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Environmental benefits of marine concrete structures

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Abstract

Environmental sustainability and adaptation to climate change are two of several reasons floating structures are of great interest. Their resilience toward rising water levels and the possibility they allow to avoid additional land use are two specific factors that have influenced a flourishing of studies on floating structures and also several applications, for example in the transport field or in food and energy production. Moving from land to water implies taking care of a new complex environment throughout all the phases of the construction and during the whole life cycle of the structure. It is necessary to take care of the marine environment since the early phases of the conceptual design of the structure, to really consider the environment as one of the decisional information on the best-suited solution for each specific case, avoiding later costly mitigation measures and using the possibility to create environmental benefits with the change. The working party WP 1.2.3 of TG 1.2 of Fib presents in the present paper the potential environmental risks and potential benefits for concrete floating structures to promote an increased awareness of the marine environment with the involvement of different expertise from the early phases of the project.

1 | INTRODUCTION

The constant increase in the use of land in recent years (Figure 1) in a world with a descendant population growth rate (source: Our World in Data) shows that we have reached a situation of per capita area requirement that is now unsustainable, which calls into question the sustainability of the entire anthropic system. To counteract the continuous increase in land use, several policies are implemented by different states, following the national rules on environmental protection.

One of these policies involves the protection of natural areas not yet anthropized, with consequent limitations on construction interventions. In the search for compatible solutions and new areas of expansion, the marine (or aquatic in general) surface is of great interest. Floating bridges, civil constructions, energy, and industrial production facilities are among the structures cited in Fib Bulletin No. 91 that have found new applications in the marine environment. The new installation area, however, involves new challenges both from a structural point of view and in terms of the effects that the structure generates in the surrounding environment.

It is therefore essential to know the effect that the structure and its use will have on the marine environment, for example in terms of impact on the biological environment, during the construction phases and throughout the whole life of the structure. These are the premises for the present bulletin: to move the attention to how the environmental analysis in the early conceptual phases of the project serves to design optimized structures also for the environment in which they are installed, trying to avoid expensive mitigation

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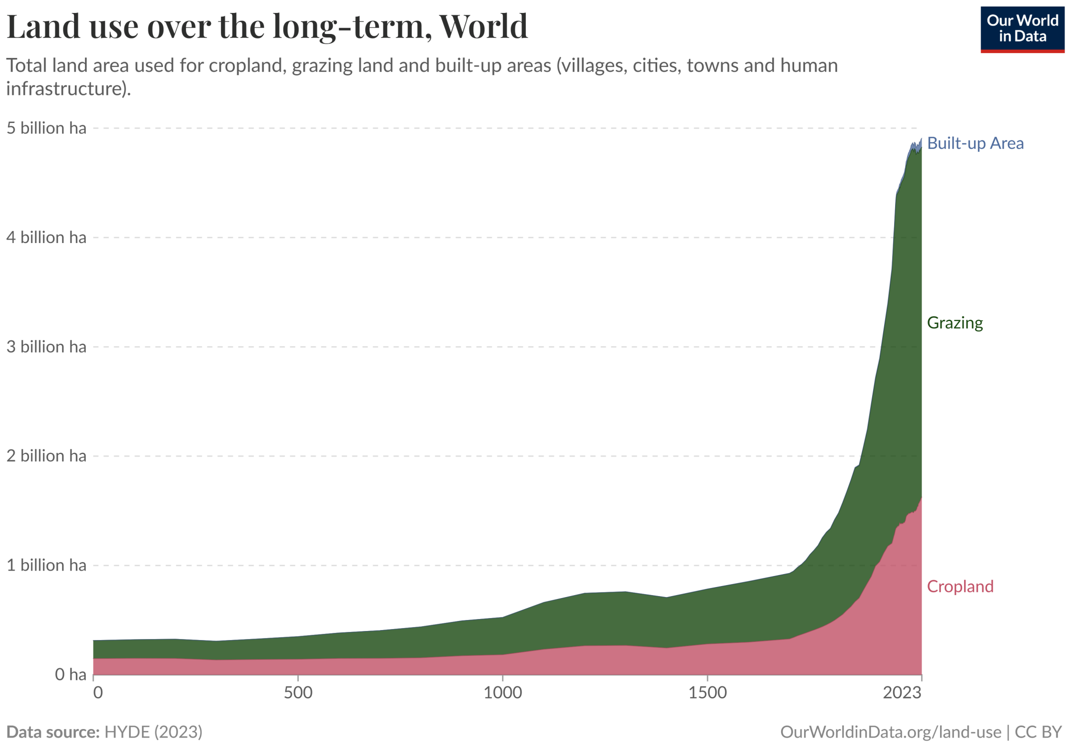

FIGURE 1 Land use in time, Source: Our World in Data.

measures inevitably necessary at a later stage and considering the floating concrete structure as a living part of the marine environment, along the whole life of the structure. The studies to which the bulletin refers and the involvement of experts in the structural but also biological sectors have made it possible to illustrate in general the risks that are encountered with a design limited only to the structural assessments, relegating the environmental considerations to a late phase, in which the choices already made are binding and the environmental issues can only be addressed with mitigation measures. At the same time, the studies shed light on the possibility of exploiting the insertion of concrete structures in the marine environment for solutions that could be favorable to the specific site environment if properly designed and monitored by experts in the field. The scope of the bulletin is then to promote interdisciplinary collaboration in the early stages of the design to consider the specific environment where the structure is built among the needs of the project.

The bulletin is addressed to all those who deal with floating structures and who care about the marine (or aquatic in general) environment. For this reason, the choice of the working party has been to adopt an illustrative presentation and a conversational language, limiting the technical details and referring to specific studies.

1.1 | Floating structures: definition and challenges

Floating structures have existed since ancient times. Even if there is no unique definition to cover the variety of these types of structures existing nowadays, exhaustive examples have been mentioned in previous publications (Figure 2, Fib Bulletin No. 91).

Floating structures can serve multiple scopes, from transport purposes to food or energy production to civil scopes, and so on. They have been constructed with a multiplicity of materials, among them concrete. Concrete in floating structures is chosen for its durability, low maintenance, and because it also serves the function of ballast, helping the structure counterbalance buoyancy. One of the challenges of concrete is its mass, especially toward the hydrodynamic loads the structure has to withstand. On the other hand, concrete has proven to be a durable material with low maintenance requirements. This, combined with the capability of floating structures to be less subject to climate change effects, such as rising water levels, makes them an attractive alternative for future durable designs.

For the purpose of the present document, we will consider concrete floating structures, including all their parts: foundations, anchorages, submerged and floating parts, and parts emergent from water.

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FIGURE 2 Floating structure, Fib bulletin 91.[1]

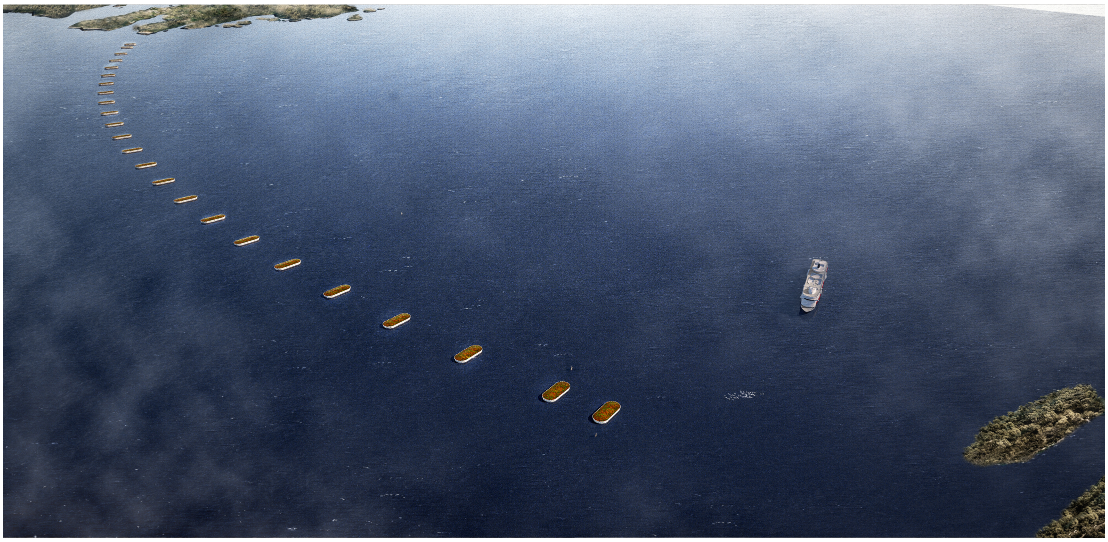

FIGURE 3 Study for crossing the Bjørnafjord with a pontoon floating tube bridge, Statens vegvesen.

1.2 | What is meant by benefit?

"Benefit" is defined as "an advantage or profit gained from something" (Ref. Oxford Languages).

For the use in the present document, regarding floating structures, we can speak about "benefit" as "net benefit" when we create a final situation better than the initial one (not generally, but for a specific issue).

An example of this meaning can be given by mentioning a study done by the Norwegian Public Roads Administration for crossing the Bjørnafjorden with a submerged floating tube bridge.[2] The solution with floating pontoons, which had the structural scope to vertically stabilize the twin-tube structure, was developed to create a new nesting area for birds on the pontoon surface (Figure 3). Since several areas along the coast are populated with red-list bird species and due to the presence of infrastructure along the coastal development in Norway, the possibility of realizing new nesting areas for birds was a way to considered as a possibility of improvement for some the local fauna since the beginning of the feasibility study.

On the other hand, a choice reflecting a positive improvement for a specific aspect could have negative or not-so-positive effects on other issues, as discussed further in the present document.

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Therefore, the definition of a level of improvement that is not defined as “net benefit” but can be called “relative benefit” is also used. This one is related to the lower level of environmental impact we can get by considering the environment from the beginning instead of the end.

As an example, still referring to the study mentioned previously, it is when the submergence of the structure is defined without taking into consideration eventual negative effects on local species that, for example, use that specific water level range, such as some specific type of fish. Some fish, like, for example, migrating salmonid fish, could use a specific water height range to enter a fjord from the open sea, and the presence of a structure at that same water height could represent a potential adverse ecological effect. We have often observed how species perform in a resilient way over time toward the presence of anthropic changes, modifying their behavior in order to take care of the anthropological presence and reach their scope. Fish or birds, which initially move away from an area subjected to recent anthropological changes, return to the same places after a period of time, modifying their route to take into account the variation in their habitat. But this situation, which may also lead to consequences of raising the risk threshold for red-listed species or which may lead to economic implications for the free fish market in the mentioned example, could, however, be avoided. Once the depth of submergence is defined, only mitigation measures are possible, while the potential adverse impact could have been avoided by including specific environmental information in the early design requirements (Figure 3).

1.3 | Planning or mitigation?

Considering the environment in the early stage of the design makes a difference.

The impact of the design choices that the predictable environmental impact can have on a project is radically different if we take into account the “environmental topic” in the early design stage or after the main decisions are made.

The difference can be explained by the words “planning,” on one side, and “mitigation,” on the other. Planning is related to “the process of making plans for something” (Oxford Languages). It implies a consideration of an issue and a consequent arrangement of further actions to take care of that issue. In the use of the present document, planning for the environment means considering the environment in the early stages of the design. This implies, first of all, gathering the knowledge of the local environment the designers are going to work in. Then, to understand the possible impact of the design on the environment and adapt the design consequently, everywhere possible.

On the other hand, relegating the consideration of the environmental impact to the mitigation procedure means taking all the principal decisions related to the project and considering the environment only at a later stage, having just the possibility to try to minimize the negative effects.

The scope of the present document is to show the importance of considering the environmental topic since the early stages of the design, showing the possibility of reaching positive results for the environment but also for the project, both in economic terms and from a sustainable perspective.

In the following chapters, examples of issues to consider when operating in a marine scenario are shown to help the community develop an awareness of the topics to consider in this precious and complex environment.

2 | POSITIVE OR NEGATIVE? EFFECTS OF CONCRETE FLOATING STRUCTURES ON THE MARINE ENVIRONMENT

Constructing in the marine environment could involve a series of possible environmental impacts that must be taken into consideration. A study done on the environmental impact of floating bridges in Norway (Figure 4,[3]) has categorized four types of impacts: habitat alterations, noise pollution, light pollution, and gateways, as shown in the following Table 1. All four categories could affect aquatic and terrestrial organisms and should be evaluated in both the construction and the operation phases of the structure.

All these elements could have negative or positive aspects, depending on the detailed information available on the local environment, on the choices made for the design with the help of environmental experts, and on the monitoring of the construction during the construction and the operational phase (in specific moments defined by the experts' group).

2.1 | The biological environment

The introduction of concrete structures to the marine environment can have profound implications for marine ecosystems. Many ecological implications have been documented in relation to the foundations of wind parks, oil and gas facilities, harbor expansion, etc.[4,5] Perhaps the best-known ecological impact of marine concrete structures is the introduction of artificial hard

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FIGURE 4 Study for a floating bridge to cross the Bjørnafjord, Statens vegvesen.

TABLE 1 Suggested evaluations for the different possible impacts.

Possible impact	Detailed evaluation
Habitat alteration	• Hydrodynamics • Artificial reefs • Migration barrier • Connectivity • Road fills
Noise pollution	• Noise during the construction phase • Noise during the operational phase
Light pollution	• Artificial light sources
Gateways	• Gateways to new ecosystems for predators

substrate.[6,7] Communities of benthic organisms are highly dependent on the type of substrate. Sandy or muddy, soft sediment attracts, for example, organisms that can bury themselves into the seafloor, such as polychaete worms, certain shellfish, certain species of crabs, and flatfish. Hard substrate, such as rocks or oyster beds, attracts species that can attach themselves to the substrate, such as anemones, mussels, coral, or algae (in shallow waters). In turn, the type of benthic community attracts different types of free-roaming species, such as fish, marine mammals, and seabirds.

The introduction of artificial hard substrate, therefore, alters the composition of benthic species, which may have a cascading effect throughout the higher trophic levels.[8] Whether this alteration is good or bad is extremely difficult to determine and is (to some extent) open to interpretation. For example, it might destroy a local soft-sediment community that includes species that are rare or species that have a high commercial value for fisheries.[5] Artificial hard substrate could also attract non-native species, which could have profound negative impacts on an ecosystem.[9] On the other hand, the introduction of artificial hard substrate can also help to restore local ecosystems,[8,10] for example, by replacing lost natural hard substrate (such as lost oyster banks due to trawling in the North Sea during the 19th century). It is also known to have a generally positive effect on the overall biodiversity, as it provides shelter for fish and crustaceans.[4] In some situations, carefully designed concrete objects have been deliberately placed in marine ecosystems for the sole purpose of nature restoration.[10] It has also been suggested as a solution to hold mooring/anchoring lines, chains, and cables in place, thus preventing damage to benthic communities due to moving cables, lines, and chains.[4] The location, size, and shape of artificial hard substrate should be carefully considered to minimize adverse ecological impact and maximize potential positive effects. In addition, careful long-term monitoring after placement is tremendously important, as it is extremely difficult to accurately predict how artificial hard substrate will impact the ecosystem prior to placement.

Another ecological impact is perhaps less known but may be equally important. For example, any measures taken to prevent biofouling may introduce polluting chemicals in the water, such as zinc, indium, and bisphenol A.[11] Concrete structures that move over the seafloor (e.g., as part of anchoring systems) can have a devastating effect on soft-sediment benthic flora and

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fauna.[4] In addition, activities related to the installation and removal of concrete structures may have numerous ecological consequences, which should be considered carefully. In particular, noise from pile-driving activities, disturbance to the seafloor, and the potential for chemical pollution should be avoided or reduced as much as possible.[12]

While many studies have focused on the effects of concrete structures that are placed on the seafloor, only a few studies have yet addressed the ecological impact of floating structures. Floating structures can influence the marine environment in several ways. For example, they might hinder the migration of certain fish species,[13] or they can provide shade and shelter for a range of species, including fish and marine mammals.[9] However, the long-term population effects of floating structures remain largely unknown.[3]

In conclusion, a positive effect of the floating structure on the marine environment can be achieved only with the involvement of specific environmental experts from the early stage of the project, which could bring the local environmental knowledge and needs among the project's requirements and guarantee a positive long-term effect on the environment with the necessary observation and follow-up along the project's life.

2.2 | Underwater soundscape—louder and louder!?

During the last decades, a heightened awareness has risen when it comes to sound in the ocean. The lack of attention over the years has most likely been due to the fact that everyday life on land is not directly exposed to noise pollution, specifically addressing the aspect of disturbances invoked on human areas of settlement, with e.g., piling noise, windmill humming, or other sounds that can be considered as pollution. There is, however, no doubt that the ocean is becoming louder and louder.[14] It has been shown that the background noise levels in the ocean have, from around the mid-20th century, risen around 3 dB per decade.[15,16] There is also recent evidence that several species of whales are changing their vocalization trying to adapt to a noisier environment[17] and concern has also been raised that various types of invertebrate organisms (both free-swimming and bottom-dwelling) may be more affected by underwater sounds than researchers previously have thought.[18] For pelagic species (in any development stage), acoustic noise is suspected to affect their ability to orient themselves in the water column, which could have significant consequences for migration in the water column and possibly threaten these species even on a populational scale.[19,20] Novel research on the hearing of diving seabirds has also gained much attention, as it has been indicated that e.g., cormorants actually hear better underwater than in air.[21] This suggests that hearing probably plays a much more important role, together with the sense of smell, when it comes to catching prey underwater, while vision seems to be subordinate.[22] Threshold values for underwater sound for these types of animals are currently unclear and must therefore be treated according to the precautionary principle.

It is hence reassuring that the recent development in risk assessment for underwater noise has veered from the standard viewpoint of only avoiding injury (PTS, Permanent Threshold Shift) and impairment (TTS, Temporary Threshold Shift) toward a more delicate and balanced assessment addressing the more complex zones of behavioral change (BDT) and masking, see Figure 5.

It is important that we take into account the underwater soundscape in the planning process of future ocean and coastal structures and facilities. State-of-the-art modeling, together with validated assumptions of source strengths and a holistic approach, is capable of estimating and predicting the total acoustic-impact load from a lifetime perspective. It is paramount that these types of noise exposure assessments not only incorporate expected noisy construction phases such as piling, blasting, or other noisy activities, but also need to address all phases throughout the lifetime of a project. For example, the decommissioning phase can be just as noisy as the construction phase, and the average increased ship/vessel activity for the operational phase can be superseded by maintenance with larger and noisier vessels over extended periods of time, occurring several times a year. All these aspects need to be included in the full noise budget of a project and fully considered in the environmental impact assessment.

2.2.1 | Impact from floating structures

For most types of floating structures, the mechanical coupling between the structure and its surroundings effectively impedes sound emission from activities on the structure. One example is from a Norwegian fjord north of Bergen "Nordhordlands bridge," where it was shown that the emitted sound into the ocean environment was considerably lower than the corresponding transport route constituted by intense ferry traffic across the Bjørnafjorden.[24] For this particular case, it could be estimated that the lifetime acoustic exposure would be many times larger for the ferry traffic solution than for a floating bridge spanning the same stretch of road. The analysis shows that there are two widely separated risk profiles

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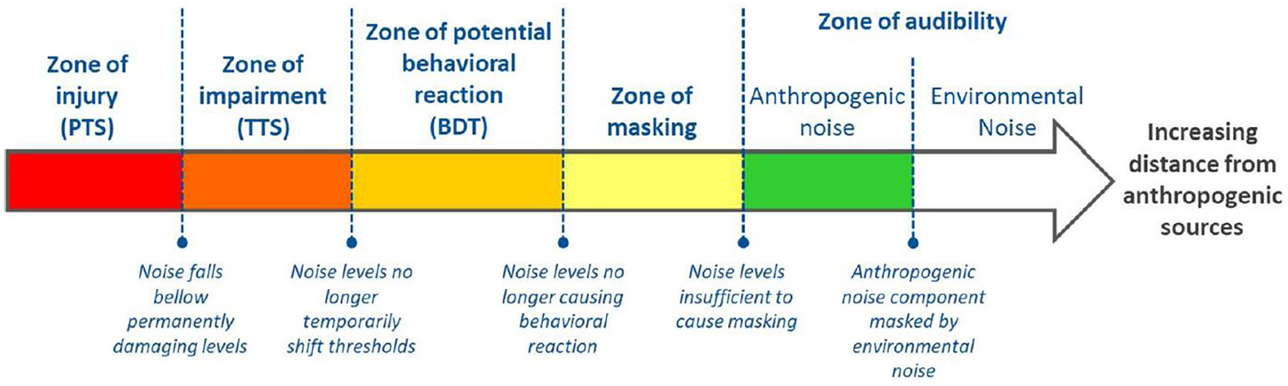

FIGURE 5 The various risk areas for anthropogenic acoustic environmental impact on wildlife.[23]

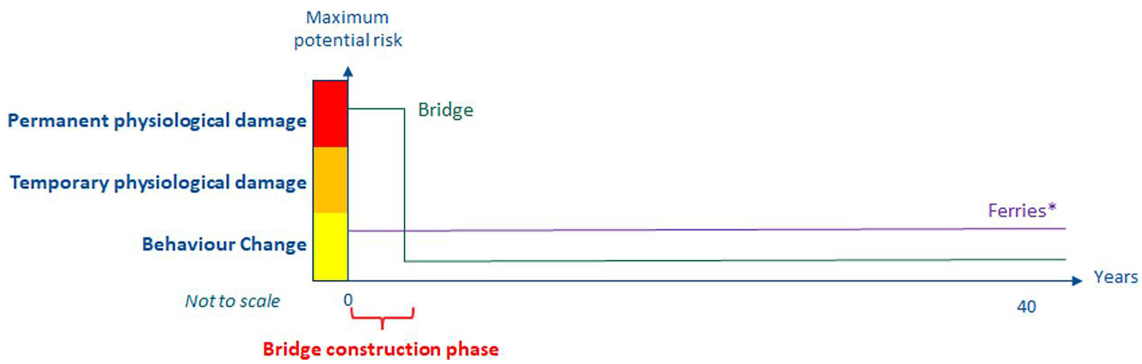

FIGURE 6 Visual representation of the evolution of acoustic risks induced by a floating bridge (construction and commissioning) versus ferries.[24]

for ferries compared to the Nordhordland Bridge. The noise from ferry traffic is spread over time and space and is also generally stronger than typical noise from floating bridges, which, in contrast, mainly causes noise during the construction phase, Figure 6.

However, it should be emphasized that both types of infrastructure create noise that can mask communication for various fauna in the area and could cause changes in behavior. In the long term, this could perhaps even cause changes in population and species composition.

2.2.2 | Particle motion—a changed paradigm for underwater noise?

Another important aspect of underwater sound, which has quite recently attracted well-earned attention in relation to the development of offshore wind farms is particle motion/acceleration.[25] This is a property of sound in water where physical motion (velocity and acceleration) is induced through the acoustic pressure gradient in the water linking the particle velocity to pressure and acoustic impedance.[26] It has been shown that several marine species are sensitive to particle motion, and scientists even suggest that this component is most likely the primary hearing sense of fish.[27]

Since the motion is difficult to measure, it is often neglected or not sufficiently investigated in assessments of acoustic noise in water. Particle motion is often very small and hard to detect, but both quantities can be much larger near strong sources (such as blasting or piling operations) or near strong gradients such as at the bottom or at the surface. The related pressure field creates a motion that is vectorial, which further complicates the measurement process.[28] Although the importance of particle motion for fish hearing is well known, it is only in recent years that evidence has been presented on how much fish and marine animals actually use this property of the acoustic field, as it contains information about both distance and direction, to find food, threats, or potential partners.

The development of offshore wind installations has been shown to lead to elevated levels of particle motion, particularly in relation to piling.[29] Important findings made by the Norwegian Institute of Marine Research[30,31] showed that larvae of cod were attracted and swam toward operating offshore wind turbines. The implications of this might lead to the larvae being attracted to an

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area where there are no (or few) places to hide. This could further impact the entire basis for larvae and small fish, which in turn can affect entire populations in areas where the grazing pressure is high.

The development of new infrastructure or ocean facilities in coastal and oceanic environments requires a robust strategy for assessing risks associated with both direct acoustic noise impacts and potential effects from particle motion. Environmental risks must be carefully evaluated and thoroughly understood by the authorities granting permits for the construction phase. Where necessary, mitigation measures or appropriate monitoring programs should be implemented and closely supervised to protect marine biodiversity to the greatest extent possible.

3 | CONSIDERATIONS ON THE CONSTRUCTION AND USER PHASE

Floating structures present additional challenges with respect to similar structures on land. Water coming from a bridge structure in an urban environment is normally collected into the available urban drainage system and then drained off treated/untreated into nature, while water coming from a floating structure usually goes untreated directly into the natural water basin. Outside a typical urban environment, the water coming from the bridge structure is collected and diverted directly without any treatment into the natural environment (soil/water) surrounding the bridge, which is the same approach as in the floating structures design and management. Considerations on the impact of normal bridges' drainage systems are therefore presented in the following chapter to extend the considerations to floating structures, for example, floating bridges. Both the construction phase and the user phase must be considered.

3.1 | The challenge of stormwater

Bridges, floating structures, and other special structures' design have always been an example of the thrive of engineers for excellence. It is a task where structural engineers must follow strict design codes while fulfilling the technical demands and needs of many other parties and users involved in the project. It is a hectic process with a preliminary phase, an actual design phase, as well as an execution phase. With recent focus on sustainability globally, bridge design has also been challenged to integrate sustainability while delivering safely functioning structures. Circular economy principles are already applied widely and skillfully by engineers as designers are constantly looking for ways to enhance the sustainability of infrastructure since the available natural resources to work with are limited. In addition, the IPCC's target for limiting the global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emissions pathways by reduction in global CO_2 emissions remains a challenge. Yet, the environmental issues related to bridge design, construction, and management have been widely underestimated or neglected due to the traditionally strong emphasis on costs considered by all stakeholders. Environmental considerations for bridges can be related correspondingly to the design, construction, and user phases of the bridge. Stormwater is of particular interest since they are present in all stages of bridge projects. Stormwater is rain and meltwater that drains off from the ground surface of developed/built land, roofs of buildings, or other corresponding impervious surfaces. When rainwater drains off from impermeable surface areas, such as asphalt surfaces on bridge decks (but also floating bridges and pier slabs with big surface areas), this rainwater is also called stormwater, as well as drainage waters from bridge foundations and from bridge construction sites.

Effective management of stormwater is based on a thorough understanding of the water cycle in the built environment.[32] Yet, when designing bridges, designers' main consideration is to provide sufficient inclination of the structure in longitudinal and transverse directions so that rainwater runs off the bridge structure gravitationally. Additionally, design instructions for bridges and other special structures allow stormwater pipes to be emptied directly into the water body below the bridge without proper treatment of stormwater, thus posing a contamination risk for the water body below (Figures 7–12).

A simple visual comparison between old (Figure 9) and new (Figure 10–12) bridge designs provides strong evidence that, for example in Finland, for almost 100 years, very little has changed in guidance and instructions for removing water (stormwater runoff) from the bridge's deck.

This is an issue that has been widely neglected, underestimated, and poorly understood. In Finland, while environmental contamination is strictly regulated and controlled by law, contamination due to stormwater runoff from bridges remains unregulated. There is a need for the development of design instructions for stormwater pipes for bridges, especially in the Nordic countries where winter is long and conditions are demanding. Such a clear and straightforward regulation will help bridge and other special structures' designers to design and create adequate structures that function without posing

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FIGURE 7 Construction site of new Kirjalansalmen bridge, Parainen, Finland (Vasileva, L. 09-2024.)

FIGURE 8 Deck of new Kirjalansalmen bridge (Parainen, Finland) with stormwater pipe emptying directly into the water body below (Vasileva, L. 09-2024).

environmental risks that can be controlled and/or avoided.

Stormwater washes off different contaminants and hazardous substances that have accumulated on the impervious surfaces, as pollutant and contaminant concentrations can vary substantially depending on the predominant usage of that surface area. The greater the area of impermeable surface is, the greater the volume of

FIGURE 9 Old Hessundinsalmen Bridge, built in 1937. Stormwater pipes are emptying directly into the water body below (Vasileva, L. 09-2024).

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FIGURE 10 Construction site of the new Hessundinsalmen bridge, opened for traffic 10/2024. Stormwater pipes at the bridge deck are emptying directly into the water body below (Vasileva, L. 09–2024).

stormwater is. One of the well-studied sources of pollution for stormwaters is the atmospheric deposition, which occurs naturally on all surfaces.[33] Pollutants accumulate on bridge deck surfaces during dry periods, and the longer the dry period, the higher the accumulation of pollutants from different sources, such as crossing vehicles, atmospheric deposition in the form of particulate matter and toxins, degradation of bridge surfaces, wear of vehicle components, and road maintenance operations.[34] The leaching of nutrients (nitrogen and phosphorus) from catchment areas into the environment by the natural runoff, but also by stormwater runoff, causes the excessive spread of nutrients into the water bodies and eutrophication of water bodies. The primary sources behind nutrient presence in bridge deck stormwater runoff are atmospheric deposition and traffic, but also rainfall is a significant source of such compounds.[35]

The limit values of quality parameters for stormwater are not clearly defined in Finland on a national level. In fact, the concentrations of certain substances harmful to the environment and health (environmental quality standards) have been defined as environmental quality standards for surface and groundwater, but not for stormwater. In Finland, the stormwater quality criteria can be found in the Land Use and Building Act,[36] which is to be revised in 2026 with a focus on stormwater. Another aspect for considering the quality of stormwaters is the European Union's newly adopted European Directive concerning urban wastewater treatment (Directive (EU) 2024/3019[37]) in autumn 2024, which is a recast of the Council Directive 91/271/EEC.[38] Directive (EU) 2024/3019[37] requires municipalities and water treatment plants to prepare comprehensive urban wastewater treatment management plans, which must consider measures to manage the loading caused by stormwater overflows and polluted discharges of urban runoff. This is yet another challenge for every national transport agency, since the responsibility for the loading caused by polluted stormwater from bridge decks or floating structures is not clearly defined. In Finland, the usual practice in stormwater management has been to apply the quality criteria for stormwater developed in Sweden (Stockholms[39]). Stockholm County uses limit values for pollutants in stormwater, which serve as an indicator of the need for stormwater treatment. The determination of limit values is based on many different and extensive background studies on stormwater quality and on the Water Framework Directive.[40] Assessments of stormwater quality and impacts on receiving water bodies are made on a case-by-case basis utilizing reference values and assessments of the sensitivity of the receiving water body (Stockholms[39]).

In stormwater runoff management, the first flush is a phenomenon in which, at the beginning of a rain event, the concentration of the contaminants and/or pollutants in stormwater runoff is the highest and this peak precedes the actual peak in the volume of stormwater runoff. Right at the beginning of a rain event, the quality of the stormwater is the worst because the dirt that has accumulated on the impermeable surface is washed away with the stormwater runoff. Stormwater washes away suspended solids (total suspended solids, TSS), on

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FIGURE 11 New Hessundinsalmen bridge, stormwater pipes of bridge deck (Vasileva, L. 09-2024).

the surface of which there are attached many contaminants, such as heavy metals, oils (poly-aromatic hydrocarbons, PAHs), microplastics, bacteria, and nutrients (phosphorus and nitrogen). This phenomenon can also be found in bridge structures. Yet, the contamination of the environment generated through the runoff from the impermeable surface of a bridge deck, floating structures, or other special structures remains unstudied and highly underestimated. In Finland, there is no data from measurements on the amount or quality of stormwater generated from the surface of bridges. This might be a good direction for the development of design approaches and risk management.

3.2 | Water-quality effects of bridges on receiving streams

The impact of stormwater runoff from bridge deck scupper drains on sensitive streams has been studied and documented in multiple research projects globally. The results of the study in the USA by Yuzhu Fu & Bakr[35] showed that upon discharge of bridge deck scupper drain runoff, instant impairment of downstream water quality took place. Seasonal analyses have shown clear variation in the parameter concentrations that were highly dependent on factors such as dry periods, rain intensity, traffic activity, and stream discharge. In addition, time interval analyses have shown that the highest concentrations of contaminants have been measured in the first 30–60 min samples, as well as that parameter concentration decreases with continuous rainfall due to dilution. Similar results have also been reported by Sajjad et al.[41] in South Korea, where stormwater runoff from an outlet drainage pipe discharged into an adjacent stream without any treatment. This has led to pollutant concentration peaks for both water quality parameters and metals prior to the peak flow rate, which confirms the existence of a first flush phenomenon from the bridge deck.

Hazardous substances from exterior building materials are also found to be washed off with stormwater. Hazardous substances used in outdoor materials can leach from the material into rainwater and end up in water bodies or soil with stormwater runoff. For example, in a recent study, PFAS were clearly higher in locations with non-wooden construction, while metals were found in all samples within the study.[42] However, in this study, the lack of differences in the metal concentration between sampling sites, including the control site, indicates that the main sources of the studied metals are something other than building materials, such as emissions from traffic, for example. In addition, the area with mainly wooden buildings had higher concentrations of biocides compared to the areas with tile and concrete buildings.[42]

A study[43] on the size distribution and sources of microplastics and polymer types in the surface waters of a northern European lake (Lake Kallavesi in Finland) has been conducted by the Finnish Environmental Institute SYKE and the University of Eastern Finland as an Academy of Finland-funded project. Uurasjärvi et al.[43] have confirmed that microplastics are also found in stormwater, as the proximity of urban areas leads to an increase in the amount of microplastics in surface water. Microplastic particles of 20 μm (micrometers) size range were observed, especially near the wastewater treatment plant discharge pipe and near the snow dump site.

3.3 | Stormwater from bridge construction sites

Stormwater from bridge construction sites is problematic due to the high concentration of suspended solids, as

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FIGURE 12 New Hessundinsalmen bridge, stormwater pipes at abutment emptying directly into local environment (Vasileva, L. 09-2024).

suspended solids are predominant, especially during the construction processes of slab/pile foundations. The special characteristics of the construction site and the conditions of the construction site must be considered, as well as other specific construction activities that may affect surface waters and groundwaters. The risk is usually assessed based on the characteristics of the construction area and the construction plans. Factors affecting the quality of construction site stormwater and the amount of water to be treated are the season of construction work and the prevailing weather conditions, as well as the phasing of construction work, which is usually only specified as the project progresses. Currently, at the construction site, the design frequency applied in conventional stormwater design is used. However, flood situations must also be considered when planning the water management of the construction site.

3.4 | Stormwater during winter maintenance of bridges

Winter maintenance of bridges represents another challenge to be considered. Snow plowed off the bridge deck is contaminated with pollutants (heavy metals, road salt, cigarette butts, and microplastics) or sand used for deicing. The contractors responsible for the winter maintenance are removing the plowed snow from bridges into dumping sites for snow, but usually some amount (sometimes not so small) of that plowed snow remains right next to the bridge's abutments. With the melting of snow during spring, all the contaminants that are stored in that snow are directly disposed of into the water bodies, thus causing environmental risk. There are documented cases of violation of the environmental protection regulations during winter maintenance of a bridge, for example in the city of Keuruu in Finland.[44]

A study on the quality of snow and meltwater and an assessment of winter stormwater risks has been conducted in Lahti and Hollola, Finland.[45] The research results indicate that quality risks generally increase with increasing traffic volumes. Especially, risks for the quality of stormwater during winter are increasing because of climate change. Milder and more episodic/fragmented winters increase the challenges for stormwater management. More snow that has not been transported away melts in densely built-up areas, thus causing maintenance challenges in existing stormwater systems.[45]

The design of stormwater runoff management practices has its own characteristics in cold climates. Climatic conditions are challenging due to damage to equipment or malfunctions that they may cause. For example, cold temperatures easily lead to frozen pipes or permanently ice-covered pools, severely affecting biological activity,

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settling velocities, and causing reduced oxygen levels during ice cover. The deep frost line is contributing to frost heaving and reduced soil infiltration, thus slowing down the stormwater management processes. The long winter season results in a short growing season, which limits the time suitable for establishing vegetation; also, flora is specific in cold climates compared to moderate ones. In addition to that, the significant snowfall causes higher runoff during snowmelt. During spring melt, there are high pollutant loads accumulated in snow, and there is also the intensive use of deicers, as well as snow storage and logistics affecting the efficiency of BMP for stormwater treatment.[46]

3.5 | Solution for reducing loading from stormwater runoff

In Finland, in cities like Lahti, Tampere, Turku, and Helsinki, municipalities have successfully implemented a solution for stormwater pollution, which involves the installation of filters on the street manholes. The efficiency of those filters has already been analyzed in a few studies, showing that with 20% of installed well filters in cities, there has been a 50% reduction in loading from stormwater. Filters help with 50% removal of suspended solids from stormwater before it reaches the Baltic Sea.[47] Filters are also suitable for larger sources of loading, work during winter, and can also be installed during the construction phase. Of course, filters must be regularly emptied and cleaned, and this will add more to the maintenance costs. Another challenge is that stormwater pipes in bridges must be designed so that the diameter of the pipe is suitable for the installation of such a filter. As a possible development, these technical details shall be cleared out so that a working technical solution for filters installed on the stormwater pipe in a bridge deck is standardized and implemented. The standard size of a stormwater pipe for bridges in Finland is 200 mm—the pipe diameter shall be reconsidered and possibly increased to a minimum diameter of 300 mm (minimum size provided after consultation with a current producer of such filters in Finland), for example, so that filters can be installed and maintained. This solution is particularly important for floating structures, since there aren't many possibilities to collect and treat the water coming from the surfaces before the discharge into the natural water basin (sea or lake). The design of a functional system for collecting the water on the structure and the provision of filters for all the drainage pipes, with a minimum diameter of 300 mm, would allow for protection of the local environment.

3.6 | Management of stormwater runoff

Taylor et al.[48] have assessed management of stormwater runoff from bridges based on risk management and developed a Best Management Practice (BMP) assessment flowchart. To select a suitable stormwater management system for stormwater from the bridge deck, the dominant risk is determined, with risks being divided into two main categories: stormwater pollution or spill events on bridges, since both need to be considered when designing management systems for bridge stormwater runoff. Blomberg & Jonsson[49] have developed a clear decision model for the selection of stormwater management, as recognition by the authors that in Sweden, there have been no clear and consistent guidelines about that issue. The results of this research point out that the risks of spill events on bridges should generally be considered negligible and should not drive the selection of a management system for stormwater. Instead, the need to protect the receiving water should be the governing factor in the decision-making process.[49] Based on those studies, management of stormwater runoff before stormwater reaches the natural environment potentially leads to a smaller risk of contamination for the natural environment. In achieving this, a set of approaches can be successfully utilized in bridge design and bridge construction as well as during bridge maintenance. These are the nature-based solutions (NbSs), which aim to protect, manage, and restore natural systems, like forests or wetlands, to benefit people, nature, and climate simultaneously. NBSs can be integrated with traditional built infrastructure, such as roads or dams, not only to enhance resilience and cost-effectiveness but also to provide solutions for water quality improvements, water supply enhancements, flood mitigation, erosion, and landslide control.[50] NBSs help adapt to and mitigate climate change through nature. Careful and thoughtful inclusion of green infrastructure (for example, water-absorbing infrastructure) in the vicinity of a bridge, during the already early planning stage for bridges, can improve the water quality of stormwater runoff from the bridge deck by both reducing the amount of stormwater runoff entering the waterbody and removing the pollutants from the stormwater runoff before they enter the waterbody.[48]

However, there is no one-size-fits-all NbS in relation to bridge design. Furthermore, solutions could be difficult to adopt for floating structures, since, for example, all the water should be collected to the shore for suitable treatment on land. It is therefore crucial that each bridge/floating structure project address the specific needs and conditions of each site. Uncertainties also remain when considering the long-term performance of NbSs, often related to climate change. It is crucial for such

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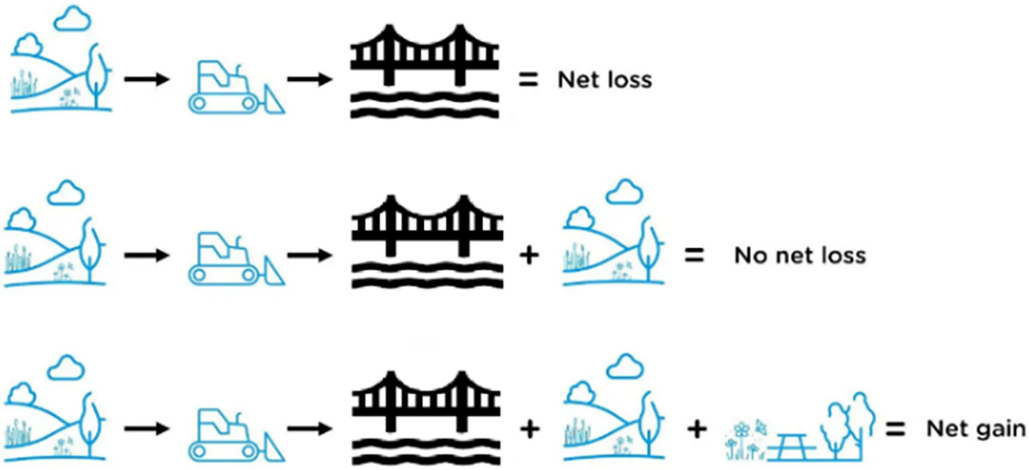

FIGURE 13 Site-level metric assessment targeting for Biodiversity Net Gain (Vasileva, L. 2024).

complicated interaction between built infrastructure (bridge/floating structure) and natural infrastructure (NbS) to understand the site-specific environmental conditions. In this task, understanding the baseline (the initial state at the site before land development) gives the highest chance for achieving fully functioning NbSs that support bridge design at every stage of the project—preliminary, general, structural, construction, and maintenance. For this purpose, a development of easily interpreted, universal metrics for measuring short- and long-term NbS performance is needed—such as a universal metric for the marine environment and on land, and it will determine the possibility for widespread adoption of NbS strategies. Consequently, monitoring of NbS projects is required.

The biodiversity net gain (BNG) approach (Figure 13) can be utilized for achieving development that leaves nature in a measurably better state than before,[51] but also for supporting the functionality of designed BMP for stormwater runoff from the bridge deck. The value and the state of nature at the bridge site can be measured using the Biodiversity Metric,[52] which uses changes in the extent and quality of natural habitats as a proxy for nature and then compares the habitat on-site before and after land development. The metric can be used for comparing proposals for a site—such as creating or enhancing on-site or off-site. The metric uses common global standards and provides a transparent and repeatable methodology to support decision-making in line with the mitigation hierarchy.

In conclusion, awareness of environmental issues and their earlier consideration within infrastructure projects is beneficial for all parties involved. With environmental considerations in mind, long-term goals and policies for the management of stormwater runoff from bridge decks are needed. A broad discussion is required concerning the adoption of stormwater BMPs for stormwater runoff from bridges and other special structures. Those management practices must be appropriate for local conditions at the bridge site, allowing for safe stormwater treatments and draining away from the bridge deck without risks for water bodies, soil, or air. There is a clear gap concerning the limit values of stormwater quality parameters for infrastructure projects, and this is a possible development direction. Decisions are needed to update the current legislation or even develop new legislation for the design and construction of stormwater runoff treatment from infrastructure. This should not be seen as another difficulty that slows down bridge projects or makes them more expensive; rather, it should be recognized as a possibility to deliver better projects with enhanced performance and resilience of bridges. Design codes should account for an adequate and environmentally safe service life.

Adoption of already available solutions for stormwater runoff management (such as filters for stormwater pipes) must be analyzed considering local climate conditions. Such filters have great potential for effectively reducing the stormwater loading on water bodies, collecting debris and solids down to microplastics, and removing pollutants in stormwater before they reach nearby rivers and ditches. Adoption of such filters, for example, in the design of floating structures (filters installed within the pontoons) can help substantially reduce stormwater loading on waterbodies by literally treating stormwater runoff on site (by collecting pollutants). The functionality of current stormwater solutions

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for bridges needs to be assessed, as well as their cleanliness and antifreeze protection and the stormwater pipe diameter that would be suitable for the installation of the filter.

A bridge is resilient when its environment is resilient, and this should be utilized in transforming the approach for infrastructure development. Such a new design paradigm will enhance the state of the environment at the bridge site, together with improving the resilience of bridges, and it will also help minimize the negative impacts and maximize the positive ones on any land development related to infrastructure projects. Bridge projects must include sufficient resources for mapping on-site conditions, measurement of environmental state, and monitoring of the performance of BMP for stormwater. Further goals can be developing innovative solutions for protecting and enhancing ecosystems, where even minor solutions on a broad scale would have a positive impact. Design frameworks can be developed to involve transdisciplinarity and co-design with the adoption of NbSs frameworks. Implementation efforts are key for NbSs acceptance and large-scale adoption in bridge projects. It is critical that policymakers update guidance and regulations to broadly enable and support bridge design with NbSs in bridge projects that will support longer service life and better function for the existing built infrastructure. Furthermore, blue-green infrastructure, as a sustainability practice, shall be more widely incorporated within the design not only of the special structures but also landscape design and functioning of the whole surrounding environment in the vicinity of the special structures. As a strategic blend of natural and man-made elements in urban areas, blue-green infrastructure combines green spaces, such as parks and gardens, with blue elements like rivers, ponds, and wetlands, resulting in the provision of shelter in public spaces, reduction of urban temperature (also for built infrastructure) and increased outdoor activities.[53] Blue-green strategies can be potentially aimed at reducing environmental impacts, conserving resources, and promoting ecological balance, which will also contribute to supporting the resilience of structures that are present at the site. They can be a powerful tool for establishing a new planning and design paradigm, where design solutions support regenerating nature instead of degenerating it.

With a regenerative approach, aiming for "less bad and more good," the construction industry will be strongly supported in achieving regenerative, climate-wise design and construction processes that do not aim only for sustainable balance but also target positive impacts and holistic wellbeing for nature and people. Together and in balance, naturally.

4 | ENVIRONMENTAL IMPACT CONSIDERATIONS OF THE GREEN SHIFT

In recent years, the pressure to lower CO_2 production has risen enormously, not only for the direct emissions related to sources owned or controlled by the reporting organization but also connected to the indirect emissions related to the sources owned or controlled by third parties that act as suppliers with respect to the reporting organization and are therefore a consequence of the activity of the organization itself (source: GHG Protocol). As concrete represents the most used material in the world, after water, renewed attention has been paid to developing new possibilities for "greener" solutions. This has been reflected in a continuous effort from the cement and concrete industry, for example providing solutions for low-carbon concrete using substituting materials and solutions not yet tested in a long exposure period.

Potential consequences could be lower durability for the structures, and for marine applications, this could have important effects on the marine environment.

The release of chemical substances of potential concern (CSPC) from concrete structures is usually low and not considered to cause increased environmental and health risk (e.g.,[54–56]). This is also valid for marine concrete structures, provided that the structure is designed and dimensioned for the marine environment. These may include low water-to-binder ratio ($w/b \leq 0.40$), high cement content, protection of steel reinforcement, increased cover, etc., to prevent damaging mechanisms from occurring due to the impact of chlorides, sulfates, carbonates, and frost action. Although these deteriorations also occur in onshore structures, they may have more impact in the submerged marine environment due to the constant contact with the sensitive water environment. Cracks due to expansive reactions may increase the surface area in contact with water and also decrease the pH, which may lead to increased transportation of CSPC. Hence, it is important that the concrete remain structurally and chemically intact during its service life.

4.1 | Concrete submerged in water

The main underlying degrading effect of concrete submerged in water is the leaching of Ca-rich phases in the hydrated binder due to destabilization of these phases.[57] In addition, chemical effects like calcium leaching, formation of magnesium silicate hydrate (M-S-H) and calcium carbonate are more pronounced in seawater compared to rivers with fresh water due to higher concentrations of bicarbonate and magnesium sulfate.[58]

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Since the pH in seawater is normally around 7.7–8.2, the degradation products of the hydrated phases are dissolved in the seawater. The porous outermost layer created makes the concrete vulnerable to further attacks, which will also increase the leaching of CSPC. However, most of the studies on the leaching of CSPC from concrete to the soil and water environment over the past decades have widely shown accepted health and environmental risks.

4.2 | Impact as a consequence of the green shift and recommendations

Several important aspects need to be considered for marine concrete structures regarding the effect of the green shift. Marine concrete structures are normally based on concrete with the traditional binder combinations of Portland clinker with coal fly ash, GGBS, and silica fume, and good-quality natural aggregates. It is likely to expect that other combinations of both binders and aggregates will be developed in the green shift. This may, for example, include binder alternatives like natural and calcined pozzolanas (NS 3650), silicon-rich slag from ferrosilicon and silicomanganese production (NS 3651), other ash types than from coal combustion, and recycled aggregates from large solid waste streams like construction, demolition, and excavation materials.[59,60]

It is recommended that new combinations of binders and aggregates be tested with relevant methods that address diffusion-controlled[61] and solubility-controlled leaching.[62] The former test was developed by CEN/TC 351 in response to Commission M/366 for developing harmonized assessment methods for evaluating the release of dangerous substances from construction products. It is recommended to test concrete specimens that include the actual aggregates and binder combination, since binders and aggregates are certified (CE marked) as single construction products based on tests in conventional concrete recipes. It is also recommended to apply a leachant that represents the actual seawater in the tests, i.e., contains the same levels of inorganic species and dissolved organic carbon.

Increased service life is one of the cornerstones in the green shift, and it applies in particular for marine concrete structures, since reuse or recycling of the concrete is significantly more difficult offshore than for land-based structures. Hence, it is recommended to develop an evaluation scheme for marine concrete that includes the tools to predict leaching impact for a longer service life (100–500 years), depending on the geographical location. The tools may include additional or modified standardized tests (e.g., longer leaching duration) and mechanistic modeling that are capable of predicting the CSPC leaching in a long-term perspective for a range of materials (e.g.,[63]). The evaluation scheme should also define specific leaching criteria that consider the site-specific local marine conditions and ecotoxicological assessments.[64] Furthermore, the green shift and the advantages of marine structures (discussed earlier) may in certain regions, lead to an increased volume of structures per seawater volume. The ratio of concrete surface to water will therefore increase, which increases the released amount of CSPC. This might be insignificant at the deep sea but may be considered when marine structures are placed in more shallow water. Hence, these aspects may be included in the evaluation scheme for marine concrete structures.

5 | CLIMATE, COSTS, DURABILITY, AND RESILIENCE

The long-term behavior of a concrete floating structure is of paramount importance due to the various possible negative implications on the environment. Floating structures are normally exposed to aggressive environments, challenging even more durability performance. The use of concrete in the offshore field has historically shown a great performance, which has often led to an extension to the end of life for floating structures. It must be mentioned that rules and regulations for floating concrete structures have provided the basis for this result of durable and reliable material use.

In addition, floating structures present in principle a higher level of adaptability to some effects of climate change, such as rising water levels, making them a promising solution for structures with a long-life expectancy.

Investing in the design for the reuse and replaceability of single modular components could enhance the possibilities for the reuse of parts of the structures and the circularity strategy.

On the emissions connected to the material used for the structures, it is important to adopt a life-cycle analysis perspective, highlighting that the robustness of a structure is the best strategy for durable and resilient structures that will help in minimizing the emissions produced for maintenance work and to extend the life of the structure, postponing as much as possible an eventual dismantling and replacing. Maintenance procedures should also be planned following a life cycle cost perspective, optimized in order to minimize the impact on the climate and the environment. The experience in the Norwegian offshore environment has shown excellent durability performance of concrete with high compressive strength, since the density of concrete is proportional to the durability of the structure (Zivkovic[65], Equinor, presentation at ONS 2024). In addition, the practice of applying epoxy coating during construction/slip casting from

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the splash zone upwards has shown no chloride penetration, also in old structures with a design life of only 30 years (Statfjord platforms, 1977–1984), saving a huge amount of maintenance costs.

To summarize the findings from the experience in the offshore field, in terms of climate, costs, and durability (from Zivkovic[65], Equinor, presentation at ONS 2024):

- Concrete structure maintenance can be designed and built for low maintenance costs and extended durability with an investment in the mix design for robust production, proper concrete cover, focus on construction quality, use of epoxy coating and anode protection underwater, and proper inspection procedures.
- Jelsa's study showed that concrete spar (Figure 14) and semi-submersible (Figure 15) have lower carbon footprints and costs than their steel counterparts.
- For costs and footprint evaluation, local production, avoiding long transport procedures, is a key driver, both for steel and concrete.

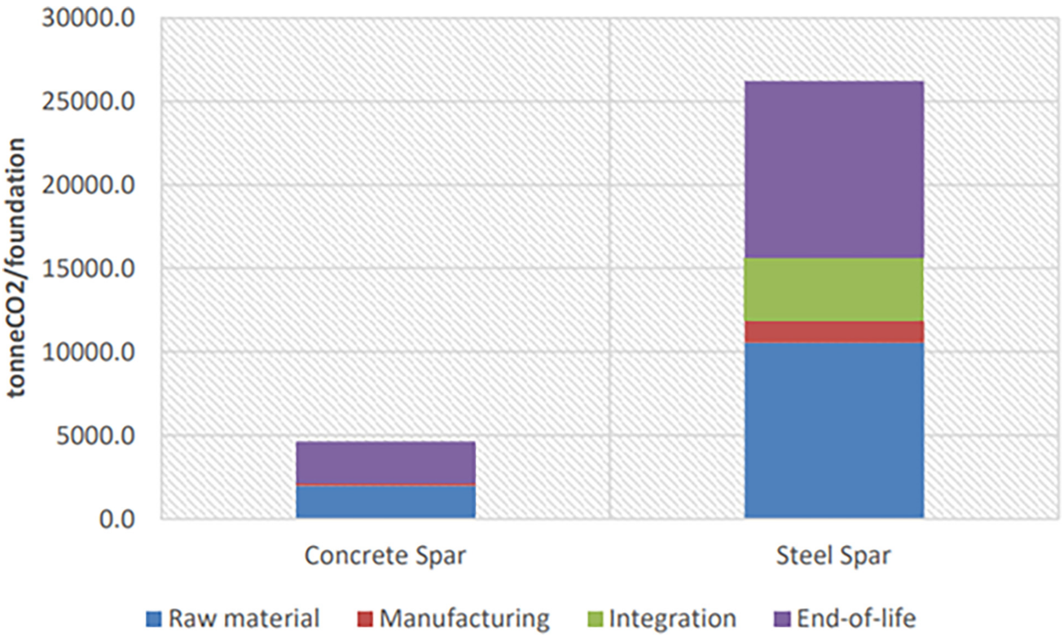

FIGURE 14 Carbon footprint comparison for spar, Jelsa study, DNV, Equinor presentation for ONS2024.

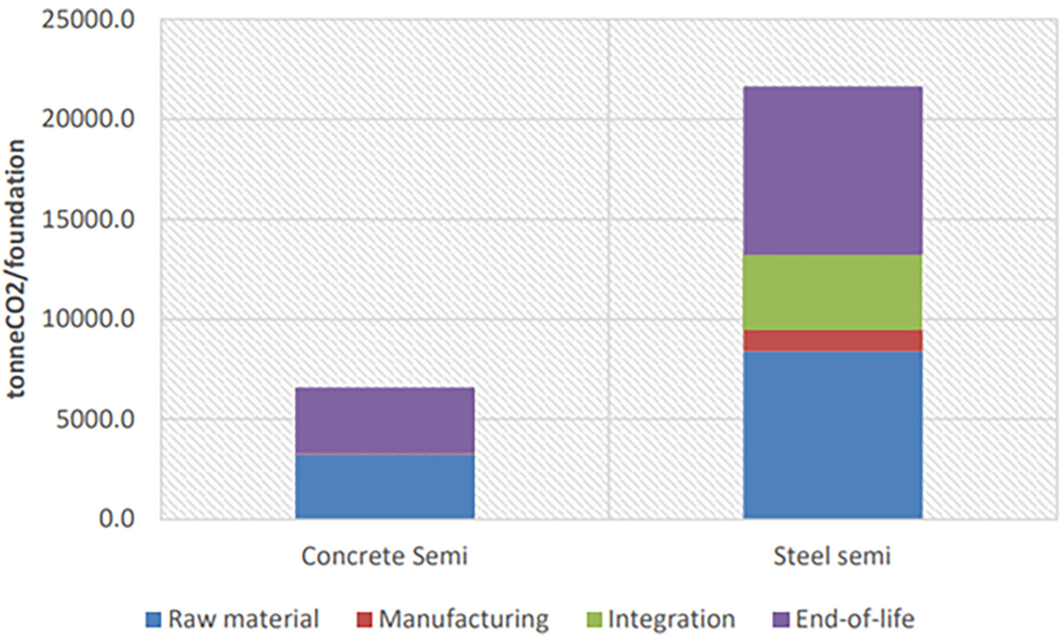

FIGURE 15 Carbon footprint comparison for semi-sumbersible, Jelsa study, DNV, Equinor presentation for ONS2024.

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New solutions are being developed to improve several aspects connected to the sustainability topic. To avoid corrosion problems in concrete, the use of aluminum reinforcement has been recently applied, for example, in Norway (in the Dare 2C research and development project). CCS (carbon capture and storage systems) are now a reality that allows us to reach net-zero solutions (see, for example: https://www.evozero.com/). Several methodologies can improve the environmental impact of concrete, especially from a climate perspective, and should be evaluated and chosen depending on a wider sustainability perspective (considering economic, environmental, and social criteria) in a life cycle analysis framework.

6 | CONCLUSIONS

The paper gives insight into some of the aspects that have to be considered to evaluate the environmental impact of floating structures:

- The biological environment
- The acoustic impact, especially in the marine environment
- The impact of the water from the drainage system of the structure on the marine environment
- The impact of non-durable material on the marine environment
- The climate impact of the structure
- The long-term effects of the structure

The knowledge of the local environment is fundamental for developing the best concept for the functional need and for the local environment together. An early involvement of different experts in the process, right from the conceptual design phase, could bring a reduction of the necessary costs for mitigation procedures and enhance a better approach for sustainable solutions, also in a long-term perspective. Considering the local environment in the early stage of the conceptual design, there is the possibility to minimize the environmental impact of the floating structure, also realizing beneficial solutions for local species or specific environmental scopes and realizing a positive result for the environment with respect to a solution where the environmental impact is considered only in the later phases of the project.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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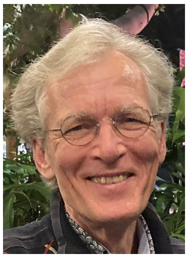

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