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Bio-Inspired Designs for Conservation Gains in Hardened Freshwater Shorelines

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Abstract

Concrete walls and metal or vinyl sheet pilings are commonly used in freshwater systems, including lakes and rivers. Such hardened shorelines are used as a means of reclaiming land for development or as erosion control measures and are typically flat surfaces void of structural complexity. Natural systems, however, have high levels of habitat complexity that yield high volumes of surface area and interstitial space that can be used for refuge, feeding, or other important ecological functions by diverse freshwater organisms. Over the last few decades, there have been innovations in marine systems where hardened shorelines are being augmented by bio-inspired sea walls that include features (ranging from holes and crevasses to simulated mangrove prop roots) to achieve conservation gains for marine life. Freshwater biodiversity is in crisis, with habitat loss and degradation representing one of the most significant drivers of decline. Drawing on lessons learned from similar initiatives in marine environments, new pilot-stage work in freshwater systems have started investigating ways to integrate habitat complexity into hardened shorelines. These interventions offer a promising opportunity to improve conservation in landscapes that has been altered. This paper summarizes the extent of hardened shoreline use in freshwater systems and its contribution to the freshwater biodiversity crisis, presents a case study to develop, deploy, and test alternative structures (embracing learnings from the marine realm), and identifies practical considerations and research needs that must be overcome for such efforts to be widely embraced.

Keywords Freshwater biodiversity · Hardened shorelines · Habitat complexity · Erosion control · Conservation innovations

Introduction

For thousands of years, humans have created hardened shorelines in coastal marine and freshwater environments to reclaim land, prevent erosion and flooding, and/or create human infrastructure such as harbours, docks, and canals. Although it is well established that the protection and restoration of natural shorelines is desirable from an environmental perspective (Prosser et al. 2018; Cooke et al. 2022), that is not always practical or possible. Hardened shorelines can take many forms but are most commonly concrete or rock wall-like structures or steel or vinyl sheet piling, and occasionally wood (See Figs. 1 and 2). A common characteristic of a hardened shoreline is that it is void of the structural complexity that is inherent in natural shorelines (Gittman et al. 2016; Cooke et al. 2022). Homogenization of habitats, the hardening of shorelines, has widely been acknowledged for contributing to the loss of biodiversity and alteration of ecological and physical processes (Rahel 2002; Thrush et al. 2006; Bugnot et al. 2021). To that end, there has been interest in developing alternative types of hardened shoreline that attempt to maintain some of the structural habitat complexity typical in natural systems to achieve biodiversity gains.

There have been many innovations in shoreline hardening for coastal marine systems under the broader umbrella of nature-based solutions (Gittman et al. 2021), including living shorelines, which use biological components like mangrove forests, oyster reefs, or riparian vegetation to maintain coastlines with little human intervention (Morris et al. 2022; Morris et al. 2024). Most living shorelines are "self-sustaining," meaning they depend on natural processes

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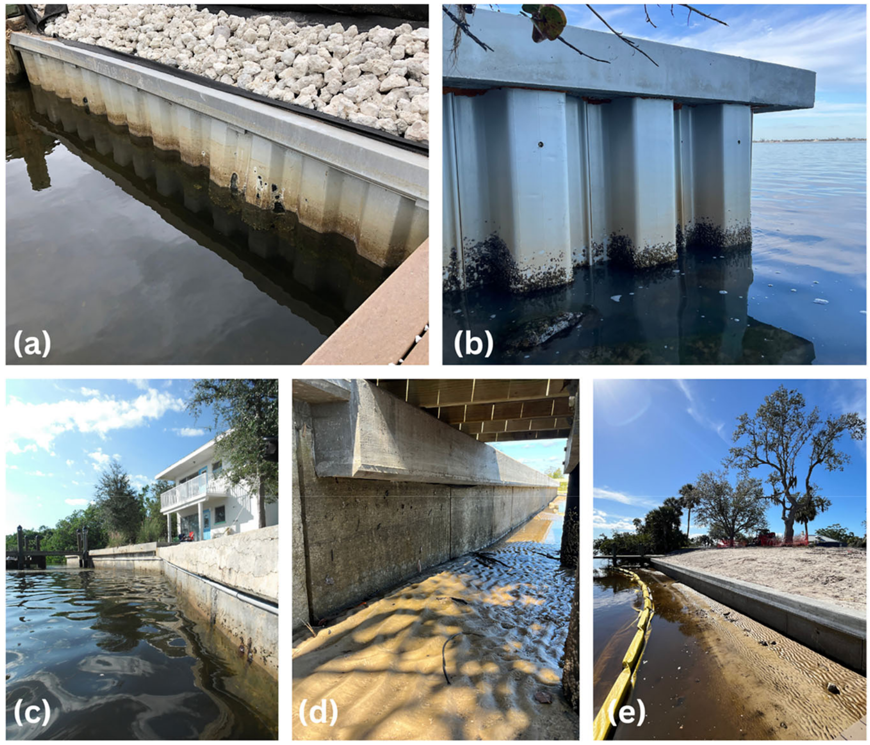

Fig. 1 Examples of hardened shorelines. **a** Aluminium sheet piling along a shoreline. **b** Vinyl sheet piling shoreline. **c–e** Various examples of concrete-based hardened shorelines, photo credits to Keith Van de Riet

Fig. 2 Examples of riprap shorelines, showing different rock sizes, placements, and configurations used for erosion control, photo credits to Mike Dusevic

to preserve their ecological and structural integrity. In tandem, eco-engineering, often known as the greening of grey infrastructure (GGI), is a rapidly expanding subject that focuses on constructing or retrofitting artificial structures to include habitat elements that promote biodiversity (Morris et al. 2019; Firth et al. 2024). For example, a Sydney, Australia-based eco-engineering project known as “the Living Seawalls project” enhances marine biodiversity on existing seawalls with textured, modular panels (Bishop et al. 2022). Since then, further eco-engineering initiatives have emerged in locations like Singapore (Loke et al. 2019), Hong Kong (Bradford et al. 2025; Lo 2023), the UK (Dennis et al. 2018), and Ireland (Firth et al. 2016). While maintaining the protective qualities of conventional reinforced shorelines, these initiatives seek to enhance ecological value. For marine species, bio-inspired eco-engineered panels that include features like tide pools or mangrove root simulations offer refuge, food sources, and possible spawning grounds (Kazemi et al. 2023). These efforts have led to the development of an entire industry supporting such efforts in coastal marine systems as part of nature-based solutions (Gittman et al. 2021).

To date, such efforts in freshwater have been limited aside from the widespread embrace of gabion baskets and rip rap, which are not always suitable, especially for situations where wall-like structures are needed. Freshwater biodiversity loss is higher than in other realms, with average population declines of over 80% according to the WWF Living Planet Index (WWF 2020), such that it is now acknowledged that we are facing a freshwater biodiversity crisis (Harrison et al. 2018). Humans have long been drawn to freshwater rivers and lakes to develop villages and cities, given the need for freshwater for irrigation, drinking water, electricity, and so on (Douglas 1994). Human encroachment on freshwater systems often involves hardening shorelines for flood protection, to mitigate erosion from currents and wave energy, or to create canals for the transport of people and materials. For example, there are some 63,000 km of canals worldwide, of which the vast majority are in freshwater systems (Lin et al. 2020). Canals often involve channelization and installation of lock infrastructure with extensive use of hardened shorelines, typically concrete or stone walls (Lin et al. 2020). Similarly, there are thousands of marinas and harbours and countless docks or retaining walls installed by shoreline property owners. The lack of physical habitat complexity along these widely distributed cemented shorelines represents a lost conservation opportunity. *What if all those hardened shorelines void of habitat complexity could be transformed to include more physical habitat complexity that, to some extent, emulates natural shorelines?* The cumulative benefits to biodiversity may be significant if even a small percentage of these constructions were modified to incorporate elements that mimic natural shorelines.

Here, we summarize the extent of hardened shoreline use in freshwater systems and its contribution to the freshwater biodiversity crisis, describe early efforts to develop, deploy, and test eco-engineered hardened shoreline structures (embracing learnings from the marine realm), and identify practical considerations and research needs that must be overcome for such efforts to be widely embraced.

Hardening and Simplification of Shorelines Negatively Impacts Freshwater Life

As a means of controlling erosion, hardened shorelines (e.g., concrete walls, metal or vinyl sheet piling; Sun et al. 2021) have been widely used in freshwater habitats, replacing dynamic natural features like vegetation, interstitial spaces, and irregular structures (Strayer and Findlay 2010) with flat, impenetrable surfaces (National Research Council 1990). These complex habitats are often absent from hardened, simplified shorelines, resulting in significant loss of ecological functionality. For example, small fish are frequently more vulnerable to predators and may therefore seek refuge in microhabitats that offer structural complexity, such as intricate surfaces or submerged vegetation (Savino and Stein 1989; Bradford et al. 2025; Ushiama et al. 2019). These types of microhabitats are not found in hardened shorelines and therefore lead to a reduction in habitat diversity and complexity, which are essential for supporting diverse aquatic life.

The resilience and biodiversity of freshwater ecosystems are often undermined by the loss of structural variety brought on by shoreline hardening, which has flow-on effects on ecosystem health (Gittman et al. 2016). Shoreline hardening considerably diminishes the biological functions of major waterways for many aquatic organisms by frequently preventing the growth of riparian vegetation (Fischer et al. 2018; Nack et al. 2015; Strayer and Findlay 2010; Wensink and Tiegs 2016). The loss of vital spawning, nursery, and refuge habitats for specialist species makes it easier for more generalist, eurytopic species to colonize and proliferate, which can be especially detrimental to some fish species (Ramler and Keckeis 2016). The ecological integrity of freshwater systems is jeopardized, and biodiversity loss is exacerbated when natural, structurally complex shorelines give way to hardened, simplified ones, which essentially change ecosystem dynamics. Making intricate structural adjustments to protected shorelines is more crucial than ever in light of these detrimental effects. Although restoring and protecting natural shorelines is ideal, soft engineering techniques have also been used extensively to manage erosion and improve ecological value in freshwater systems. These techniques include the use of vegetated buffers, the placement of large woody debris, and bioengineering methods (Gippel et al. 1996; Kondolf et al. 2006; Roni et al. 2015). Therefore, freshwater systems may require more creative shoreline hardening methods, and marine efforts might serve as an inspiration for these potential solutions. While protecting and restoring natural shorelines ought to be a priority, there may be ways to enhance freshwater biodiversity and ecological function by installing environmentally friendly hardened surface designs when appropriate.

Learning from the Marine Realm

The adaptation of artificial reefs from offshore environments to inshore seawalls and intertidal ecosystems has gained momentum only in the past couple of decades. Early attempts at eco-engineering include simple changes such as planting planter boxes to create plants on vertical surfaces (Waltham and Sheaves 2018) or making large holes in seawall blocks (Edwards 1994; Chapman and Underwood 2011). These pioneering techniques opened the door for more intricate, modern developments like engineered salt marshes (Strain et al. 2018), man-made rock pools, the Living Seawalls project in Sydney (Bishop et al. 2022), and Mangrove Reef Walls in Florida (Bridges et al. 2021). Prior to this emerging trend in marine-friendly bulkhead design, the prevailing standard was an “all or nothing” approach to conservation gains, with living shorelines as the sole alternative to hardened waterfronts. However, living shorelines require adequate area and suitable water depth requirements that are often incompatible within densely developed canal environments, particularly those that provide water access for area residents (e.g., requiring functional docks, boat mooring, recreational access, etc.). Even in those situations that can accommodate natural living shorelines, communities may exhibit resistance to blocking waterfront vistas or access to water in public and private areas, which further limits the likelihood of living shorelines being widely adopted in these environments (Osland et al. 2022). Thus, alternative approaches to establishing natural inspired systems alongside developed shorelines are needed.

Studies have shown human-made structures have the potential to support diverse marine life and increase the filtration capacity of altered shorelines well beyond that of existing natural edges due to the added surface area

(Layman et al. 2014). However, seawalls and other marine structures are relatively featureless vertical conditions and lack the structural complexity of natural intertidal habitats (Gittman et al. 2016; Chapman and Blockley 2009; Firth et al. 2015). Furthermore, studies show supporting evidence that extending the available habitat across areas of human-altered landscapes would provide a simulacrum of the historical natural shoreline. One survey found that replacement of large swaths of landscape (50-80%) causes dramatic decline in species richness within human-altered shoreline environments in marine and estuarine settings, whereas fragmentation that permits patches of habitat to exist within proximity to each other has little to no effect on most near shore marine species (Harwell et al. 2011; Bishop et al. 2017; Aguilera et al. 2020).

Eco-engineering projects have been carried out all over the world, including global-scale tile experiments such as the World Harbour Project (Strain et al. 2021) and a recent follow-up (Mayer-Pinto et al. 2024), as well as projects in the United States (like Florida and California; Patranella et al. 2016), Asia (like Singapore and Hong Kong; Loke et al. 2019; Bradford et al. 2025), Australia (like Living Seawalls), and Europe (like the UK and Ireland; Dennis et al. 2018; Firth et al. 2016). However, it is important to note that the impacts of these eco-engineering projects have varied across different latitudes and environmental conditions. These examples demonstrate the scalability and worldwide applicability of nature-based design breakthroughs and reaffirm the importance of learning in diverse geographic scenarios. In terms of the evidence for increasing habitat complexity in marine or estuarine canal environments, several studies show the benefits of even relatively simple additions to these environments. In one study near Sarasota, Florida, artificial structures of varying composition were placed against seawalls in canals and resulted in a density of fish present 200 times that of control areas without the structural treatment (Edwards 1994). In a 14-month study in Dania Beach, Florida, researchers found significantly higher species abundance and richness in artificial reefs placed adjacent to seawalls (Patranella et al. 2016). Using eco-engineered tiles, a study conducted in Sydney Harbour, Australia, discovered that reintroducing habitat complexity to marine urban structures can improve biodiversity and that a range of habitat features that are suited to species-specific and environmental gradients are essential for long-term support of diverse communities (Bishop et al. 2022).

The adoption of eco-engineering is heavily influenced by stakeholder communication and public perception, in addition to design and ecology. Several studies have stressed the significance of community perception research (e.g., Kienker et al. 2018; Strain et al. 2019; Ying et al. 2024) and stakeholder-oriented recommendations (O'Shaughnessy et al. 2020) to guarantee that designs satisfy both social and environmental requirements. Projects in freshwater that seek to duplicate marine success stories can benefit from these strategies. The widespread adoption of eco-engineering faces both design and regulatory challenges. Environmental permitting for waterfront construction may involve multiple local, state, and federal agencies, and depending on the waterbody, may require special reviews for imperilled species. In some cases, policies put in place to regulate the negative impact of waterfront construction may create barriers to remedial approaches (USACE 2024). However, with an increase in awareness and growing acceptance for living shorelines and eco-engineering, regulatory agencies have begun to make efforts to reduce barriers to projects that integrate nature-based solutions (Sloey et al. 2025). In terms of design challenges, the functional requirements of seawalls and canals create limited areas for natural systems, and the location and visual impact of integrating natural systems can meet with property owner opposition. Therefore, the design of shoreline structures to support natural systems may need to consider the functional and aesthetic dimensions to become widely accepted.

Seawalls, piles, and other dock structures create surface area, and the choice of building material can play a substantial role in supporting tidal species (Chase et al. 2016; Theuerkauf et al. 2014). For example, the seawall industry has largely shifted toward vinyl and composite panels in many areas, and these new materials have gained a reputation for deterring oyster recruitment (Tomasko 2023). This is particularly troubling because oyster reef decline has been recorded globally, estimated at 85% (Beck et al. 2011; McAfee and Connell 2021; McAfee et al. 2020). Additionally, recent historical assessments have highlighted the disappearance of oyster reefs in Europe by revealing their former extent (Thurstan et al. 2024). Thus, the shift toward materials that inhibit recruitment of natural systems threatens to undermine the last remaining surfaces oysters are clinging in these environments. Fortunately, there is a growing movement to address hardened shorelines with enhancements or alternatives that reestablish oyster reefs and the associated habitats.

One such alternative uses biomimicry to create an eco-engineering panel, known as "Mangrove Reef Walls(see Fig. 3). These mangrove-inspired habitat panels have been installed on the east and west coasts of Florida beginning in 2016(Bridges et al. 2021; 2016; Fleshler 2016; Meszaros 2017). The panels mimic the aerial prop root patterns of Red Mangrove (*Rhizophora mangle*), and incorporate a variety of habitat features, including textured surfaces, pockets and holes, and root-like extensions. The panels are made from marine-friendly concrete, which is designed to accelerate recruitment of marine organisms, and the installation of panels fits within

Fig. 3 Mangrove Reef Walls as an example of biomimicry in shoreline engineering. These eco-engineering panels mimic natural mangrove root systems to enhance habitat complexity and ecological value, photo credits to Keith Van de Riet

environmental permitting exemptions for seawall enhancement projects. In one installation, the panels were applied over an existing aluminium seawall, completely devoid of oysters prior to the introduction of the concrete panels. Within a year and a half, a thriving oyster reef was established at the furthest end of a canal, which may be attributed to the material used in attracting marine organism (see Fig. 3). Over several years since the first installations, the panels have been observed to support dozens of species, including larger recreational fish, such as Common Snook (*Centropomus undecimalis*), hiding below the panels, and multiple species of Herons (*Ardeidae*) using the panels to perch or hunt for prey. Lastly, the introduction of these types of artificial reefs can add value to waterfront properties; the panels are eligible for Waterfront Edge Design Guidelines (WEDG) credits, which contribute toward environmental certification of a shoreline as identified in the WEDG Manual in Credit 3.1 Edge Compositions (WEDG 2023). The adaptation of marine habitat panels toward structurally complex hardened shorelines in freshwater ecosystems may be mutually beneficial. Lessons learned on both fronts can inform a more effective approach to addressing the challenges of integrating nature-based designs within human-dominated environments.

Exploring Use of Structurally Complex Hardened Shorelines in Freshwater Systems

The ecological issues raised by conventional shoreline armoring techniques frequently lower habitat complexity and species richness. There is a need to better understand how alternative structures for hardened shorelines in a freshwater context can be used for conservation gains. The studies discussed below summarize controlled laboratory and field experiments intended to advance the development and application of structurally complex hardened shorelines in freshwater ecosystems.

The first phase of this research study began with a laboratory experiment of fish behaviour by Frempong-Manso et al. (2024). This study tested how Bluegill (*Lepomis macrochirus*) of different size classes responded to panels with varying habitat complexity, constructed using bamboo and mounted inside experimental raceways. After a 10-minute acclimatization period, the fish were observed for 20 minutes during the exploring phase, and their positions relative to each treatment were measured over time. The findings indicated that fish, while there was variance within fish size classes, the proportion of times that fish spent near the treatment panels generally increased with panel complexity, with smaller bluegills favoring the highest level of habitat complexity and larger bluegills favoring both medium and high habitat complexity. These results demonstrated the significance of adding complexity to shoreline hardening designs that support fish of various life stages and brought attention to ontogenetic variations in habitat preferences. By using a laboratory experiment, the researchers were able to explore and understand important ecological principles, such as habitat complexities preferences that would help inform future shoreline hardening designs for this research project.

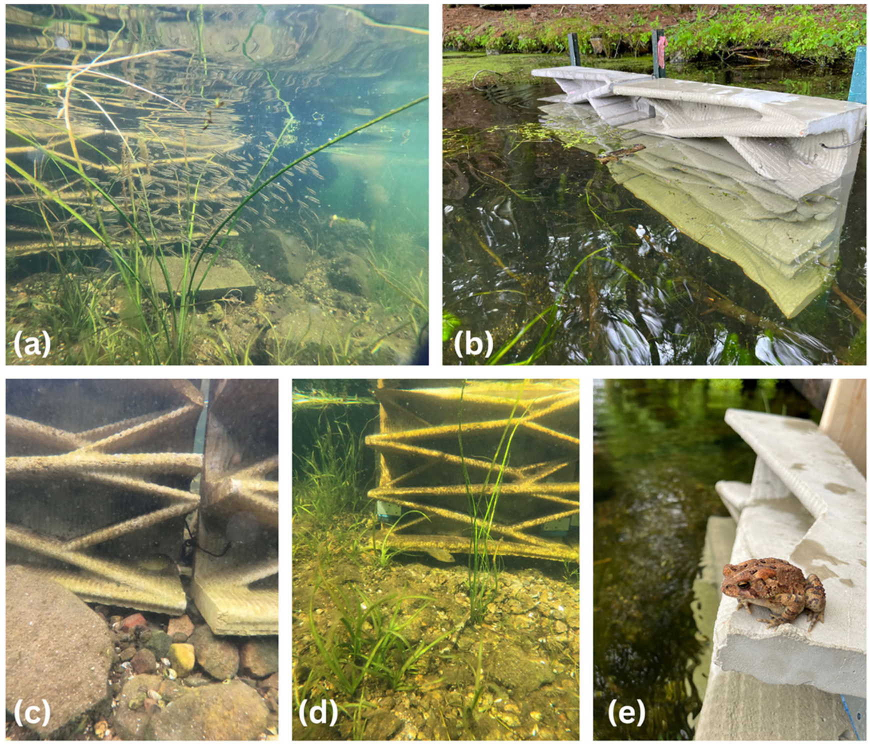

Fig. 4 Wildlife interactions with textured panels used in a freshwater shoreline habitat study. **a** A smallmouth bass fry ball swimming near a textured panel. **b** Textured panels deployed in a lake during a short-term study. **c** A rock bass using a textured panel as shelter. **d** A bluegill utilizing the textured panel. **e** A toad observed using the textured panel, photo credits to Acacia Frempong-Manso

In a second lab study, Frempong-Manso et al. (2025) assessed the habitat preferences of four fish species: Rock Bass (*Ambloplites rupestris*), Banded Killifish (*Fundulus diaphanus*), Bluegill, and Yellow Perch (*Perca flavescens*). Similar to the first lab study, fish were placed in experimental raceways, and we assessed their habitat complexity preferences. Fish were exposed to three treatments that varied in structural complexity, and different relief depths of 5.08 cm, 7.62 cm, and 10.16 cm. Each species exhibited a different pattern of use across the panel designs, reflecting their differing ecological traits and habitat needs. For example, Banded Killifish were more commonly found next to lower-relief treatments, whereas species such as Rock Bass and Bluegill favoured panels with deeper relief depths. We found that habitat use was influenced by both species and treatment type. The proportion of time spent near the panels revealed species-specific preferences that were related to the degree of habitat complexity, consistent with their natural habitat requirements. The complexities of natural systems cannot be replicated by laboratory studies alone, but it is a crucial first step. By bridging the gap between theory and practice, the insights obtained by these two laboratory studies served as the basis for scaling up the work to field settings.

To assess the ecological viability of these designs in natural freshwater settings, researchers (i.e., Frempong-Manso, Van de Riet, and Cooke, unpublished data) moved from controlled laboratory experiments to field applications. Concrete panels were placed along certain shoreline segments in Lake Opinicon (a part of the Rideau Canal Waterway) in eastern Ontario, Canada, as part of field experiments, and fish community structure and behaviors in the vicinity of different treatments were tracked over a two-month period during the summer (which is a limited study length compared to other studies). Four distinct treatment types were tested: natural shorelines (unaltered shorelines), altered shorelines (physical or man-made modifications), flat concrete panels (traditional shoreline hardening), and textured panels (textured panel with natural forms; see Fig. 4b). In order to evaluate biodiversity outcomes in realistic contexts, these interventions were positioned in locations on Lake Opinicon that are vulnerable to boat traffic and various forms of recreational pressures such as fishing and non-fishing activities (i.e., swimming, kayaking, and wildlife viewing). The study area includes zones with moderate boating activity, while there are no formal boating restrictions, certain fishing activities are regulated. Preliminary findings show, fish abundance differed depending on the type of treatment. More fish were found to be supported by flat panels and natural shorelines as opposed to textured panels or modified shorelines. Bluegill and pumpkinseed, for instance, were found in all treatments, demonstrating their adaptability to a variety of environmental conditions. Logperch (*Percina caprodes*), on the other hand, was only found close to natural shorelines, indicating a greater reliance on characteristics not seen in man-made structures. In contrast, species like Smallmouth Bass (*Micropterus dolomieu*) and Largemouth Bass (*Micropterus salmoides*) were

Fig. 5 Demonstration installation of textured panels in the Rideau Canal at Dows Lake in Ottawa, Canada. This setup was designed to show waterway managers and regulators how the panels could be used in real-world applications, photo credits to Sean Landsman

more frequently seen near textured panels, which may suggest that they prefer more intricate structures. These results imply that the placement and design of eco-engineered textures are important, even though they might not always enhance biodiversity on their own. When assessing the ecological efficacy of shoreline improvements, they also stress the importance of considering the habitat needs of specific species rather than merely their overall abundance. However, this field trial laid the foundation for future work and provided valuable information on the feasibility of installation methods and design.

To demonstrate how textured concrete panels could work in a practical environment, a demonstration installation was carried out at Dow's Lake, a popular public area within the city of Ottawa, Canada, as part of the project's outreach and feasibility assessment (see Fig. 5). The purpose of this phase was to provide local waterway managers and regulators with a tangible example of how these habitat-enhancing structures could be incorporated into vertical wall environments. Despite the lack of formal data collection during this phase, it was crucial in identifying logistical considerations for future deployments, improving installation methods, and visualizing possible uses (Frempong-Manso, unpublished data). In essence, this step was needed for habitat practitioners to see what was possible in a relevant field context. In addition to being a significant first step toward wider adoption, the demonstration demonstrated the feasibility of incorporating fish habitat structures into already-existing hardened infrastructure.

Recognizing that community support is essential for the effective implementation of eco-engineered designs, researchers designed a study to understand cultural and recreational ties in the Rideau Canal shape perceptions of shoreline hardening, and support for alternative shoreline stabilization methods (Frempong-Manso, unpublished data). Through the use of a structured social science survey, various viewpoints on the topic were elicited and collated. Many residents voiced their support for environmentally friendly shoreline designs, emphasizing the value of preserving biodiversity and enhancing the biological health of the canal. Others expressed worries about the panels' appearance, the possible expenses of upkeep and installation, and the possible effects of such modifications on the canal's historic character. Recent research on public attitudes toward eco-engineering have revealed similar results, highlighting the significance of striking a balance between ecological results and aesthetic and cultural values (Huang et al. 2025; Dodds et al. 2025). For this type of shoreline hardening method to be fully adopted, both cultural and aesthetic factors must be balanced with ecological benefits. Ultimately, demonstrating that effective conservation tactics need to incorporate local communities' values and lived experiences with scientific research.

Practical Issues and Research Needs

While novel, structurally complex shoreline hardening methods show promise, there are several practical issues that need to be resolved before they can be widely adopted in freshwater systems. Seasonal changes pose serious problems, particularly in areas with severe winters. The frequent cycles of freezing and thawing make fully hardened concrete susceptible to frost and/or ice damage. The severe freeze-thaw cycles paired with the presence of water lead to concrete structures having accelerated structural wear and degradation, exacerbating deterioration challenges for shoreline hardening (Islam et al. 2010). Therefore, it is critical to design long-lasting adaptations for shoreline hardening that can withstand these recurring fluctuations will involve finding a balance between ecological functioning and resilience.

The addition of intricate habitat features to existing hardened shorelines poses practical challenges compared to starting from scratch. The most practical and economical solutions will be those that can be easily integrated into existing infrastructure. However, modifications to shorelines will need to be tailored to environmental conditions specific to that ecosystem and region. For example, because the ecological dynamics and habitat requirements differ greatly in marine and freshwater environments, a design that is best suited for a marine habitat will likely not be appropriate for a freshwater habitat. To ensure that ecological benefits are maximized, these designs will need to be ecosystem specific, and context driven. Moreover, the work described above is largely focused on fish. There is a need for additional research on periphyton, invertebrates, and herptiles (among other taxa) to understand the potential ways in which structurally complex panels may be colonized or used by other taxa.

This type of work will require an interdisciplinary strategy that strikes a balance between technical and ecological considerations. Material science will be essential during this process, as building materials such as steel, concrete, rock, or wood are typically used for shoreline hardening methods due to their engineering value and longevity (Nordstrom 2014), and their ability to prevent the spread of invasive species that could take advantage of these structures. Previous studies suggest that while artificial structures might increase the diversity of species in an area, they can also help invasive species spread and may not fully mimic natural habitats (Bulleri and Chapman 2010; Burt et al. 2011; Chapman and Bulleri 2003; Gauff et al. 2023; O'Shaughnessy et al. 2020; Schaefer et al. 2024). However, this offers an opportunity to investigate how materials and designs may be improved to better support native biodiversity, enabling man-made structures to work as useful extensions of natural habitats in areas that are hardened. For example, invasive Zebra Mussels (*Dreissena polymorpha*) are common in many freshwater systems, such that it is possible that some materials would become fully encrusted thus potentially eliminating interstitial spaces that were part of the design features.

Shoreline habitats are mostly shaped by the hydrologic regimes or the natural pattern of water level variations. Water level oscillations can render these habitats unsuitable or even lethal for certain species. For instance, boat wake and wind-waves can strand young fish or dry up nests (Adams et al. 1999; Wolter and Arlinghaus 2003), and wind-driven seiches around Lake Erie have stopped zebra mussels from establishing on shallow soils (Bowers and de Szalay 2005). These water flow patterns are altered by hardened shorelines, and human-induced hydrological alterations can have rapid and significant impacts on ecosystems nearby (Lanham et al. 2025, Strayer and Findlay 2010). Research must therefore measure the overall ecological effects of shoreline hardening on ecosystems and investigate how different species groups react to these changes in shoreline modifications.

Social science research can provide insight into public opinion and acceptance by identifying potential adoption barriers and developing communication strategies to foster community support (Grey 2017). This research focus could help us develop shoreline alteration techniques that are not only socially and environmentally sustainable but also enhance freshwater ecosystems overall. Promoting the ecological and aesthetic advantages of these structures to stakeholders, especially municipalities and property owners, will require public acceptance and community support. However, it can sometimes be difficult to balance both the economic and social needs of all parties due to disparities in stakeholder preferences and interests, particularly for those who own waterfront properties. Conflicts frequently arise in the governance process because of different opinions on the risk that these hardening methods pose (Lubken et al. 2011) and the efficacy of erosion control techniques (Prati et al. 2016). It will be crucial to characterize the viewpoints and attitudes of stakeholders, especially property owners and municipal government officials, to ensure the effective implementation of these structures. Understanding these many points of view allows for the improvement of communication strategies and the customization of educational programs, which would increase community support and public acceptance needed to achieve wider support for the aesthetic and ecological advantages of using different shoreline hardening methods (Gray 2017).

Conclusion

While there is much promise for improving freshwater ecosystems through eco-engineered shoreline designs, several obstacles need to be overcome before they can be widely implemented. The work conducted on this topic in freshwater systems thus far have demonstrated that practical application will require striking a balance between biological requirements and structural durability, particularly in regions vulnerable to extreme weather events like freeze-thaw cycles. Materials that can tolerate environmental stressors and sustain biodiversity must be used in shoreline designs to ensure long-term durability. The successful integration of eco-engineered shorelines will also depend on social acceptance. Communities sometimes hold differing opinions on the long-term feasibility, cost, and aesthetics of such initiatives, especially municipalities and owners of waterfront properties. To overcome these obstacles, fostering public and government (especially municipal/regional) buy-in will require addressing issues around the upkeep and appearance of these structures, as well as understanding local viewpoints. Additionally, studies on design elements and materials must continue to look for ways to maximize the benefits that these structures provide for native species while not benefitting invasive species. These structures offer an opportunity to achieve conservation benefits associated with shoreline alterations and serve as a practical tool in contexts where the maintenance of natural shorelines is not feasible.

Data availability

No datasets were generated or analysed during the current study.

Author Contributions AFM led the conceptualization and writing of the manuscript. KVdR contributed to the conceptual framing and provided critical input on eco-engineering design considerations. SJC provided guidance on structure, contributed to the development of key ideas, and reviewed and revised the manuscript. All authors contributed to manuscript revisions and approved the final version.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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