warwickshire, UK. *Earth Surf. Process. Landf.* **26**, 631–646 https://doi.org/10.1002/esp.212 (2001).
5. Hooke, J. M. An analysis of the processes of river bank erosion. *J. Hydrol.* **42**, 39–62 https://doi.org/10.1016/0022-1694(79)90005-2 (1979).
6. Couper, P., Scott, T. & Maddock, I. Insights into river bank erosion processes derived from analysis of negative erosion-pin recordings: observations from three recent UK studies. *Earth Surf. Process. Landf.* **27**, 59–79 https://doi.org/10.1002/esp.285 (2002).
7. Augustowski, K. & Kukulak, J. Rates of frost erosion in river banks with different particle size (West Carpathians, Poland). *Geogr. Fis. Din. Quat.* **40**, 5–17 https://doi.org/10.4461/GFDQ.2017.40.1 (2017).
8. Augustowski, K. & Kukulak, J. The role of frost processes in the retreat of river banks. *Water* **13**, 1812 https://doi.org/10.3390/w13131812 (2021).

9. Bera, B., Ghosh, S. & Sarkar, S. Field based inventory of river bank erosion susceptibility model (BESI) of Raidak-II river in the Himalayan foreland basin. *Phys. Geogr.* **45** https://doi.org/10.1080/02723646.2023.2261180 (2023).
10. Wolman, M. G. Factors influencing erosion of a cohesive river bank. *Am. J. Sci.* **257**, 204–216 https://doi.org/10.2475/ajs.257.3.204 (1959).
11. Glinicki, M. Mechanika gruntów. *Mechanika Gruntów* (Wydawnictwa Politechniki Białostockiej, 1983).
12. Kukulak, J., Augustowski, K. & Olszak, J. Factors affecting the rates and modes of landslide colluvium removal in river channels of Podhale (Western Carpathians). *Water* **14**, 3577 https://doi.org/10.3390/w14213577 (2022).
13. Deng, S., Xia, S., Zhou, M., Zhou, Y., Liu, X. & Li, Z. Riparian groundwater level variation and its impacts on bank erosion in the Middle Yangtze River. Water Resour. Res. 58, e2022WR032354. https://doi.org/10.1029/2022WR032354
14. Zhao, K. et al. A review on bank retreat: mechanisms, observations, and modeling. Rev. Geophys. 60, e2021RG000761. https://doi.org/10.1029/2021RG000761
15. Zhou, Y., Xia, J., Deng, S. & Han, Z. Bank erosion under the impacts of hydraulic erosion, river stage change and revetment protection in the Middle Yangtze River. *Geomorphology* **448**, 109043 https://doi.org/10.1016/j.geomorph.2023.109043 (2024).
16. Vallejo, L. E. Mechanics of the stability and development of the Great Lakes coastal bluffs. PhD thesis, University of Wisconsin–Madison (1977).
17. Hohenthal, J., Alho, P., Hyyppä, J. & Hyyppä, H. Laser scanning applications in fluvial studies. *Prog. Phys. Geogr.* **35**, 782–809 https://doi.org/10.1177/0309133311414605 (2011).
18. Pilarczyk, K. W. et al. Control of bank erosion in the Netherlands: state-of-the-art. In Proc. Hydraulics Engineering Conference, ASCE, New Orleans, 1–32 (1989).
19. Wyżga, B., Zawiejska, J., Radecki-Pawlik, A. & Hajdukiewicz, H. Environmental change, hydromorphological reference conditions and the restoration of Polish Carpathian rivers. *Earth Surf. Process. Landf.* **37**, 1213–1226 https://doi.org/10.1002/esp.3273 (2012).
20. Bertrand, F. Fluvial erosion measurements of streambank using photo-electronic erosion pins (PEEP). PhD thesis, University of Iowa (2010).
21. Higson, J. L. & Singer, M. B. The impact of the streamflow hydrograph on sediment supply from terrace erosion. *Geomorphology* **248**, 475–488 https://doi.org/10.1016/j.geomorph.2015.07.037 (2015).
22. Tabunshchik, V., Gorbunov, R. & Gorbunova, T. Anthropogenic transformation of the river basins of the northwestern slope of the Crimean Mountains (the Crimean Peninsula). *Land* **11** (2022). https://www.researchgate.net/publication/365765967_Anthropogenic_Transformation_of_the_River_Basins_of_the_Northwestern_Slope_of_the_Crimean_Mountains_The_Crimean_Peninsula
23. Saynor, M. J., Erskine, W. D. & Evans, K. G. Bank erosion in the Ngarradj catchment: results of erosion pin measurements between 1998 and 2001. Supervising Scientist Report 176 (Supervising Scientist, 2003).

24. Watson, A. J. & Basher, L. R. Stream bank erosion: a review of processes of bank failure, measurement and assessment techniques, and modelling approaches. Landcare ICM Report No. 2005-2006/01, Motueka Integrated Catchment Management Programme Report Series, 1–32 (Landcare Research, 2006).
25. Lague, D. Terrestrial laser scanner applied to fluvial geomorphology. In Remote Sensing of Geomorphology (eds. Tarolli, P. & Mudd, S. M.) Developments in Earth Surface Processes **23**, 231–254 (Elsevier, 2020).
26. Cebulski, J. Współoddziaływanie osuwisk i koryt rzecznych w polskich Karpatach fliszowych. PhD thesis, Polska Akademia Nauk, Kraków (2021).
27. Cebulski, J. Impact of river erosion on variances in colluvial movement and type for landslides in the Polish Outer Carpathians. *Catena* **217**, 106415 https://doi.org/10.1016/j.catena.2022.106415 (2022).
28. Myers, D. T., Rediske, R. R. & McNair, J. Measuring streambank erosion: a comparison of erosion pins, total station, and terrestrial laser scanner. *Water* **11**, 1846 https://doi.org/10.3390/w11091846 (2019).

Figures

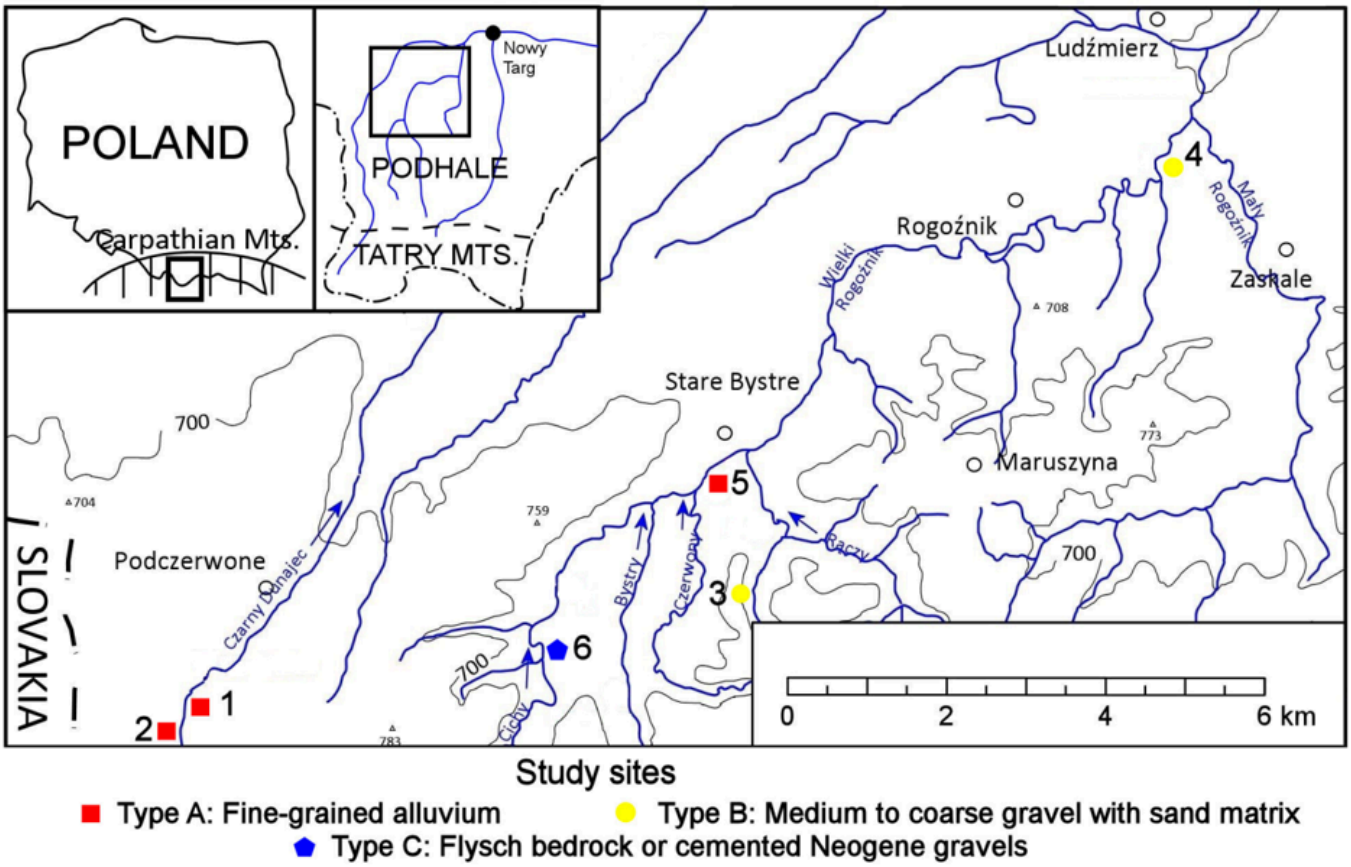


Figure 1

Location of the six riverbank monitoring sites along the Czarny Dunajec, Molczy, Cichy, and Wielki Rogoźnik rivers in the Podhale region, southern Poland.

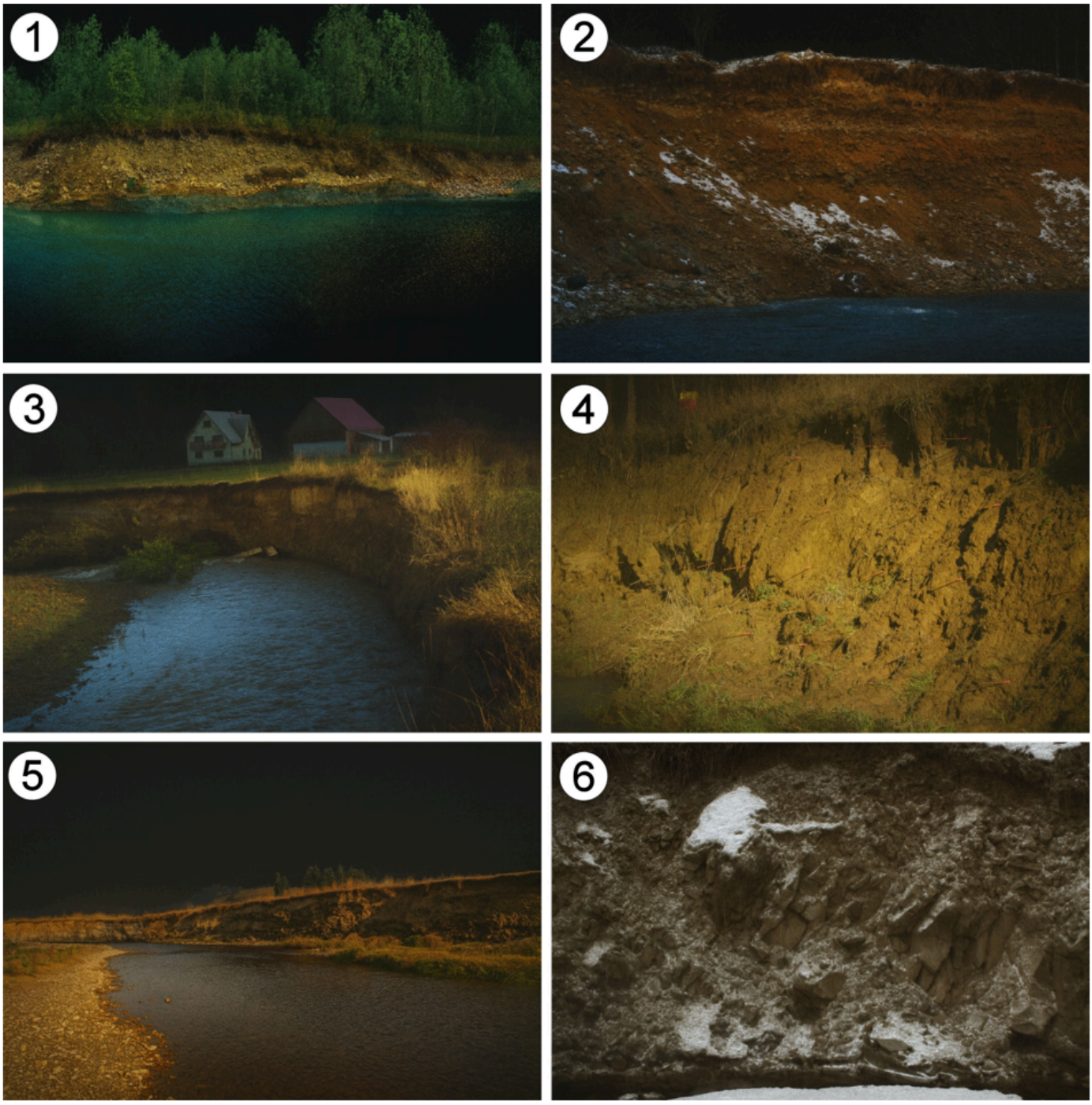


Figure 2

Examples of riverbank materials and morphological characteristics at the monitored study sites representing the three lithological types (A–C).

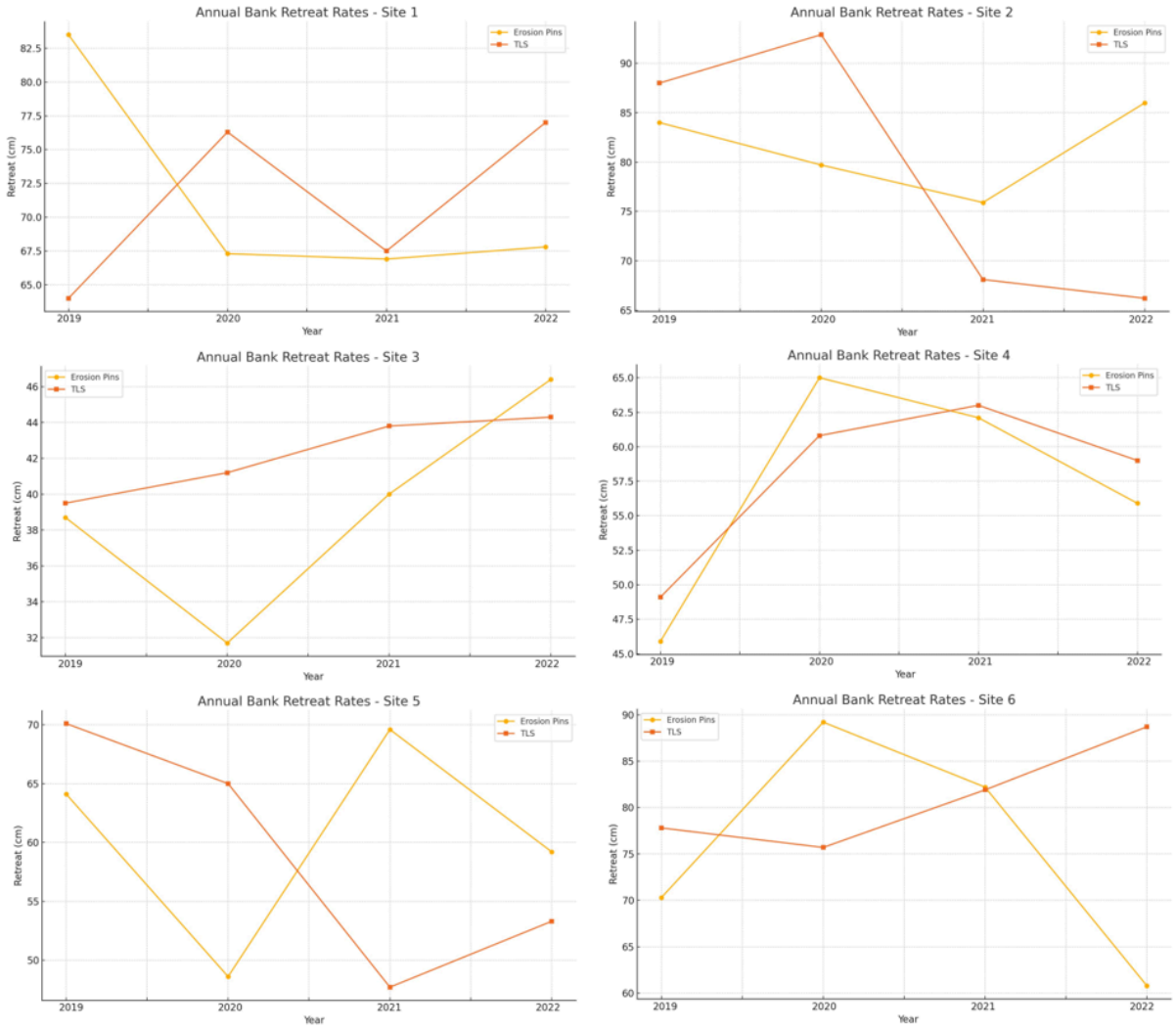


Figure 3

Annual riverbank retreat rates measured using erosion pins and terrestrial laser scanning (TLS) at the six monitoring sites during 2019–2022.