



OPEN Artificial riffles as a driver of bed morphology enrichment in a trained upland river

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Artificial riffles are increasingly used in river renaturalization to stabilize incised channels and enhance habitat diversity. However, their long-term structural stability remains under-researched, particularly in reservoir-impacted systems. This study evaluates the nine-year persistence of 12 artificial and 4 seminatural riffles in the regulated upland Bóbr River (Poland) using RTK GPS field surveys, hydraulic and grain size measurements, and hydromorphological assessments (River Habitat Survey). The results demonstrate a clear divergence in evolution based on construction quality. Well-executed riffles ($n = 6$) maintained high morphological and hydraulic stability ($p > 0.05$) throughout the monitoring period (2015–2023). In contrast, poorly-executed structures ($n = 10$) underwent significant degradation, characterized by a significant increase in mean channel depth ($p = 0.037$) and flow velocity ($p = 0.014$). In these structures, the winnowing of finer fractions led to a coarsening of the substrate, with the median grain size of the riffle runs increasing from 35 mm to 78 mm, resulting in a fragmented ‘dragon’s teeth’ morphology. While artificial riffles proved to be a durable and nature-friendly alternative to traditional bed-stabilization works, their long-term success is strictly dependent on adherence to design grain size distributions (D_{50} , D_{84}) and proper substrate mixing. These findings provide critical technical benchmarks for the sustainable renaturalization of incised, gravel-bed upland rivers.

Keywords River renaturalization, Artificial riffles, Boulder ramps, Riffles reinstatement, Bóbr river, River monitoring

The alteration of riverine ecosystems by human activity is evident, with streambed homogenization emerging as compelling evidence of this impact, particularly as a consequence of channelization. This process, primarily intended for ‘flood protection’, has led to increased erosion and diminished sediment deposition in numerous rivers and streams worldwide¹.

The repercussions of these alterations extend to habitat suitability for benthic organisms, particularly as the intricate features of the streambed diminish. While sandy bottoms may still host certain species, structurally complex habitats—such as those characterized by medium-sized cobble and gravel—foster greater biodiversity and productivity among bottom-dwelling organisms².

Bed morphological diversity—the alternation of riffles and pools—creates a repeating mosaic of mesohabitats with sharp contrasts in depth, velocity, turbulence, and substrate size that strongly structure benthic and fish communities³. Riffles typically provide shallow, fast-flowing, oxygenated, coarse-grained patches, whereas pools offer deeper, lower-velocity habitats with distinct sedimentary and hydraulic environments⁴; the sequence thus sustains co-occurring but compositionally different assemblages of species and functional guilds across short distances⁴. Fish exploit this spatial heterogeneity dynamically: ontogenetic and diel/seasonal shifts in habitat use within riffle–pool sequences have been documented for salmonids and associated species, highlighting the role of alternating units as feeding, refuge, and spawning habitats across life stages⁴.

Because ecological quality assessments often rely on biotic responses, riffle habitats are frequently targeted as representative sampling units that concentrate sensitive taxa and capture changes in ecological status⁵. Channelization and river training, however, tend to simplify bed topography and disconnect channels from riparian and floodplain environments, reducing habitat heterogeneity and lateral subsidies; these practices have been linked to lower macroinvertebrate densities, richness, and biotic-index values in regulated reaches⁶. Renaturalization measures that recreate hydraulic and sediment heterogeneity—including constructed/artificial rock riffles—aim to re-establish riffle–pool structure, promote sediment sorting and oxygenation, and improve

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habitat for macroinvertebrates and riffle-associated fishes⁷. Yet, evidence syntheses show that biological responses to reach-scale habitat enhancement are often modest and context-dependent, with stronger and more consistent gains where catchment-scale stressors are also mitigated⁸; recent evaluations similarly report that constructed rock riffles can increase physical heterogeneity without corresponding biodiversity gains in streams constrained by persistent urban pressures⁹.

Consequently, the loss of riffle-and-pool channel habitats diminishes the overall diversity of streams and rivers. To address this, conservationists have developed various river renaturalization techniques. Among these, the construction of artificial riffles stands out as a widely practiced method. Although the concept has existed in the literature for forty years, its exact origins remain unclear due to its widespread adoption¹⁰. Artificial riffles have been implemented extensively across North America and Europe¹¹.

The scope of renaturalization undertaken in streams varies depending on the level of degradation and specific project objectives. Ideally, river renaturalization should aim to restore the continuity of the river corridor, both in the riverbed and on the floodplain, often through the construction of riffles using a combination of boulders, cobble, and gravel¹⁰. The necessity for such interventions stems from the legacy of large-scale channel regulations carried out on mountain and submontane rivers in the 20th century, which resulted in many adverse consequences, most notably the loss of vertical channel stability.

This issue heavily affected rivers throughout Southern Poland and has been particularly well documented in the Carpathian tributaries of the Vistula River¹². The process accelerated significantly in the second half of the 20th century, aggravated by the local exploitation of in-channel substrate¹³, and led to numerous detrimental effects on river systems¹⁴.

On typical Polish submontane rivers, repeated pool–riffle sequences are characteristic features of gravel-bed rivers with channel gradients < 0.02 m/m. These morphological structures provide diverse habitat conditions for aquatic plants and animals. Therefore, the renaturalization of pools and riffles is a crucial component of river renaturalization projects. The construction of artificial riffles is also considered a beneficial practice in river engineering for enhancing bed stability and dissipating energy within trained reaches¹⁵. By controlling vertical channel incision, these structures help maintain the geomorphic integrity of the riverbed, thereby protecting the structural stability of riparian flood-defense infrastructure. The effectiveness of such structures is well-established and has been investigated, for instance, in Carpathian streams in terms of both abiotic¹⁶ and biotic parameters¹⁷. However, while many studies examine the impact of artificial riffles on river fauna¹⁸, there is a scarcity of research describing the long-term persistence and stability of the structures themselves.

While previous research has extensively documented the positive impacts of artificial riffles on fish community structure and macroinvertebrate diversity^{19,20}, these studies often treat the physical structures as static elements of the habitat. Consequently, there is a scarcity of research that critically evaluates the long-term geomorphological stability and technical durability of these features from a hydraulic engineering perspective.

This study addresses this gap by emphasizing the physical persistence of artificial riffles over a nine-year period, offering direct insights for future engineering design and the implementation of nature-based solutions. Here, we evaluate the long-term effectiveness of artificial riffles as a nature-based solution for reversing the detrimental effects of river channelization on the Bóbr River in Wojanów (Southwestern Poland). While various forms of block ramps and bed-narrowing structures have been implemented in Poland since the 1970s, primarily for hydraulic regulation, the structures investigated here represent a modern approach to river renaturalization. Unlike traditional rigid ramps often incorporating concrete or fixed boulders, these artificial riffles are constructed entirely from loose, natural substrate with a continuous grain size distribution. This design focuses on bed stabilization and sediment ‘feeding’ of the river, aiming to maximize the improvement of hydromorphological quality in a reach already subjected to partial regulation. Importantly, the successful implementation of this nature-based approach resulted in the cessation of further planned traditional engineering works, providing a sustainable alternative to conventional river training.

As the first implementation of its kind in Poland, this study was designed to demonstrate a viable alternative to the ‘hard’ engineering methods traditionally used in national river management. By providing a functional and durable substitute for conventional hydraulic structures, this approach seeks to balance flood protection with ecological integrity. Consequently, the primary objective of this study is to determine whether such structures provide sustainable, long-term bed stabilization and hydromorphological recovery. Specifically, we aim to: (i) quantify the physical durability and positional stability of artificial riffles over a nine-year period (2014–2023); and (ii) test the hypothesis that artificial riffles function as a process-based renaturalization measure that enhances bedform diversity and ecological function while maintaining structural integrity.

Study area

The Bóbr River, with a length of 272 km and a catchment area of 5,876 km², is the largest left-bank tributary of the Oder River (the second-largest river in Poland). The river’s source is located in the Western Sudety Mountains (780 m a.s.l.), while its confluence with the Oder River lies at 37 m a.s.l. The mean annual discharge at the Wojanów gauging station is 4.5 m³/s, and its average channel slope is 0.00276 m/m. The surveyed section is 5,400 m long and flows through the Jeleniogórska Basin, located in the middle course of the river, where the watercourse is characterized as a small upland silicate river (Fig. 1). Mean annual precipitation ranges from 700 to 1,400 mm. The hydrological regime of the Bóbr River is defined by two distinct and fairly regular flood periods: snowmelt (March–April) and rainfall (July–August). The Bóbr River and its tributaries drain a catchment with a high proportion of rocky and forested terrain.

The location of the study section in a submontane basin, where the steep gradient of the mountainous catchment abruptly decreases, results in the accumulation of floodwaters and a high risk of flash floods. This threat is mitigated by a series of dam reservoirs located both upstream and downstream of the study area, necessitated by the lack of sufficient retention on the floodplain terraces. The bedrock at the study site belongs to

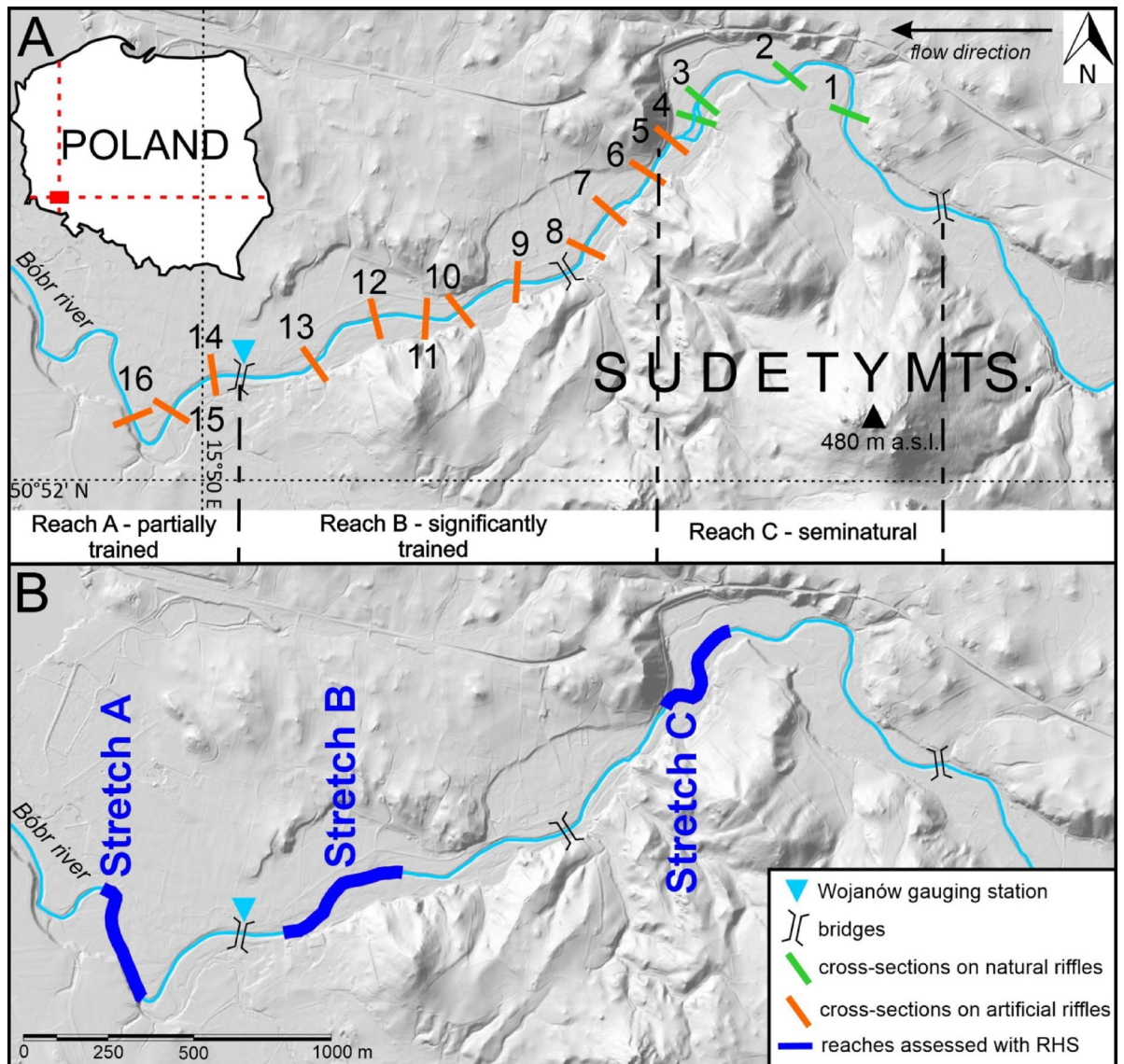


Fig. 1. Study area. A — studied sub-reaches, riffles and cross-sections; B — stretches assessed with RHS method. The maps were created using a free software QGIS version 3.34 (<https://www.qgis.org/download>).

the Karkonosze-Izera block, primarily represented by coarse- to medium-grained porphyritic granites²¹. There is a significant variety of morphological forms; the valley floor is filled with Pleistocene sediments, surrounded by granite hills and outcrops. These surrounding hills are covered by a thin layer of Pleistocene sediments consisting of glacial till, sands, and gravels.

The bed of the Bóbr River channel is underlain by fluvio-glacial sediments of erosional origin. The alluvium composition in the studied section is complex, including fluvio-glacial gravels, local porphyritic granites, and other rocks formed during the Variscan orogeny in the Western Sudety Mountains: basalts, aplites, and pegmatites—often weakly rounded or sharp-edged²². According to Rosgen's typology of natural channels²³, the channel incision index for the Bóbr River reach near Wojanów indicates a Type C channel. This channel is currently too deep and lacks sufficient sinuosity, which is a direct consequence of regulation works carried out since the 19th century (Fig. S1). The natural tendency of such a channel to regain equilibrium involves increasing its sinuosity and channel widening²⁴.

Since at least the first half of the 19th century, the studied reaches of the Bóbr River have been subjected to channel regulations, including: (i) adaptation for timber floating through the removal or re-routing of natural riffles, extraction of cobbles and boulders, and exploitation of gravel bars; (ii) meander cut-offs, resulting in reduced channel sinuosity; (iii) reinforcement of concave banks with riprap using stone quarried directly from the channel; and (iv) clearance of riparian woody and shrub vegetation (Fig. S1). High flows and floodplain inundation of the Bóbr in 2013, along with related flood damage near Wojanów (Fig. 1), prompted the Regional Water Management Authority to regulate a 7 km reach of the river. Initially, river training plans proposed widening and deepening the channel along the entire reach, affecting both previously regulated and natural

sections. The banks of the new channel, designed with a trapezoidal cross-section, were to be lined with stone riprap extending from the toe to the top of the bank. All natural bed morphology was to be removed using heavy machinery and explosives, while the bottom was to be reinforced with concrete sills. Furthermore, a well-developed meander in the upper reach was slated for elimination to straighten the river's course, and riparian trees were to be cleared. Work on this river regulation project started in 2012. However, following a dialogue established in 2013 between local water and environmental authorities and the public, the scale of the planned works was significantly reduced. In addition to ceasing work according to the current design, 12 new artificial riffles were designed and constructed in 2013–2014; while 4 already existing seminatural riffles were corrected and strengthened.

The sudden interruption of work left the river in a very different state, which formed the basis for distinguishing three sub-reaches with different degrees of transformation (Fig. 1A):

- (i) *Partially trained* sub-reach A (950 m long): characterized by predominantly natural channel morphology, with localized engineering interventions limited to two short sections (each several tens of meters long) where one bank was reinforced with riprap in 2013–2014. Additionally, a secondary flow channel was re-established using engineering methods in 2014. Woody riparian vegetation remains confined to the immediate vicinity of the channel.
- (ii) *Significantly trained* sub-reach B (2,350 m long): defined by extensive and continuous channel modification. The channel was originally regulated in the 19th century and further modified in 2013–2014 through widening and deepening, re-profiling and smoothing of the banks to a 45° inclination, and reinforcement of the lower half of both banks with riprap. These interventions were accompanied by the total removal of woody riparian vegetation.
- (iii) *Semi-natural* sub-reach C (2,100 m long): defined as a section with no visible anthropogenic modification of the channel bed or banks, and with woody riparian vegetation restricted to a narrow zone adjacent to the channel margins.

How the artificial riffles were made?

One of the co-authors (P. Nawrocki) participated in discussions with the Regional Water Management Authority in Wrocław that led to the construction of 12 artificial riffles in 2013–2014. He also facilitated cooperation with an external consultant responsible for defining design parameters and training the contractor. The authors were not involved in the technical design or construction of the riffles but conducted long-term monitoring of their performance.

Artificial riffles are engineered riverbed structures designed to replicate the hydraulic and morphological characteristics of natural riffle–pool sequences. Their construction typically follows a specific longitudinal profile: a gentle upstream slope leads to a crest, which serves as a vertical control point for the upstream pool, followed by a downstream slope that facilitates energy dissipation (Fig. 2). The substrate consists of a graded mixture of stones, where larger boulders provide a stable framework and smaller materials fill the voids to enhance ecological complexity and bed stability.

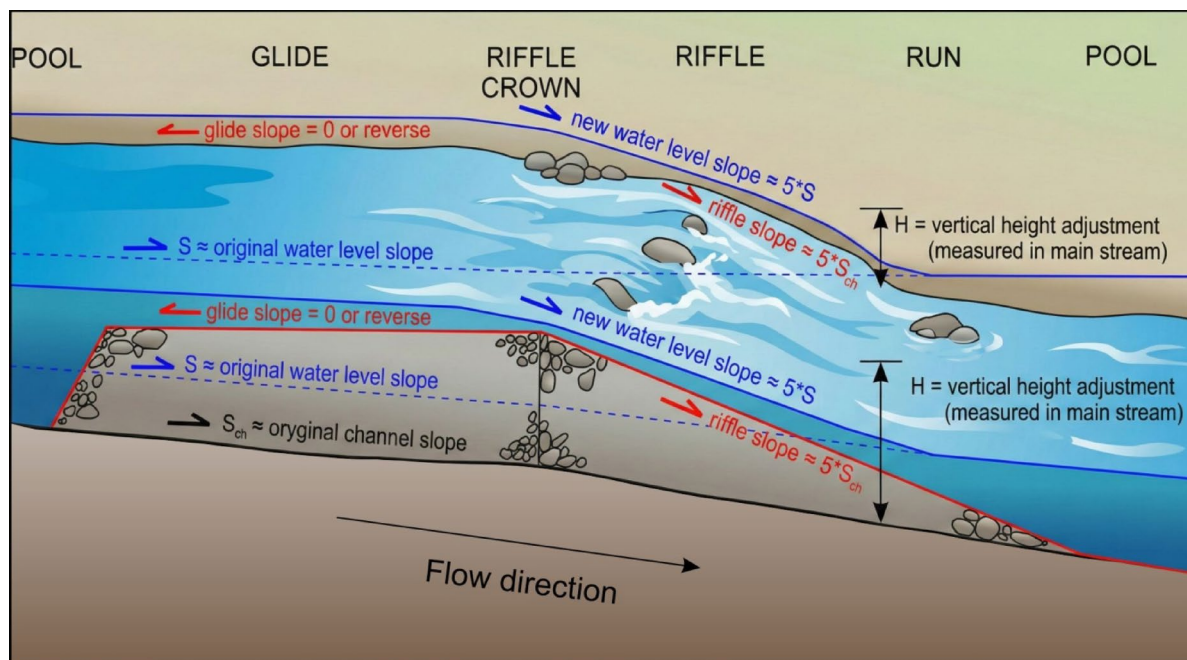


Fig. 2. Graphical visualization of the riffle–pool sequence for a typical artificial riffle on the Bóbr River.

The concept of artificial riffles has existed in the literature for nearly 30 years and was originally developed to address issues in lowland alluvial rivers in eastern England, where numerous small stream renaturalization projects were planned²⁵. The initial objective of this concept was to promote the spontaneous renaturalization of riparian features and biodiversity, which were generally overlooked in standard river corridor surveys.

The design and configuration of these structures are tailored to the specific character of the river, taking into account factors such as hydraulic and hydromorphological parameters, aquatic vegetation, and fish assemblages. The implementation of artificial riffles in the Bóbr River serves to manage flow in the incised channel and ensure vertical stability by acting as positive bed forms. Using the Hey and Thorne regime Eq²⁶, calculations were performed. To determine the regime geometry of the Bóbr River, the equations for Type II bank vegetation (1–5% tree/shrub cover, the specific forms of the equations used are as follows:

- 1) Bankfull Width $W = 2.97 \cdot Q_{bf}^{0.50}$
- 2) Mean Depth $d = 0.22 \cdot Q_{bf}^{0.37} \cdot D_{50}^{-0.11}$
- 3) Riffle Slope $S = 0.013 \cdot Q_{bf}^{0.33} \cdot D_{50}^{0.86}$
- 4) Flow velocity $v = 1.53 \cdot Q_{bf}^{0.13} \cdot D_{50}^{-0.11}$

Where Q_{bf} is the bankfull discharge (m^3/s), and D_{50} is the median grain size (m).

Assuming that:

- 1) Calculated channel width $W = 2.97 \cdot Q_{bf}^{0.50} \approx 23$ m.
- 2) $L = (5 \div 7) \cdot W =$ between 115 and 161 m.

These assumptions were consistent with the actual situation in the field.

The design of the riffle-pool sequences incorporated the spacing parameter (L), defined as the distance between successive riffle crests. According to the equilibrium principles, L was initially calculated to be within the range of 5–7 bankfull widths (W). In practice, the spacing ranged from 115 to 161 m, as the final placement of each structure was adjusted to coincide with the channel's inflection points. This ensured that the artificial riffles were integrated into the river's natural morphology, mimicking the irregular spacing characteristic of natural gravel-bed systems rather than following a strictly uniform distribution.

The goal was to ensure the longevity of the structures under varying rates of bedload supply from upstream. Given that upstream sediments had a median grain size of 46 mm, it was recommended that the riffles be constructed using material approximately 3–4 times coarser.

The project involved the installation of 12 artificial riffles in trained sub-reaches A and B, designed to emulate natural riffle-pool sequences, while in the semi-natural sub-reach C, the work focused on the crest elevation correction of existing natural riffles (Fig. S2). Each structure was designed with a specific longitudinal profile consisting of a gentle upstream ramp (slope 1:10 to 1:20), a central crest acting as a vertical hydraulic control, and a downstream run (slope 1:15 to 1:30) for energy dissipation²⁷.

The construction material consisted of a continuously graded mixture of angular rock debris (sourced from a local quarry) and rounded fluvial gravel. To ensure long-term structural stability and prevent internal erosion (piping), the design specification required a well-graded substrate where finer fractions fill the voids between larger boulders, creating a stable framework²⁸.

In practice, although all artificial riffles shared the same design specifications, the execution quality varied across the study sites due to the contractor's varying levels of commitment and adherence to the project guidelines. Well-executed riffles involved using appropriately graded material and pre-mixing the substrate components on the bank before placement into the riverbed, resulting in a flat, uniform crest and even flow distribution. In contrast, poorly executed structures resulted from the contractor's failure to follow these specifications. They were characterized by the use of incorrectly graded material and layered material placement directly in the river without prior mixing.

The correction works on all four riffles (1–4) in the semi-natural reach were performed professionally. Therefore, we have classified them as part of the total group of six well executed riffles. In the trained sub-reaches, riffles 7, and 15 were characterized by high-quality execution. Conversely, the remaining ten riffles in the trained sections exhibited lower construction standards, primarily due to the use of excessively coarse rock material, inadequate mixing of the rock substrate with gravel, or an insufficient proportion of rounded gravel. This technical oversight led to the winnowing of loose gravel during subsequent flood events, resulting in a degraded crest morphology (resembling 'dragon's teeth') and the formation of lag deposits on the downstream slope. The durability and morphological evolution of these structures were monitored through cross-sectional surveys at the riffle crests in 2014 and 2023.

Results

Persistence of artificial riffles over the observation period

As mentioned above, the studied riffles were constructed with varying degrees of workmanship, which directly affected their long-term durability. Nevertheless, these structures withstood a series of minor floods, including two events that exceeded the bankfull flow, estimated at approximately $60 m^3/s$.

The overall characteristics of the channel and riparian area, including the density and type of vegetation cover, have changed slightly compared to pre-2014 conditions. In 2023, the crests of all examined riffles (constructed from rock material with a median grain size of 120 mm) remained in their original positions, regardless of the extent of regulatory work conducted in the channel (Fig. 3). Nine years post-construction, the grain size distribution on the riffle crests remained remarkably stable across the six well-executed structures. In contrast, the ten poorly executed riffles exhibited signs of crest erosion, resulting in a morphology resembling 'dragon's teeth' (Tab. S1). While all riffles persisted, these discrepancies in execution have had a clear impact on their long-term functionality.

However, conditions differed in the middle and distal parts of the riffles. Well executed structures (Fig. 1A, numbers 1–4, 7, and 15) were characterized by a compact run structure with well-graded and mixed material.

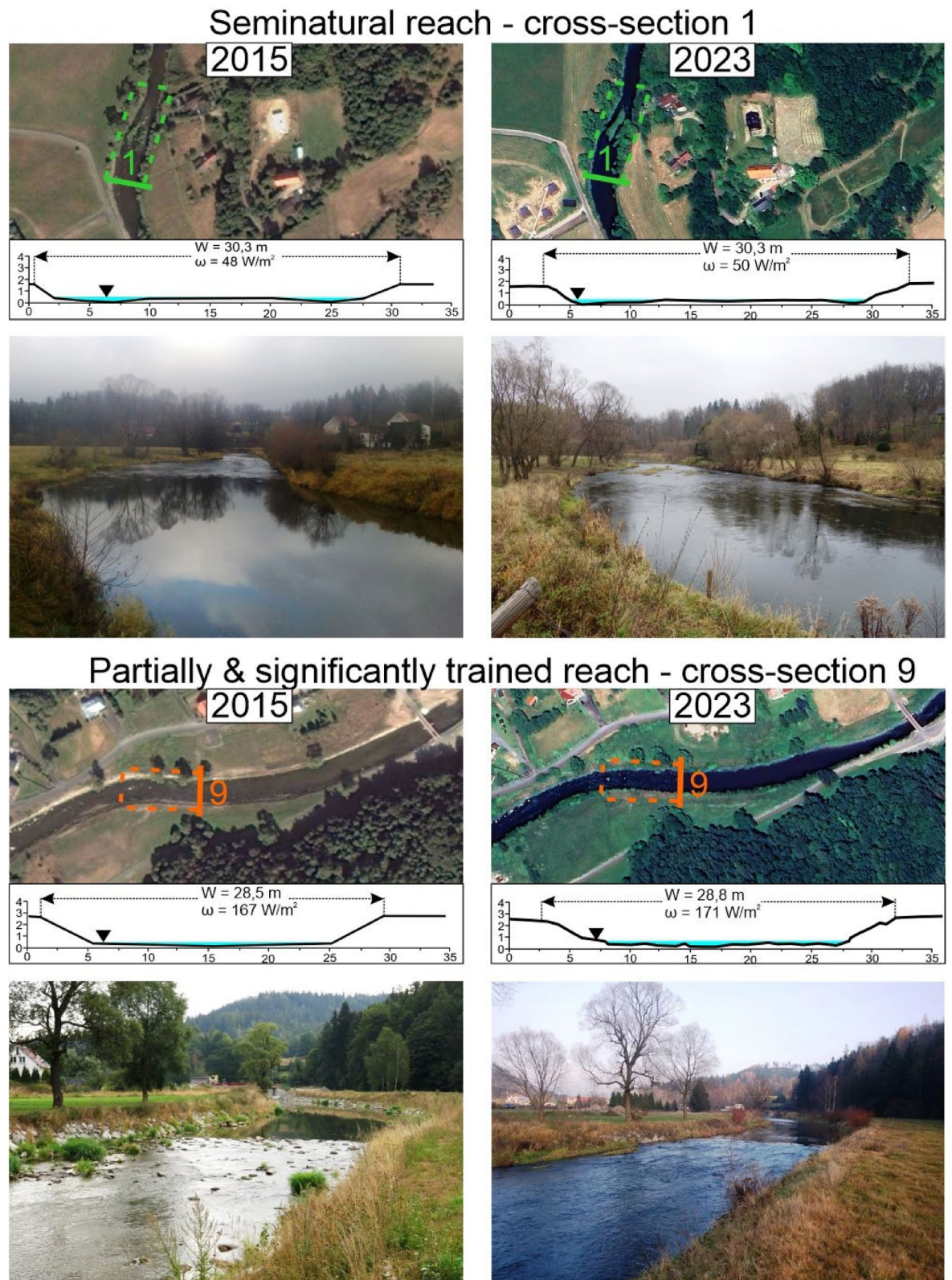


Fig. 3. View of the studied artificial riffles in semi-natural and trained sub-reaches in 2015 and 2023.

The mean grain size on the runs of these six riffles remained stable, measuring 35 mm in 2014 and 37 mm in 2023. These structures coped well with the floods, becoming increasingly armoured and uniform—both upstream and downstream. In contrast, on the ten poorly executed riffles, the material on the riffle run underwent significant

erosion and coarsening, with the median grain size increasing from $D_{50} = 35$ mm in 2014 to $D_{50} = 78$ mm in 2023 (Tab. S1).

The remaining ten structures exhibited clear signs of erosion, specifically scouring in the distal section and the formation of elongated gravel-sand lenses (ranging from 3 to 15 m in length) encroaching into the pool. Despite these localized changes, neither significant accumulation nor general bed degradation was observed throughout the wider study area. GPS-based measurements taken along the flow line of individual structures using RTK technology showed no significant vertical changes over the nine-year period. These riffles exhibited distinct behaviour during high-flow events. A deficiency of suitably graded fine material resulted in its erosion and subsequent displacement towards the downstream section of the riffle. Consequently, the riffle crests have effectively transformed into rocky reefs. While these structures do not, in themselves, constitute a barrier to migration, they are significantly more susceptible to scouring and entrainment within the bedload.

Comparison of hydromorphological and hydraulic parameters within the studied riffles

The visual assessment of the persistence of the artificial riffles is corroborated by the analysis of hydromorphological and hydraulic parameters. A comparative analysis of these parameters across the riffle cross-sections revealed distinct variations in long-term stability, which were closely associated with the technical quality of construction (Tab. S2). For the well executed riffles ($n=6$), both geomorphic and hydraulic parameters remained stable throughout the study period (2015–2023), with no statistically significant changes observed (all $p > 0.05$) (Tab. S3).

In contrast, the poorly executed group ($n=10$) exhibited significant morphological transformations driven by erosive processes. These structures showed a significant increase in mean channel depth (Wilcoxon signed-rank test, $W=7.0$, $p=0.037$) and mean flow velocity ($W=4.0$, $p=0.014$). These changes were accompanied by an increase in unit stream power ($W=8.5$, $p=0.049$), confirming progressive morphological degradation characterized by scouring and a diminished capacity for energy dissipation.

The longitudinal channel profiles measured in the vicinity of each riffle clearly illustrate that variations in water depth and bed forms are evident, regardless of the degree of regulation. These changes provide significant benefits in terms of improving hydromorphological diversity, ecological value, and erosion protection, particularly in the sections previously most heavily impacted by regulation (Fig. S3).

Changes in hydromorphological condition over time

The three sub-reaches distinguished in our research were characterized by varying degrees of hydromorphological transformations (Fig. 1A):

- (i) Significantly trained sub-reach A: HQA index after river training < 30 , HMS index > 75 .
- (ii) Partially trained sub-reach B: HQA index after river training $= 37–49$, HMS index $= 44–75$.
- (iii) Semi-natural sub-reach C: HQA index > 50 , HMS index < 8 .

River stretches A and B (Fig. 1B) showed evidence of earlier channel regulation, including rip-rap bank reinforcement and bank reprofiling. River training carried out in August 2014 substantially increased the intensity of hydromorphological modification in both stretches, shifting them to the highest modification class according to the HMS index (Fig. 4A and B). In subsequent years, HMS values remained high, reflecting the long-lasting effect of stone rip-rap reinforcement as a permanent alteration of channel hydromorphology.

Before the training works, both stretches were characterized by moderate hydromorphological diversity, mainly due to the limited occurrence of erosive and depositional features. After river training, Stretch A maintained relatively stable HQA values, whereas Stretch B showed a marked decline followed by gradual recovery toward pre-training conditions (Fig. 4A and B). The works strongly reduced the diversity of fluvial forms, which were subsequently represented mainly by side bars, with a slow increase in vegetated forms observed in later years (Fig. 5A and B).

Stretch C (Fig. 1B) retained a more semi-natural character and showed no evidence of previous hydromorphological modification. It was distinguished by higher morphological diversity, associated with the frequent occurrence of natural forms such as eroding and stable cliffs, side and point bars, natural berms, and mid-channel bars. Following side-channel activation in April 2016, HQA values increased, while HMS rose only temporarily as a result of ongoing renaturalization works (Fig. 4C). The improvement in habitat quality was related to the development of additional fluvial forms, particularly those associated with the formation of a mature island (Fig. 5C).

Changes in riparian tree and shrub cover were most pronounced in the intensively trained Stretch B (Fig. 6B, S5). Woody vegetation was largely removed before river training, but substantial regeneration occurred in the following years, with cover returning to pre-disturbance levels after approximately six years. In the partially trained Stretch A, vegetation changes were moderate and followed a similar recovery trend, especially along the right bank (Fig. 6A, S4). In the semi-natural Stretch C, riparian cover remained comparatively stable; a temporary decline on the right bank resulted from partial tree removal during side-channel restoration, followed by gradual recovery (Fig. 6C, S6).

Discussion

Effectiveness and durability of artificial riffles

The loss of geomorphic complexity in regulated rivers is widely recognized as a key driver of ecological degradation^{29,30}, yet effective approaches to restoring both channel form and ecosystem function remain limited. The case presented here represents the first application in Poland of artificial riffle construction based on equilibrium equations for gravel-bed channels derived by Thorne and Hey²⁶.

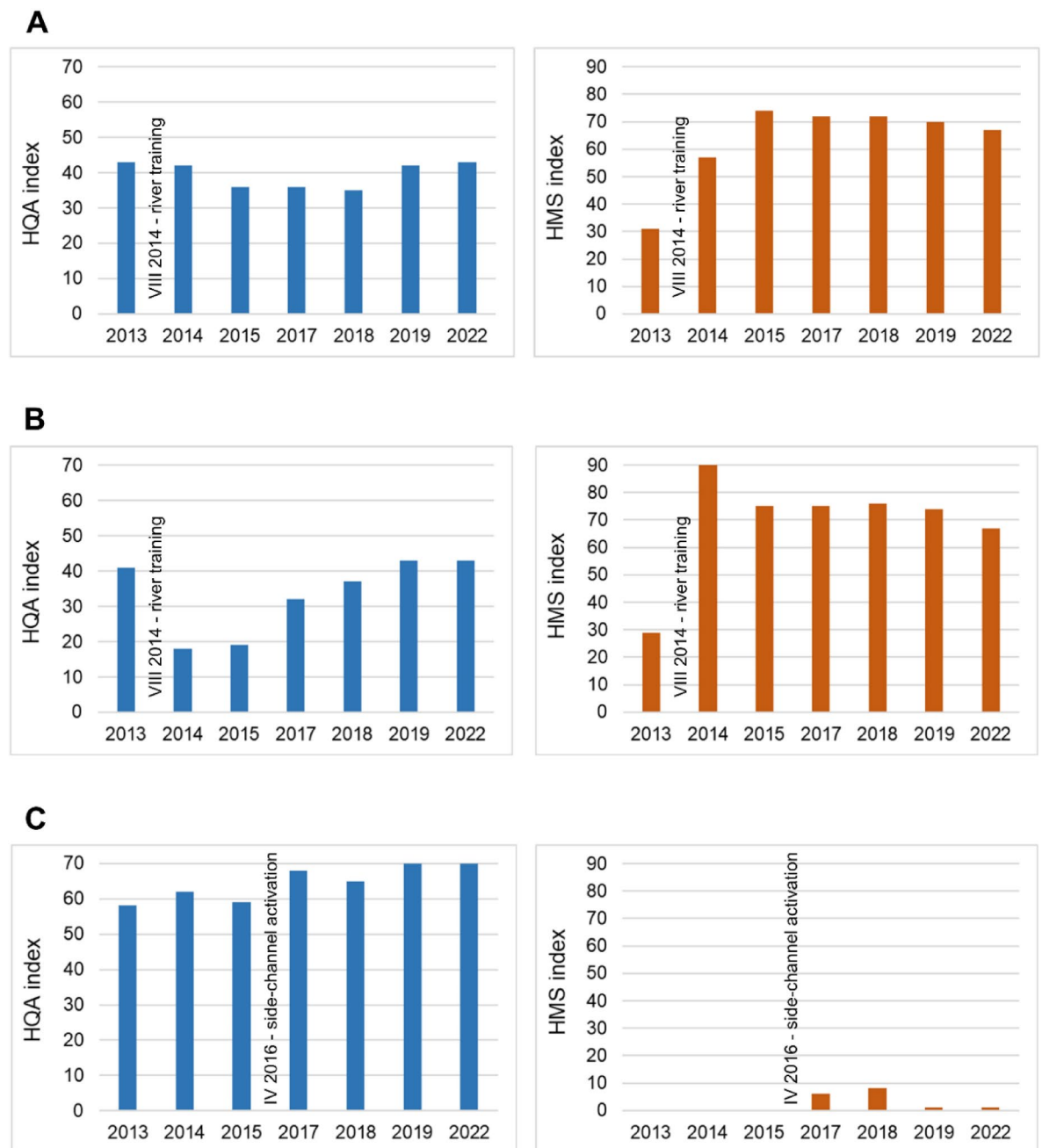


Fig. 4. Changes in the values of hydromorphological metrics HQA and HMS over time: A, B, C – 500 m research stretches indicated in Fig. 1B. High values of HQA indicate a high degree of river morphological diversity. High values of HMS indicate extensive anthropogenic morphological modifications of the river.

All examined riffles proved to be durable features over the nine-year monitoring period. This long-term persistence is noteworthy, as international literature frequently reports high failure rates or significant damage to river restoration structures within the first few years following installation^{31,32}. Our results, showing positional stability and low sensitivity to bankfull flows (particularly in riffles constructed according to design criteria), demonstrate that geomorphologically-informed design can overcome the common problem of structural instability reported in other mountain and upland systems³³.

The long-term performance of the artificial riffles was found to be highly dependent on the precision of their technical execution. In riffles where the material was layered rather than pre-mixed, hydraulic forces caused the selective erosion of finer fractions. Similar processes of ‘winnowing’ and subsequent structural coarsening have been observed in restoration projects in the UK and USA, where inadequate substrate grading led to the loss of intended hydraulic functions^{28,34}. Our observation of ‘dragon’s teeth’ morphology and internal erosion confirms that the ‘devil is in the details’ of substrate preparation, a finding that aligns with international calls for higher engineering standards in nature-based solutions.

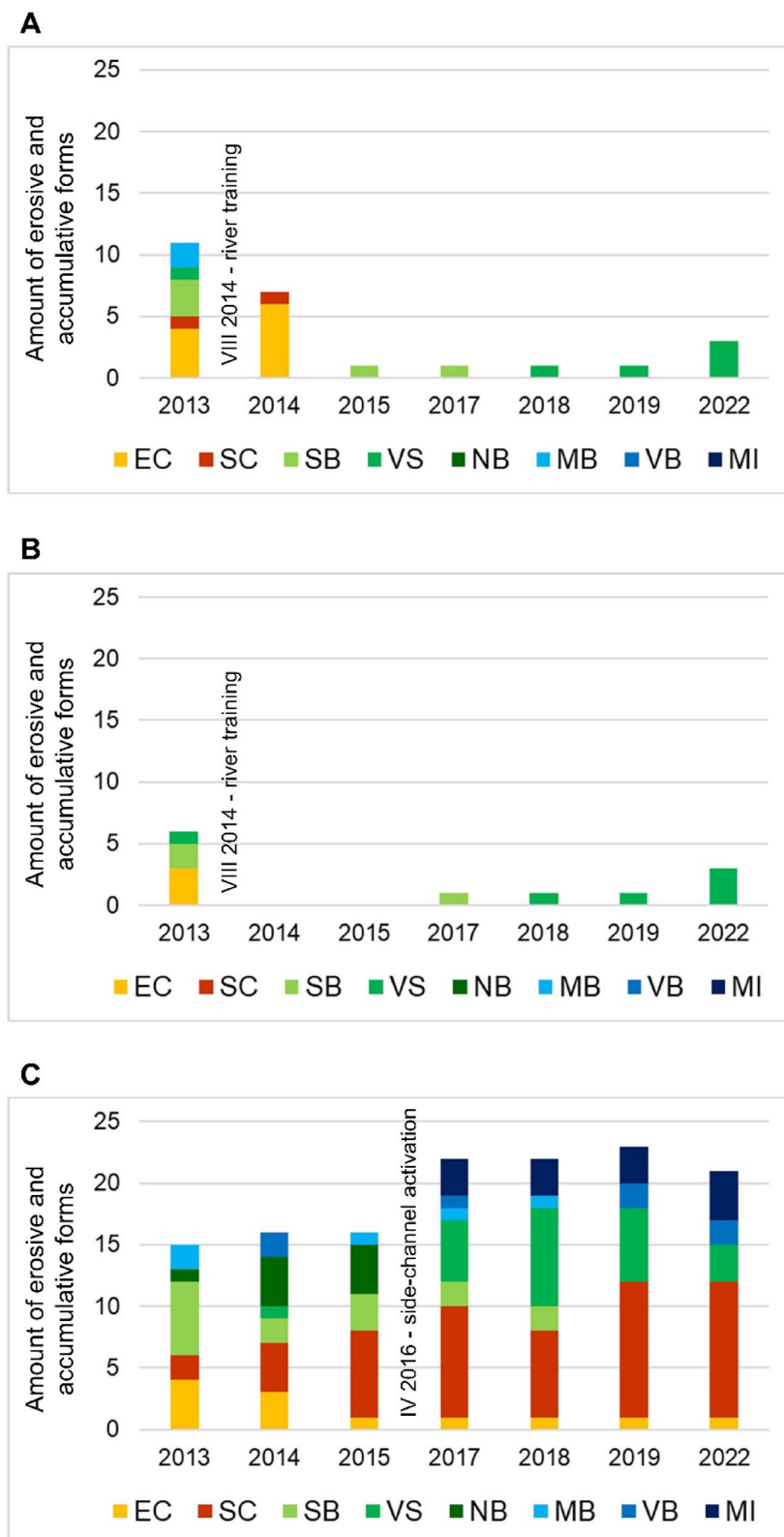


Fig. 5. The frequency of occurrence of erosive and accumulative hydromorphological forms: A, B, C – 500 m research stretches indicated in Fig. 1B; types of hydromorphological forms: EC – eroding cliff, SC – stable cliff, SB – unvegetated side/point bar, VS – vegetated side/point bar, NB – natural berm, MB – unvegetated mid-channel bar, VB – vegetated mid-channel bar, MI – mature island.

Influence of construction quality and grain-size composition

Despite this overall stability, the performance of artificial riffles is strongly influenced by construction quality and material composition.

In a river affected by gravel deficit (as is typical for mountain rivers downstream of reservoirs, including the Bóbr), the long-term persistence of the riffle–pool sequence depends on continued sediment supply and transport. In its absence, riffles may persist structurally but undergo progressive coarsening, with finer fractions being winnowed from steeper sections. As a result, they may evolve towards coarse, reef-like forms, as already observed for riffle No. 13 in the significantly trained sub-reach (Fig. 1A).

Regarding future evolution, continued winnowing of the finer gravel matrix will likely lead to a ‘perching’ effect, where the coarse boulder framework remains elevated while the downstream pool and adjacent bed continue to incise due to the sediment deficit. In terms of flood protection functionality, this evolution presents a dual risk. First, as documented in studies of in-stream structures, the transition from a smooth, well-graded riffle to an irregular, high-roughness rocky reef increases local turbulence and may redirect high-velocity flow vectors toward the banks, potentially triggering lateral erosion and compromising riparian stability during extreme events^{36,36}. Second, if the structural integrity of the ‘reef’ is eventually breached during an extreme flood, the sudden release of the stored hydraulic head could initiate a knickpoint migration (headward erosion) upstream, a process characteristic of degrading channels suffering from sediment starvation^{37,38}. Therefore, while the structures currently persist, their transition into rocky reefs represents a shift from a dynamic, energy-dissipating feature to a rigid hydraulic obstacle, necessitating long-term monitoring to ensure they do not become catalysts for localized bank instability.

The material used in most riffles was coarser than specified in the design calculations. This led to partial loss of gravel from the riffle crest and run during flood events. While this enhances structural durability under high flows, the literature indicates that the increased median grain size—particularly on riffle runs—limits their suitability as spawning habitat, since rheophilic fish require specific upper limits of gravel size to successfully excavate redds³⁹. At the same time, the development of sand-filled scour channels in the distal parts of many riffles increases bed heterogeneity and provides refuge habitats for fish.

The role of sediment supply and long-term morphodynamic context

These observations highlight the importance of considering artificial riffles within a broader morphodynamic context.

Riffle–pool sequences in gravel-bed rivers emerge from a dynamic balance between hydraulic forces and sediment transport processes, which remain an active area of research⁴⁰. Similar structures may also develop downstream of flow obstructions such as large wood⁴¹. Long-term observations⁴² indicate that such features persist as long as the key structural element remains stable, although high flows may disrupt them.

In comparison, the riffles in the Bóbr River—constructed using coarse rock material—exhibit greater structural persistence, which is particularly relevant in regulated rivers with flood protection requirements. While artificial riffles should ideally be located where natural ones would form, natural riffle development typically requires multiple high-flow events. By contrast, artificial structures can reproduce these features immediately when designed based on hydromorphological principles.

The results demonstrate a clear divergence in hydromorphology changes between technically trained sub-reaches and the seminatural section. In sections A and B, the sharp increase in HMS values and the temporary collapse of HQA scores post-training reflect a state, where bank reinforcements (rip-rap) and reprofiling created a static environment. This homogenization effectively suppressed the formation of natural erosive and accumulative forms, a phenomenon commonly known in mountain rivers^{41,42}. Conversely, the activation of the side-channel in stretch C acted as a catalyst for morphological enrichment, leading to a sustained increase in HQA index. While the physical bed and banks morphology in trained sections remained largely static by anthropogenic modifications, the riparian vegetation showed significant resilience, recovering to pre-intervention levels within approximately six years. However, this biological recovery alone cannot compensate for the lack of instream heterogeneity, if the fluvial processes remain constrained^{43,44}.

Artificial riffles as process-based interventions in regulated channels

The functional role of artificial riffles becomes clearer when contrasted with the behaviour of regulated rivers lacking such structures.

Examples from regulated European⁴⁴ and Carpathian rivers^{45,46} show that channelization commonly leads to a nearly uniform bed profile. Incised channels, often deepened by 2–3 m, attempt to re-establish morphological equilibrium by eroding banks and mobilizing sediment, thereby initiating a delayed and uncontrolled recovery of riffle–pool sequences⁴⁷. This process contributes to lateral instability and increases flood risk, particularly in “hungry rivers” affected by sediment deficit in southern Poland^{46,48}.

In the absence of large-scale renaturalization measures, local responses often involve bank reinforcement using woody debris or stone revetments. However, such measures address symptoms rather than underlying processes. In contrast, the introduction of artificial riffles represents a more process-based intervention.

Implications for renaturalization practice and river engineering

Taken together, these results suggest that effective river renaturalization requires an integrated approach that combines sediment management with the reintroduction of bedform diversity.

Artificial riffles, when properly designed and constructed, can restore key elements of channel morphology, enhance habitat diversity, and stabilize incised channels. As such, they represent a nature-based solution that bridges the gap between traditional engineering approaches and ecological renaturalization, offering a practical pathway towards improving river resilience and ecological quality. Our results demonstrate that artificial riffles,

when embedded within a process-based renaturalization framework, can simultaneously enhance bedform diversity, support ecological functions, and provide a durable alternative to conventional channelization, thereby offering a practical pathway towards more resilient river systems.

The findings of this study are inherently linked to the specific hydromorphological context of the Bóbr River, which is characterized as a reservoir-impacted system. The chronic sediment deficit resulting from upstream impoundments (e.g., Pilchowice Reservoir) likely influenced the observed stability of the riffle crests, as they were not subjected to significant burial by natural upstream bedload. In systems with high natural sediment supply, the morphological evolution of these structures might differ, as excess bedload can overwhelm static interventions, potentially leading to their burial or incorporation into natural migrating bar sequences^{30,31}.

Consequently, the scope of applicability for this study is most relevant for upland and mountain gravel-bed rivers affected by bed incision and sediment starvation. In contrast, for lowland sandy-bed rivers, the design and effectiveness of artificial riffles would require significant adjustments. In such environments, different sediment transport dynamics and lower substrate stability would necessitate a focus on subsidence prevention and different material grading to avoid the riffles functioning as unintended low-head dams.

Outlook

The nine-year monitoring of the Bóbr river confirms that artificial riffles act as a durable and effective alternative to traditional concrete sills in upland rivers. Despite being subjected to flows exceeding bankfull discharge, the constructed riffles maintained their vertical stability and successfully arrested channel incision without causing adverse aggradation. The study demonstrated that the “compromise” approach—combining limited regulation with renaturation measures like channel splitting and riffle construction. It effectively mitigated flood risk while preserving hydromorphological diversity to a greater extent. However, the results also highlight the critical importance of the granulometric composition of the construction material; while coarser riffles ensured structural stability, only those with a properly balanced gravel fraction fully replicated the biological function of natural spawning grounds. We believe that this example of difficult yet successful cooperation between scientists, water authorities, river engineers and non-governmental organisations will be a milestone at the start of new, more comprehensive renaturalization activities. Beyond their site-specific effects, our findings highlight the broader importance of collaboration between scientists, water management authorities, engineers, and non-governmental organizations in designing and implementing effective renaturalization measures. Such cooperation enables the integration of scientific knowledge, technical expertise, stakeholder involvement and local management priorities, thereby increasing the likelihood of achieving both ecological, engineering and social objectives. In this context, artificial riffles can serve not only as a technical intervention, but also as a platform for interdisciplinary collaboration, facilitating the transition towards more process-based and adaptive approaches to river renaturalization.

Methods

Field measurements

At the onset of the study in 2014, the river reach bore the legacy of systematic training initiated in the 19th century, which primarily involved bank stabilization and longitudinal channel narrowing. While these historical hydro-technical interventions had altered its natural state, the prolonged absence of maintenance works had allowed for significant progressive self-renaturalization. Therefore, the aim of these measurements was to ascertain positive and negative changes within the surveyed sections between 2014 and 2023.

In order to distinguish between the different channel morphological units, we used commonly used classification of Wheaton et al.²⁴, simplified to four units that repeat cyclically: riffle-run-pool-glide.

Depending on the degree of channel transformation by regulations, we divided the study section into three sub-reaches (Fig. 1A): *seminatural* (sub-reach C), *partially trained* (sub-reach A) and *significantly trained* (sub-reach B). After the regulation works in 2014, 16 cross-sections running across riffle crests were delimited for the study (one cross-section for one riffle). All field measurements took place at similar low-flow conditions ($Q \approx 2 \text{ m}^3/\text{s}$). Channel morphology, gradient and water depth was surveyed with an optical level with 10 mm accuracy. The grain size distribution of the bed substrate was determined by measuring 100 consecutive particles on the riffle run, following the Wolman sampling technique. The bankfull discharge was determined based on two independent sources: the rating curve of the Wojanów gauging station, located directly within the study area, and HEC-RAS hydraulic modelling conducted by JOT engineering company, Skanska construction company and the Regional Water Management Authority. Based on the cross-sections surveyed in 2014 and 2023, the same modelling approach was used to derive key hydraulic parameters: bankfull area, bankfull width, mean channel depth, bankfull discharge, mean flow velocity, and unit stream power. During the cross-sectional surveys, flow velocity was measured using a Valeport 801 electromagnetic current meter.

In 2022–2023 under similar hydrological conditions, the cross-sections were measured using the Trimble R4 RTK GPS receiver with a vertical accuracy ca. 20 mm and compared with the location of geodetic benchmarks left in 2014 in order to precisely detect any possible erosion of the riffles. In addition, in 2023, 7 longitudinal profiles of the channel were measured using same GPS and a level staff in order to study the differentiation of the channel bottom and water depth in the vicinity of seminatural riffles (within the *seminatural sub-reach*; Fig. 1A) and artificial riffles (in trained reaches). By comparing the extensibility, hydromorphology and grain size of these structures, it was possible to determine their survivability during flood events and their impact on channel processes. Design hydraulic parameters and stability criteria for the artificial riffles were presented in Tab. S4.

The hydraulic parameters required to compare bankfull flow conditions at the 16 studied riffles between 2014 and 2023 were obtained from design documentation provided by Skanska and the Regional Water Management Authority (RZGW). These data were derived from hydraulic simulations previously performed by these entities using HEC-RAS software. A Wilcoxon signed-rank test was used to examine differences in average values of the

hydraulic parameters characterizing the studied riffles in 2015—after the completion of works—and in 2023. Differences were considered statistically significant with p -value < 0.05 .

Assessment of hydromorphological condition

The hydromorphological evaluation was conducted at each site according to the River Habitat Survey (RHS) method^{49,50} in the years 2013, 2014, 2015, 2017, 2018, 2019, and 2022. RHS gathers data from 500-m stretches of rivers. Field observations are conducted in two stages:

- The first stage is carried out on ten spot-checks (profiles), spaced equally every 50 m. The attributes recorded in each spot-check include: river bed and bank material, dominant flow type, natural habitat features as well as types of modifications. The attributes are recorded across the channel in a 1 m wide transect. Moreover, the structure of aquatic and bank vegetation as well as land use of a bank zone is recorded in 10 m wide transects.
- The second stage is synthetic assessment of the entire river section and it delivers an over-view of the entire survey site, where the natural features and modifications, which were not recorded in the previous stage (e.g., occurred between spot-checks) are recorded.

Two numerical metrics based on the RHS protocol were calculated^{51,52}. High values of Habitat Quality Assessment (HQA) indicate a high degree of river morphological diversity. High values of Habitat Modification Score (HMS) indicate extensive anthropogenic morphological modifications of the river. The HQA and HMS indices are multimeric encompassing many parameters recorded during field studies⁵¹. A detailed list of parameters taken into account in their calculation is given in Appendix Fig. S7. When calculating these indices, it is important to assess the heterogeneity of hydromorphological parameters and their frequency of occurrence; however, it is unimportant to specify which spot-checks they occurred in. There are 5 categories of HQA values⁵²: 1 - very diverse (> 56), 2 - diverse (50–56), 3 - moderately diverse (37–49), 4 - poorly diverse (30–36), 5 - little diverse (< 30). There are also 5 categories of HMS values⁴⁶: 1 - natural (< 3), 2 - slightly modified (3–8), 3 - moderately modified (9–20), 4 - significantly modified (21–44), 5 - highly modified (> 44).

Analysis of archival orthophotomaps

The study used archival orthophotomaps from 2012 to 2021 to assess changes in tree cover in the riparian zone and to visualize progressive changes in the hydromorphological state. These orthophotomaps came from various sources (GUGiK - <https://mapy.geoportal.gov.pl/>, Google Earth Pro application, and our own drone raid), but they had in common: making during the growing season (from the end of April to the turn of September and October), the same coordinate system (EPSG: 2180), similar horizontal resolution (25–50 cm/px), and the same colour composition (RGB - natural colours). Only the orthophotomap from 2015, originating from our own drone raid (using a DJI Matrice 210 RTK V2), had a higher resolution of 5 cm/px. All orthophotomaps were calibrated in the PL-1992 coordinate system (EPSG: 2180) based on the buildings and roads existing throughout the observation period. In the next step, clumps of trees and shrubs located within a 10-meter buffer from the riverbank edge were vectorized based on the orthophotomaps. Next, for each RHS stretch, the total length in metres covered by trees and shrubs was measured, separately for the right and left banks. All sources used in this publication are summarized in Tab. S5.

Hydrological situation in 2014–2023

Based on the Wojanów water gauge station operating since 1956, it can be seen that large floods occur relatively frequently here (Fig. 7A). A particularly high flows occurred in 1997–2013 with a maximum discharge of 229 m³/s in 1997. In the regulation design developed for the studied reach, maximum permissible flow was assessed to 272 m³/s and estimated bankfull flow ~60 m³/s. Since the construction of the artificial riffles, the river has exceeded or equalled the bankfull twice: 2014 and 2021. However, it was generally a low-flow period without major floods (Fig. 7B).

Due to the limited capacity of small dam reservoirs and the presence of steep-gradient mountainous tributaries, rainfall-induced floods on the Bóbr River are characterized by a steep rising limb and a long, gradual recession of the flood wave. The 2014 flood was triggered by three days of intermittent rainfall, which extended the rising limb, whereas the 2020 event was marked by a rapid surge followed by a swift decline to sustained high water levels. In both instances, these elevated stages persisted for over a week.

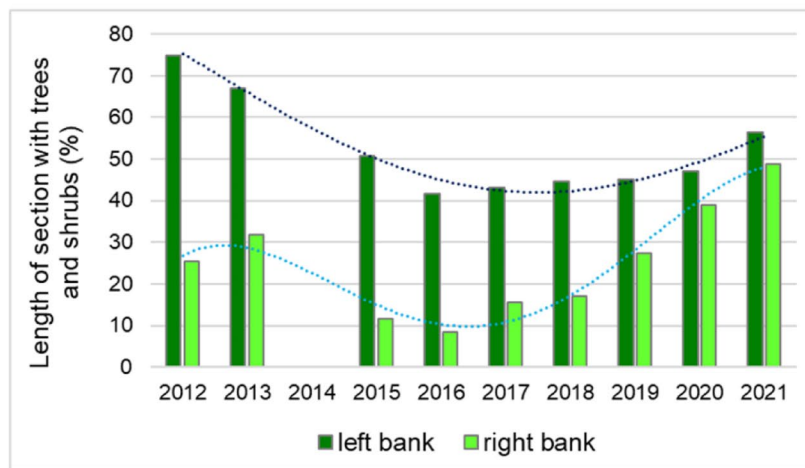
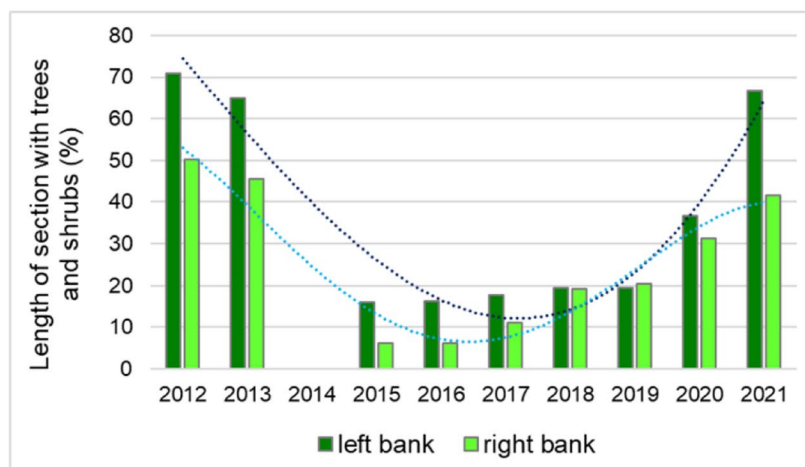
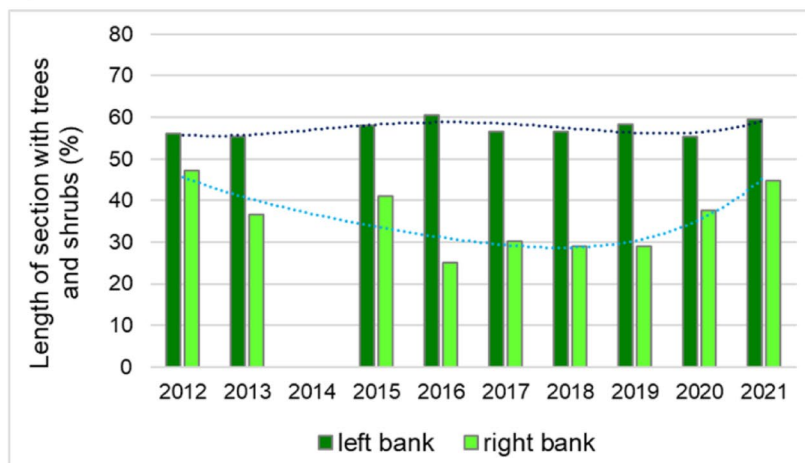
A**B****C**

Fig. 6. Changes over time of tree cover in the riparian zone: A, B, C – 500 m research stretches indicated in Fig. 1B (See also Fig. S3, S4, S5).

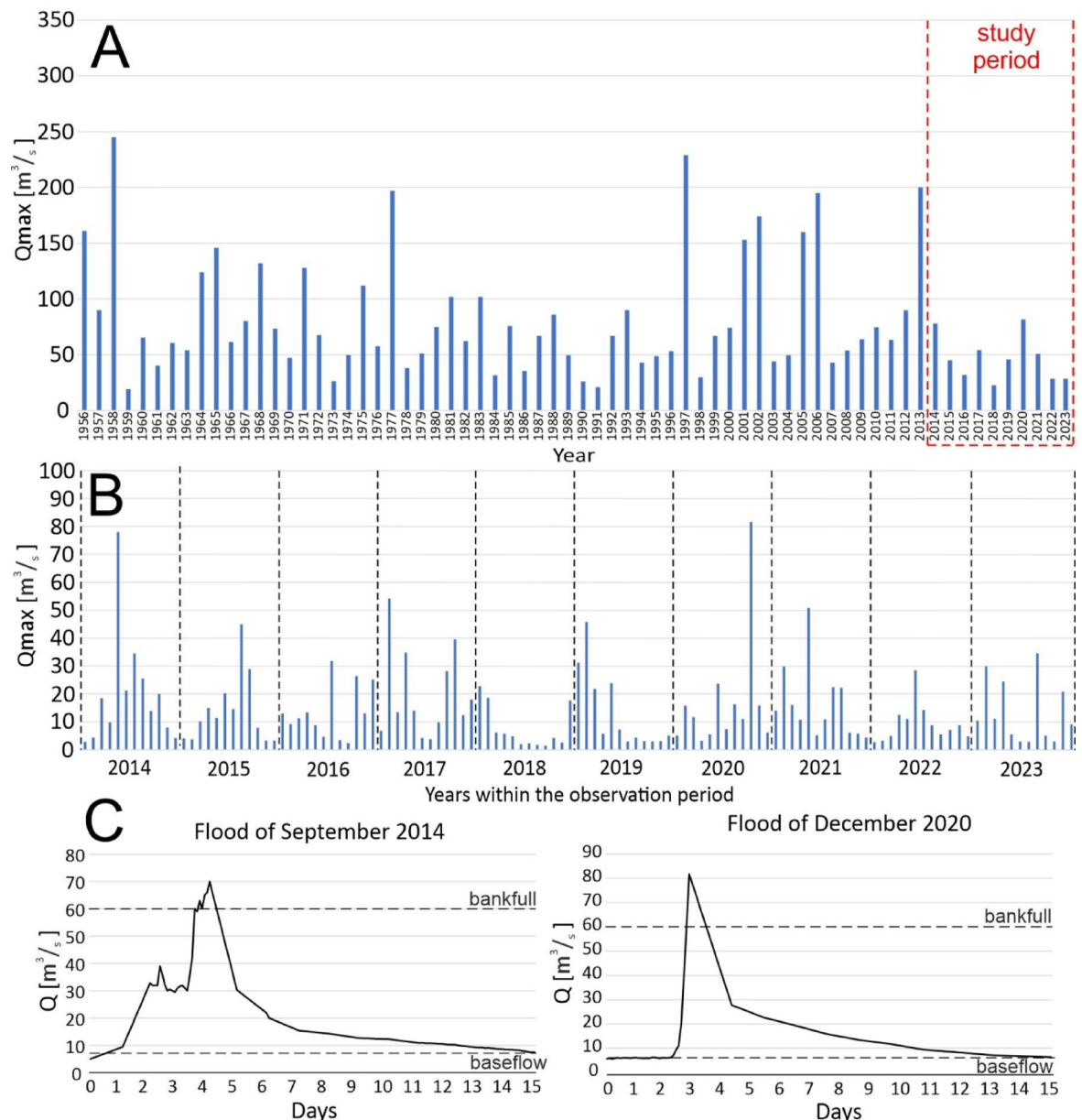


Fig. 7. Maximum annual flows on the Bóbr river recorded at Wojanów gauge station in 1956–2023 (A), maximum monthly flows during the observation period (B) and flood hydrographs from 2014 and 2020 (C).

Data availability

Data would be made available by the corresponding author upon request.

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Author contributions

PM: Conceptualization, Field Experimentation, Formal analysis, Writing original draft, Methodology, Preparing figures and Appendices, Literature research. SzJ : Field Experimentation, Formal analysis, Writing original draft, Methodology, Preparing figures and Appendices, RHS Analyzing. PN : Conceptualization, Field Experimentation, Writing original draft. KP : Field Experimentation. All authors reviewed the manuscript,

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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