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The intensity of erosion and its causes on the shores of artificial reservoirs: The role of slope gradient and vegetation cover

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ABSTRACT

Kaunas Reservoir, the largest artificial body of water in Lithuania, has been characterized by active coastal erosion processes since its formation, which are currently exacerbated by more intense precipitation, water level fluctuations, and recreational use. The aim of the study was to assess the condition of the Kaunas Reservoir shores and to determine the differences in erosion intensity in different sections, linking them to slope gradient, vegetation cover, and recreational activity characteristics. The research was conducted at three study sites (1–3) along the coast; at each site, the height of the shore, slope gradient, vegetation cover, signs of erosion, and recreational load were measured in ~50 m sections (GPS coordinates, photo documentation). The highest vulnerability was found at site 1: slopes were 2.6–5.6 m, gradients were often >30° (up to ~42°), vegetation cover was 11–28%; 5 out of 10 sections were classified as class 3, the rest were identified as class 2. In the third location, the banks were stable: low to medium (slopes 10–20°), cover 68–85%, the shore is protected by continuous strips of reeds; all sections were class 0–1. Class 1 prevailed in the second location (80% of sections), while class 2 was recorded in only two locations, where the cover has decreased to ~56–58%, the slope was ~19–19.5°, and the height was ~2.4–2.5 m. A pattern emerged: when the slope is >30° and the cover is <30%, there is a transition to class 3; when the slope is <20° and the cover is >60–65%, the classes that remain are usually 0–1. Recreational activity (informal access paths, campfire sites) acts as a catalyst where the cover has already weakened. It is recommended to apply combined measures in the first place (bank toe protection, biotechnical slope reinforcement, sowing and mulching, surface water drainage, access control), local restoration of the cover and closure of unofficial access points in the second place and thirdly a conservation regime, preserving the integrity of reed beds and avoiding new access to water. Regular monitoring (≥2 times per year) would allow distinguishing episodic hydrometeorological impacts from constant recreational loads and assessing the effectiveness of the applied measures.

Keywords: Kaunas Reservoir, shoreline erosion, slope stability, recreational impacts, vegetation cover.

INTRODUCTION

Kaunas Reservoir is the largest artificial body of water in Lithuania, formed by damming the Nemunas River in 1959. This reservoir, with a water surface area of about 63.5 km² and a coastline of more than 200 km, is characterized by complex relief, diverse sediment structure, and high landscape contrast. Since their formation, the shores of the lagoon have been dynamic: affected by hydrodynamic processes, ice drift, precipitation, and groundwater, they are constantly changing, and in some places, active abrasion is taking place.

This study assessed the condition of the Kaunas Reservoir shores based on key geomorphological and surface indicators that directly determine slope stability. In recent years, erosion processes have been exacerbated by intensifying rainfall and greater seasonal water level fluctuations. Recreation activities – informal access paths, campfires, trampling of paths – create an additional load, resulting in the loss of vegetation cover, the formation of gullies, and the exposure of plant roots. For these reasons, the shores of the Kaunas Reservoir are considered some of the most sensitive parts of the ecosystem, requiring regular monitoring and repeated measurements.

Three coastal sections located a short distance from the city of Kaunas were selected for the study. This location was chosen due to the growing development of surrounding residential areas, increasing population, and recreational load; the most significant changes in human impact are expected here in the upcoming years. This selection allows assessing the current situation and establishing a baseline for future monitoring.

The study was conducted at three sites of varying vulnerability, located along the coastline and marked 1–3. At each site, the height of the coastline and the slope gradient were measured in 50 m long sections, the vegetation cover was assessed, visual signs of erosion and recreational activity were recorded, and reed beds were marked; coordinates were recorded using GPS and photographs were taken. This work deliberately did not inventory the species composition of trees – the focus was on the factors directly related to slope stability and practical management solutions.

The aim of the study was to assess the condition of the Kaunas Reservoir coastline and to determine the differences in the intensity of coastal erosion at different study sites, linking them to slope gradient, vegetation cover, and recreational impact. The objectives were as follows:

1. Measure the height of the shore and the slope gradient, assess the vegetation cover and assign erosion classes to individual sections according to uniform criteria.
2. Establish the correlation between slope gradient, vegetation cover, and erosion class, as well as compare these relationships between the three study sites (1–3).
3. Assess the correlation between reed beds and signs of recreational activity (paths, campfire sites, access to water) as well as slope stability.
4. Present priority directions for coastal management and monitoring based on the identified patterns, taking into account the increasing recreational load on the city.

BACKGROUND

Shoreline (bank) erosion is one of the most important problems affecting the shores of water bodies, directly influencing the stability of ecosystems, biological diversity, and human activity. It manifests itself in various forms in different regions, ranging from slow slope movements to sudden landslides caused by both natural and anthropogenic factors. Erosion processes are closely related to the hydrological regime, sediment composition, vegetation cover, and land use intensity (Hughes, 2016; Poesen, 2018). In the context of Lithuania, this problem is particularly acute in artificial water bodies, such as the Kaunas Reservoir, where the shores are characterized by uneven geological structure, complex relief, and intense human impact.

In recent decades, the problem has been exacerbated by global factors such as climate change, which manifests itself in heavier rainfall, stronger winds, and greater seasonal fluctuations in water levels. Studies show that these phenomena accelerate coastal erosion, increase sediment transport, and alter coastal morphodynamical processes (Wierzbicki et al., 2025; Yasarer and Sturm, 2016). As a result, traditional engineering measures are not always able to adapt to the growing impact, and, therefore, more attention is being paid to sustainable, nature-based solutions.

Hydraulic structures play an important role in the dynamics of coastal changes. In the lower reaches of the Vistula, it has been found that the Włocławek dam retains a large proportion of suspended particles, so that the water flowing below the dam becomes "cleaner" and its erosive power increases, resulting in a rearrangement of erosion and accumulation zones. Other studies have shown that structures such as bridges, by changing the flow field and turbulence, have a significant impact on the sediment balance (Szatten et al., 2018). Similar processes have been observed in the Rabo River in southern Poland – after the straightening of the channel and the reinforcement of the banks, some sections stabilized, but lateral erosion intensified in the adjacent areas. Therefore, the authors emphasize that it is necessary to assess the entire section, rather than fragments (Łapuszek and Wolak, 2019).

Natural morphodynamical processes also have a significant impact on bank erosion. In Slovakia, it has been found that on the outer side of a meander (in a concave bend), bank damage increases when the bend is sharper, i.e., when the radius of curvature is smaller than the width of the channel. In addition, the steeper the slope, the more intense the erosion processes, so the slope can be considered a suitable indicator for classifying the intensity of erosion (Jakubis and Jakubisova, 2022). A similar meander-controlled pattern has been documented for the middle Narew River, where long-term planform analysis showed persistent right-bank bend erosion and lateral channel migration, with only limited net change in overall channel position over two centuries (Grabińska et al., 2014).

Vegetation has a dual effect on slope stability. Many studies emphasize that mixed forests, denser grass cover, or shrubbery are more effective at protecting slopes from erosion than single-species coniferous forests, as the root system strengthens the soil and retains surface runoff (Pauliukevičius, 1995; Tisserant et al., 2021). On the other hand, the Walanae River (Indonesia) has shown that although bamboo roots increase slope resistance to sliding, the large mass of above-ground biomass on static slopes can reduce stability, so bioengineering measures are only effective if the vegetation is properly maintained (Pertiwi et al., 2021). Recent studies confirm that nature-based solutions – bio fascines, willow stakes, and live stakes – are sustainable alternatives to engineering measures that also increase biodiversity and ecosystem resilience (Paxton et al., 2024).

Recreational activities are also an important factor. Intensive boating, tourist flows, and infrastructure development cause mechanical erosion of slopes: grass cover is trampled, roots are exposed as well as paths and campfire sites are formed (Lemieux et al., 2024). This changes not only the stability of the shores, but also the structure of ecosystems and the services they provide. Studies have shown that natural vegetation can effectively reduce the impact of recreation (Symmank et al., 2020), but this requires balancing environmental protection measures with social and economic interests (van Rees et al., 2023).

Studies of the Kaunas Lagoon coastline have been conducted in Lithuania before (e.g., Černulienė and Semaškienė, 2016), identifying sensitive areas and emphasizing the role of vegetation cover. In this work, insights from the literature were used as a theoretical basis for assessing the situation in 2025, without making a quantitative comparison with the previous data. The observations obtained and the methodology applied (recording of the shore height, signs of erosion, vegetation, and recreational traces) form a reference point for future comparative analyses when more shore observations have been accumulated over several years.

MATERIALS AND METHODS

Research was conducted on the shores of the Kaunas Lagoon to assess the intensity of coastal erosion processes and the factors determining them (Figure 1).

Three study sites were selected to represent different shoreline conditions: Site 1 – strongly eroded and subject to intensive recreational use, Site 2 – moderately impacted, and Site 3 – relatively stable, serving as a reference. At each site, representative shoreline stretches of ~50 m was delineated (10 sections at Site 1, 8 at Site 2, and 10 at Site 3).

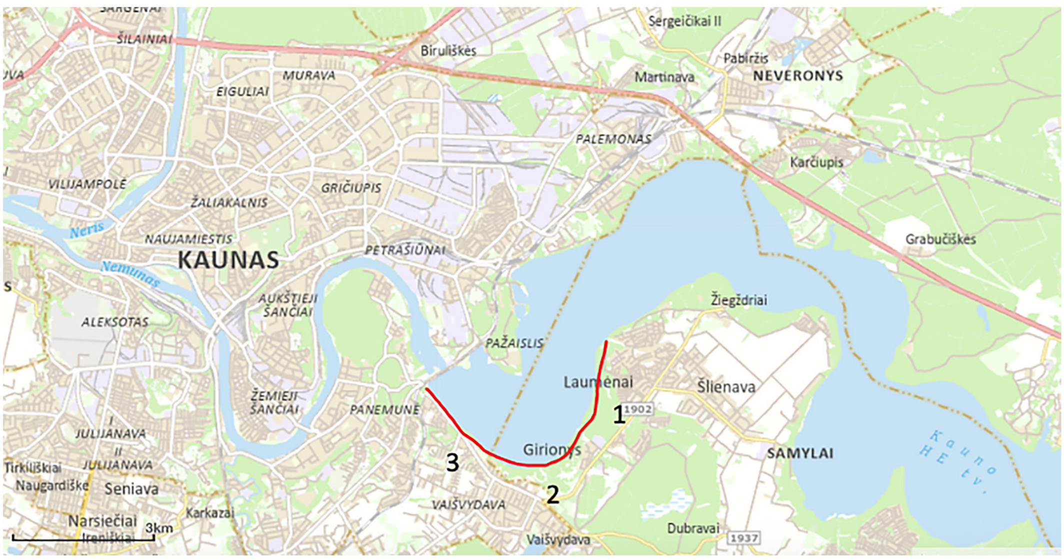

Figure 1. Location of study sites along the Kaunas Reservoir shoreline (1–3)

At each section, the following parameters were recorded:
- Bank height, measured from the toe to the crest and grouped as low (≤1.5 m), medium (1.5–3 m), or high (>3 m).
- Slope gradient, calculated from repeated measurements of vertical height (h) and horizontal distance (d) using the formula 100·h/d; mean uncertainty per section was ~±0.5%. Gradients were classified as gentle (≤27%), moderate (27–58%), or steep (>58%).
- Vegetation cover, visually estimated in 5% increments, distinguishing grass and shrub layers; reed belts were noted as present/absent.
- Signs of erosion, including root cavities, fresh slumps, exposed roots, and bank toe undercutting.
- Recreational traces, such as trampled paths, slope trampling, and illegal campfire sites, which were described and photo documented.

Natural processes (wave action, ice drift, groundwater washouts, wind erosion) were also noted where present, but their intensity was not quantified in this study.

Each ~50 m section was assigned to an erosion class according to two main indicators: vegetation cover and visible erosion features. The following scale was applied:
- 0 – undisturbed (≥96% cover; no or negligible disturbance),
- 1 – slightly disturbed (66–95% cover; isolated erosion marks),
- 2 – moderately disturbed (36–65% cover; localized slumps, toe erosion),
- 3 – intensively eroded (≤35% cover; frequent or continuous collapses, root cavities >30 cm, obvious toe erosion).

All measurements were carried out at comparable water levels. GPS coordinates and photo documentation ensured repeatability and traceability of results.

To separate natural drivers from recreational disturbance, the authors relied on spatial patterns of indicators: natural processes typically left continuous traces along broader shoreline stretches (e.g. wave undercutting, ice-scour), whereas recreational signs were localized at specific access points (paths, campfire sites). This approach allowed a qualitative separation of natural and recreational impacts; however, hydrodynamic drivers were not measured quantitatively.

RESULTS

After assessing the shores of the Kaunas Reservoir at research sites 1, 2, and 3, it was determined that shore erosion processes are active and occur with varying intensity.

The shore heights, erosion classes, and vegetation cover indicators for research site 1 are presented in Table 1. The most pronounced coastal erosion processes were recorded in these sections. According to the measurements of the sections, the coastal height varies from 2.6 to 5.6 m (average ~4.0 m), so medium and high slopes prevail, with some places even higher (Figure 2). The slope gradient varies from 27 to 42°, so erosion classes 2–3 were determined in most sections.

The erosion classes were distributed as follows: class 3 was found in five out of the ten sections whereas class 2 appeared in the remaining five; classes 1 or 0 were not recorded at all (typical images – Figure 2). This means that this section is

Table 1. Characteristics of shoreline sections at Study Site 1

Shoreline section	Bank height (m)	Slope angle (°)	Erosion class	Vegetation cover (%)
1	2.6	29	2	28
2	3.1	31.5	2	28
3	3.7	34	3	23
4	4.2	32	2	26
5	4.6	37	3	23
6	4.9	38	2	25
7	3.3	30	2	27
8	2.9	27	3	11
9	5.2	41	3	13
10	5.6	42	3	24

Figure 2. Typical examples of shoreline erosion at study site 1

dominated by moderate and intense erosion, with almost no stable slopes.

The vegetation cover at this study site is sparse and fragmented. Grass and shrub cover encompasses only 11–28% of the slope area (average ~23%), leaving a large part of the soil exposed to erosion. Vegetation cover indicators are lowest in intensively eroded sections (e.g., 11% in section 8, 13% in section 9), which is consistent with the field signs – erosion at the foot of the slope and root niches – and indicates that the vegetation cover layer no longer performs a protective function here. Class 3 is found not only on the highest slopes (>5 m), but also on slopes of medium height (~3.7 m) and a gradient of about 34°, where the cover is significantly reduced (about 20–25%). Meanwhile, Class 2 sections more often coincide with slightly higher percentages of cover (25–28%) or slightly lower slopes (2.6–3.3 m), which leads to the conclusion that the amount of vegetation cover, together with relief parameters, is decisive for stability.

From a procedural point of view, erosion in this study site is likely to be caused by several factors at once. Higher and steeper slopes are mechanically less stable, and low percentage of grass cover does not ensure surface reinforcement, so heavy rainfall and the associated surface runoff easily initiate washouts and root pockets. In addition, the impact of open water areas causes waves to erode the foot of the slope, weakening its support, which explains why class 3 is also found where the slope height is not maximum, but vegetation cover is poor. The process is further exacerbated by heavy rainfall, which causes the saturated soil to become unstable. In some places, groundwater washouts are also observed, creating voids within the slope. Such conditions may eventually lead to landslides.

Recreational activities have a significant impact on the destabilization of the banks. There are gazebos and recreational infrastructure in this area, so visitors' flow is high. Intensively trodden paths, campfire sites, and damage to grass cover further promote erosion. In some places, the soil has completely lost its surface layer, so rainwater easily washes away the sand, deepening the slope grooves and forming gullies. Such places become erosion hotspots that are rapidly expanding.

In summary, several unfavorable factors coincide at the first study site, namely medium to high slope height, very poor vegetation cover, and anthropogenic disturbance. Due to this combination, half of the coastal sections fall into the intensive disturbance (3) class, while the other half fall into the moderate disturbance (2) class. From a practical point of view, this indicates priority stabilization sites, primarily, sections with <20–25% vegetation cover, especially when the slope height is > ~4.5 m, as this is where erosion processes are most active and spread most rapidly.

The heights of the banks, erosion classes, and vegetation cover indicators at the second study site are presented in Table 2. The banks of these shores are much more stable: according to the measurements of the sections, the height of the banks varies from 1.1 to 2.5 m, and the slopes are gentle in most places. The slope in most sections is about 12–19.5°, so the hydraulic load on the slope is lower; specific estimates are presented in Table 2. The vegetation is dense and evenly distributed—the grass cover is almost continuous (56–78%, usually around 60–70%), supplemented by trees and shrubs. This root system of vegetation stabilizes the slopes and effectively inhibits washouts, so erosion is limited here (Table 2).

The distribution of erosion classes confirms this picture of stability: 80% of the sections are classified as class 1, which is slightly eroded, while class 2 is found in only two places – where the vegetation cover has decreased to ~56–58% and the height of the bank is greater (about 2.4–2.5 m). This shows that even on flat terrain,

localized reduction in vegetation cover can weaken the resistance of slopes, but the overall appearance of the shores remains stable (Table 2).

Despite the favorable conditions, isolated anthropogenic risks have been recorded: in some places, illegal campfires and paths trodden by visitors leading directly to the slope have been identified. Such traces locally damage the grass cover and form initial erosion grooves, which, if left uncontrolled, can expand and eventually increase the intensity of erosion. This not only damages the grass cover, but can also cause the soil and roots to burn. Therefore, even relatively stable banks should be monitored, especially where the vegetation cover is reduced or where visitor flows coincide (typical images are shown in Figure 3). Such activities are incompatible with the protection regime of the regional park and indicate that education as well as visitor control in this area are insufficient.

The heights of the banks, erosion classes, and vegetation cover indicators for the three study sites are presented in Table 3. At the third study site, the banks are low and of medium height: according to the measurements taken at eight points, the bank height varies from 0.9 to 2.3 m, and the slopes are gentle in most places. Due to this morphology, the banks are less sensitive to surface runoff caused by precipitation and the effects of waves. The vegetation cover is dense and evenly distributed: grass and shrub covers 68–85% of the

Table 2. Characteristics of shoreline sections at Study Site 2

Shoreline section	Bank height (m)	Slope angle (°)	Erosion class	Vegetation cover (%)
1	1.1	12	1	78
2	1.3	13	1	74
3	1.5	14.5	1	70
4	1.7	15.5	1	68
5	1.9	16.5	1	66
6	2.0	17	1	65
7	2.2	18	1	62
8	2.4	19	2	58
9	2.5	19.5	2	56
10	2.3	18.5	1	60

Figure 3. Typical examples of shoreline erosion at study site 2

slope (usually around 70–80%), supplemented by a continuous strip of reeds along the shore, which acts as a natural breakwater and helps to stabilize the shoreline (Table 3, Figure 4).

Slopes are gentle to moderate (10–20°); all sections are in erosion class 0–1. The distribution of erosion classes confirms the picture of stability. Classes 0–1 prevail in all sections: class 0 was found in four sections (1, 3, 5, and 8), and class 1 appears in four sections (2, 4, 6, and 7). No moderately (class 2) or intensively eroded (class 3) sections were recorded. The cases where class 1 was identified usually coincide with a slightly higher shore height, about 1.8–2.3 m, and a lower than usual proportion of vegetation cover, about 68–72%, but even in these places, the reed belt cushions the waves and prevents the spread of erosion processes (Table 3).

Recreational pressure at this study site is minimal. Due to dense reeds and thickets, the shores are difficult to access, so no traces of trampled paths or campfires have been observed. This distinguishes these shores from more intensively visited areas and allows the vegetation cover as well as reed beds to perform their stabilizing function undisturbed.

Natural processes have been observed in isolated areas. Minor groundwater washouts and sand drifts have been observed, but their scale is local and does not have a significant impact on the overall condition of the banks. The low to medium slopes, abundant vegetation cover, and continuous reed belt allow the third study site to be considered one of the more stable sections of the Kaunas Lagoon. Erosion processes here are inhibited by natural barriers (vegetation and reed belt) and low recreational load.

DISCUSSION

The study data show a clear correlation between vegetation cover, relief, and erosion intensity: at the first study site, where the slopes are higher (2.6–5.6 m) and the cover is low (11–28%), classes 2–3 prevail; At the third study site, where grass cover is abundant (68–85%) and the shore is protected by a continuous strip of reeds, all sections fall into classes 0–1. At the second study site, under average conditions (56–78%), class 1 dominates, while class 2 is only recorded where the grass cover has decreased to ~56–58%. This is further confirmed by the slope gradients: at the first study site, they often exceed 30° (up to ~42°), at the third site they reach about 10–20°, and at the second site about 12–19.5°; this differentiation in gradients coincides with the erosion classification. This trend is consistent with studies showing that coastal vegetation acts as a mechanical and hydraulic filter, reducing the energy of surface runoff

Table 3. Characteristics of shoreline sections at Study Site 3

Shoreline section	Bank height (m)	Slope angle (°)	Erosion class	Vegetation cover (%)
1	1.2	12	0	78
2	1.6	16	1	72
3	0.9	8	0	85
4	1.4	14	1	74
5	1.1	12	0	82
6	1.8	18	1	70
7	2.3	20	1	68
8	1.5	15	0	80

Figure 4. Typical examples of shoreline erosion at study site 3

and the impact of waves (Gholami and Khaleghi, 2013; Tisserant et al., 2021). The shores of the third study site act as a continuous buffer zone limiting the erosion of the foot of the slope.

Where vegetation cover is sparse and slopes are steep, recreational activities become a major factor accelerating erosion. Field and model studies show that natural vegetation strips reduce the impact of waves and mitigate the effects of human disturbance – trampling, soil compaction, and water flow concentration (Symmank et al., 2020). This pattern is clearly evident from the data: at site 1, trampled paths and campfire sites coincide with class 2–3 erosion hotspots, while at site 2, where such traces are rare, class 2 is only found where vegetation cover is reduced to below ~60–65%. Both grade 2 sections at site 2 have a slope of ~19–19.5° and reduced cover, while at site 1, grade 3 areas are most often recorded when the slope is >30° and the cover is <30%.

Similar long-term effects of human activity on river morphology have been documented in the Atrak River (Iran), where land use changes and channel regulation caused significant alterations in meandering patterns and measurable bank erosion (Yamani et al., 2011).

Climatic factors exacerbate this picture. With more intense precipitation events, fluctuating water levels, and more frequent strong winds, erosion at the foot of the coast and slope washouts are accelerating, especially when there is a lack of vegetation cover (Li, Fang, 2016; Yasarer et al., 2016). Although in this study, hydrodynamic processes such as wave action and coastal currents were only identified qualitatively (e.g. traces of bank toe undercutting, ice scour), previous research on the Kaunas Reservoir has already demonstrated the importance of water level fluctuations and wave activity for shoreline stability (Žaromskis, 2001). Future monitoring should therefore include direct hydrological measurements (wave sensors, water level loggers, UAV-based surveys) to better quantify their role in shoreline erosion. Regional observations show that such conditions are becoming more frequent in Central and Eastern Europe, increasing the risk to sensitive areas (Wierzbicki et al., 2025). At study site 1, class 3 was recorded where cover was <20–25% and slope height was >4.5 m, consistent with this trend: climate fluctuations mostly affect the sites where anthropogenic disturbance has already weakened the protective function of vegetation. Recreational disturbance particularly accelerates degradation on steep slopes (>30°), as the reduction in cover quickly causes slopes to move into a higher erosion class.

Simple thresholds and corresponding actions are proposed for practical planning. When the slope is >30° and the vegetation cover is <30%, the following combination should be applied: protect the foot of the slope with a stone cover with a filter layer or a log-and-branch toe protection, reinforce the slope with oak stakes and bundles of branches, use coconut fiber mats, sow and mulch, regulate surface runoff (gutters, slope correction), and direct visitor flows – install stairs in place of ski runs, barriers, path coverings, and remove illegal campfire sites. When the slope is 20–30° and the coverage is 30–60%, the first step should be to restore the grass and shrub cover (e.g., hydroseeding, mulching), preserve or expand reed belts, close unofficial access points, and leave a few clearly marked access routes. When the slope is <20° and the cover is >60–65%, a conservation regime is applied: preserve the integrity of reed beds (do not remove, do not break up with new passages, do not mow during vegetation), do not install new access points to water, maintain paths only in designated areas, and carry out periodic monitoring (at least twice a year).

It is advisable to use UAV photogrammetry and GIS analysis for monitoring, as they allow accurate recording of changes in the coastline and microrelief of the slope, distinguishing seasonal episodes from long-term trends and quickly assessing the impact of measures (Medeiros et al., 2025).

Although the present observations were limited to the vegetation season and therefore did not capture seasonal variation, it should be noted that seasonal changes (e.g. reed die-back in autumn or reduced grass cover in early spring) may increase shoreline vulnerability. For this reason, long-term monitoring is planned, with repeated measurements at least twice a year on the same shoreline sections, supplemented by UAV photogrammetry, RTK-GNSS profiling, and the registration of water level and wave dynamics. Such an approach will make it possible to distinguish between seasonal fluctuations, episodic events, and long-term erosion trends.

Beyond the studied freshwater setting, global syntheses from muddy-coast environments show that hard, grey structures often underperform and shift erosion hot-spots, whereas well-matched nature-based solutions (NbS) can stabilize shores, restore habitat and protect people when implemented under a pragmatic governance framework (Yasmeen et al., 2024). These findings align with the authors' recommendations to combine vegetative buffers, live staking and toe protection, rather than relying solely on rigid revetments.

In summary, two factors mainly determine the stability of shorelines: the amount of vegetation cover and the slope gradient. When the cover is dense and the gradient is low, the shorelines are stable; when the cover is sparse and the gradient is high, erosion intensifies. This gives rise to three directions: at the first study site – restoration of the foot and slope together with access control; at the second study site – local hotspots (restoration of cover, closure of unofficial access points); at the third study site – maintaining the current condition, protecting reed beds and preventing new access points.

Limitations and future work

This study was based on one-season field observations and did not include a quantitative assessment of shoreline retreat rates (cm/year) or sediment transport. Hydrodynamic parameters, such as wave action and water level fluctuations were not directly measured, although their influence is recognized as important in the erosion process. In future research, UAV photogrammetry, repeated GPS surveys, and integration with hydrological monitoring data are recommended to separate the effects of natural drivers from recreational pressure and to provide long-term erosion dynamics.

CONCLUSIONS

1. The highest vulnerability was recorded at the first study site: slopes 2.6–5.6 m high, often with a gradient >30° (up to ~42°) and poor

vegetation cover (11–28%). Five out of ten sections were classified as class 3, the rest were classified as class 2; no sections were classified as class 0–1.
2. The second site was mostly stable: slopes were 12–19.5°, cover was 56–78%; 80% of sections belong to Class 1. Class 2 was found in only two places, where the cover has decreased to ~56–58% and the slope is slightly higher (about 2.4–2.5 m).
3. The third location is stable: low to medium slopes (0.9–2.3 m), slopes are 10–20°, high vegetation cover (68–85%), the shore is protected by continuous strips of reeds; all sections are Class 0–1.
4. A clear pattern emerged: when the slope is >30° and the cover is <30%, a transition to class 3 is likely; when the slope is <20° and the cover is >60–65%, class 0–1 usually remains. Recreational impacts (informal access paths, campfire sites) act as a catalyst where the cover is already weakened.
5. Management priorities: the first priority is a combination of measures – protection of the foot of the slope (stone cover with a filter or log-frog toe), slope reinforcement with live oak stakes/branch bundles, coconut fiber biomats and fiber rolls, sowing and mulching, surface water drainage, visitor flow management (stairs, barriers, path covering), and elimination of illegal campfires. In the second location, local measures are sufficient, i.e. restoration of the surface and closure of unofficial access points. In the third location, conservation regime is supposed to dominate, that is, preserving the integrity of the reed beds, not creating new access points and maintaining existing paths only in designated areas.
6. Limitations of the assessment are one season and a limited set of physical factors; for further analysis, continuous monitoring (at least twice a year) and, if possible, UAV/GIS profiling is recommended to distinguish episodic hydrometeorological events from constant recreational load.

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