



Sustainable use of sand in nature-based solutions

D5.3

Recommendations for sustainable use of sand in nature-based solutions

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Disclaimer

The proposed recommendations are based on the findings from SUSANA, including empirical research, modelling, workshops and interactions with SUSANA's Industrial Advisory Board, as well as the best available knowledge from other studies and monitoring at the time of publication. The research also shows that substantial knowledge gaps remain and that the current understanding is not yet complete. Therefore, emerging insights may require the recommendations to be revised over time.

Executive summary

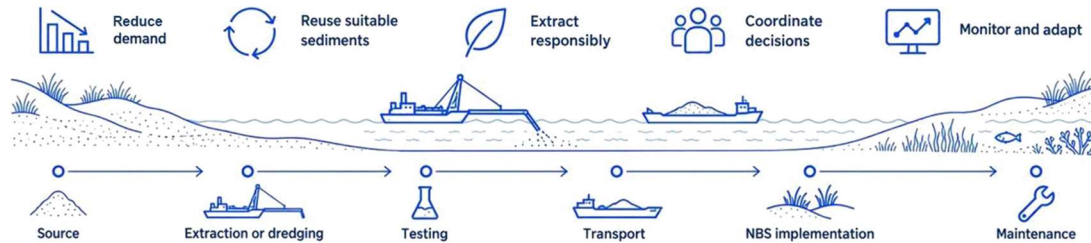
Sustainable Use of Sand

Context for Nature-Based Solutions

High-quality marine sand is finite. The core principles are minimizing sand use, replacing high-quality sand where feasible, and minimizing the impacts of unavoidable extraction.

0.3 million m³ → Almost 3 million m³
1976 2025
10× more marine sand extraction

GOAL / Core principles for one connected sand system



WHY / Why it matters



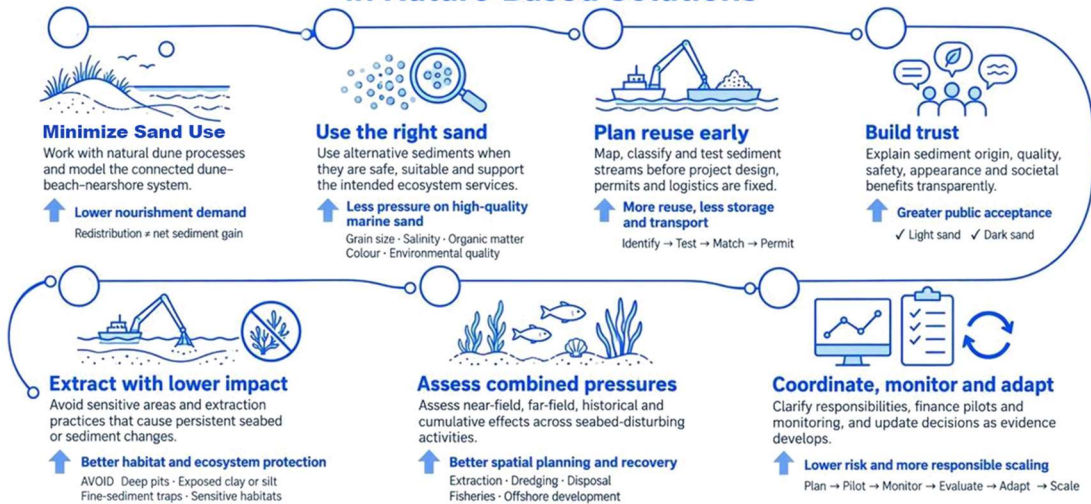
WHO / Who needs to act?



NEED / A governance framework and shared strategy for sand reuse and impact mitigation across connected coastal and marine systems.

SUSANA — Sustainable use of sand in nature-based solutions

Recommendations for Sustainable Use of Sand in Nature-Based Solutions



Reduce demand. Enable safe reuse. Protect sensitive ecosystems.

SUSANA — Sustainable use of sand in nature-based solutions

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This document is intended for all actors involved, or potentially involved, in the sand supply chain for sandy coastal nature-based solutions (NBS). While many of the recommendations are primarily directed towards policy and governance, they are also relevant to contractors, dredging companies, implementing agencies, consultants and research organizations.

The recommendations have been formulated from a scientific perspective and build on the findings of SUSANA, complemented by relevant insights from previous research and monitoring. Their purpose is to provide evidence-based advice that can inform policy development, project planning, permitting, implementation and monitoring. In particular, they aim to support more integrated consideration of sand availability, ecosystem service delivery, ecological impacts and long-term sustainability across the NBS impact zone, when decisions on sand use for NBS are made.

The recommendations are intended to support future discussions, decision-making and the responsible upscaling of NBS for a climate-resilient coast. They also highlight areas where coordination, adaptive management, monitoring or further evidence may still be needed.

1. Introduction

Nature-based solutions (NBS) are defined as the sustainable management and use of nature for tackling societal challenges such as climate change and flooding. NBS are increasingly implemented to ensure coastal safety under climate change. Their major advantage compared to traditional 'hard' approaches is the combination of benefits, not only increasing coastal protection, but also positively affecting recreation, coastal food webs and food provisioning, water quality and biodiversity. Sandy coastlines consist of dynamic, interconnected ecosystems including subtidal (sandbank) areas, foreshores, beaches and dunes, and NBS for coastal safety typically require large amounts of sand for their build-up and maintenance. Examples proposed in sandy continental shelf seas include sand engine, dune-in-front-of-dike and artificial islands. However, sand is a strategic resource with many applications, first and foremost for the growing construction industry. Today, sand and gravel are worldwide the second-largest resource extracted and traded by volume after water. But sand is also a finite resource, and the United Nations Environmental Program (UNEP) identified sand shortages as a worldwide impending problem.

In the Belgian Part of the North Sea (BPNS), the amount of sand extracted has risen from 0.3 million m³ in 1976 to near 3 million m³ in 2025 (Continental Shelf Service 2025), and scarcity of high-quality aggregates is predicted in the mid-term. The lack of a long-term strategy to manage the finite supply of sand in view of large-scale implementation of NBS, will have major consequences, not only for the dredging industry, but also for the Belgian blue economy as a whole, due to price increases, dependency on foreign countries and eventually loss of businesses. In the blue economy, sand is needed not only for NBS, but also for the installation of large-scale infrastructure, e.g. related to wind farm installations or harbor developments. This looming conflict between increasing sand needs on the one hand and sand availability and ecological impacts of extraction activities on the other hand is also observed in other countries along the North Sea. Sand extraction potentially induces changes in key ecosystem functions that underpin benefits to humans, such as climate regulation, food provisioning, and water purification, collectively referred to as ecosystem services. Consequently, human-induced changes in the marine ecosystem can directly affect human well-being. Within SUSANA, the ecosystem impacts of both sand extraction and the construction of a specific NBS using alternative sand, namely dune-in-front-of-dike, were evaluated within an integrated ecosystem services framework. Alternative sand sources refer to sand that can substitute high-quality marine sand without requiring the extraction of new virgin sand resources. They consist of sand that becomes available as a by-product of dredging, infrastructure or construction works and can be beneficially reused in NBS. They are usually more heterogeneous than the high-quality, medium- to coarse-grained (> 250 µ), relatively homogeneous sands of the North Sea sandbanks and therefore less suitable for industrial construction use. The term does not include sand obtained through new extraction from other natural deposits, such as river sand or other virgin terrestrial or marine sources. Using a coherent modelling approach based on novel empirical research, scenarios of future NBS development were used to evaluate the differences in ecosystem service impacts between the use of alternative sands and conventional high-quality sand extracted from sandbanks.

Both beneficial reuse and the sustainable use and extraction of natural sand represent key strategies for ensuring a continued responsible supply of sand, while safeguarding multiple blue economy sectors. Achieving greater alignment between the sand demand for NBS implementation and the ecosystem service impacts associated with sand extraction is therefore essential. True ecosystem-based management requires a holistic assessment of human activities, including the indirect impacts of resource use beyond the immediate boundaries of the activity itself. The strategy proposed here is

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based on a scenario analysis in which ecosystem service impacts generated locally by the NBS are compared with impacts on ecosystem services at the sand extraction sites, while also evaluating the effectiveness of different mitigation strategies. Based on the findings generated within SUSANA (empirical research, modelling and stakeholder workshops), recommendations are proposed to support sustainable use of sand in NBS.

2. Recommendations

Cross-cutting principle: evaluate NBS across the full sand supply chain

The core strategic lesson from SUSANA is that NBS for coastal safety must be evaluated across the full sand chain, and not solely at the implementation site. A dune-in-front-of-dike may generate local benefits for coastal safety, recreation and dune development, but these benefits must be weighed against the impacts of obtaining the sand. The use of alternative sand in NBS may reduce pressure on high-quality sandbanks, if they are able to support comparable ecosystem services, meet strict sanitary and environmental standards, and are socially accepted to coastal users.

The long-term strategy for the use of sand in NBS should therefore be based on three linked principles:

1. Minimize sand requirements by stimulating more sustainable and nature-driven coastal zone management, including natural dune elements. Natural dune-building processes may reduce future nourishment requirements and should therefore be stimulated where appropriate. However, dune growth does not necessarily represent a net sediment gain: newly formed dunes may partly develop through redistribution of sand from the beach and nearshore zone, potentially causing erosion that must later be compensated for through nourishment. Coupled dune–beach–nearshore modelling is needed to distinguish local sediment redistribution from a genuine reduction in external sand demand.
2. Reduce reliance on finite high-quality marine sand by using alternative sands where they can deliver comparable ecosystem services and meet environmental, logistical and operational requirements.
3. Mitigate the environmental impacts of marine sand extraction through a systematic and integrated approach, following the mitigation hierarchy by prioritizing extraction in less sensitive marine ecosystems and optimizing extraction volumes, timing and methods.

The recommendations below are structured around two central questions. First, are alternative sand sources useful for building NBS, and can they support the desired ecosystem services? Second, what is the impact of sand extraction on ecosystem services, and how can the use of alternative sand reduce or mitigate this impact? A final set of overarching recommendations addresses the decision-support and governance arrangements needed to implement these insights in practice.

2.1. On the use of alternative sand sources for building nature-based solutions

Recommendation 1. Use alternative sand sources where they can support the intended ecosystem services of NBS

Alternative sand sources should be considered a strategic component of future NBS implementation, provided that their physical, ecological and societal suitability is assessed in relation to the specific function of the NBS. SUSANA shows that alternative sands can contribute to the development of dune-in-front-of-dike systems and can support multiple ecosystem services, including coastal safety, recreation, sand nuisance prevention and habitat development. However, their performance is not uniform and depends strongly on sediment characteristics such as darkness of the sand, organic matter content and moisture retention.

Alternative sand sources should also be evaluated in relation to how they influence ecological development trajectories and sediment dynamics over time. Coarser grain sizes, elevated organic matter content, differences in salinity, or altered moisture-retention characteristics can affect both aeolian transport and vegetation establishment. In some cases, alternative sediments may provide a relatively stable substrate that promotes early plant establishment and dune initiation, while subsequent deposition of locally transported beach sand gradually shifts the system towards conditions more typical of natural dunes. When alternative sediments are deployed over larger areas, however, they may also alter patterns of aeolian erosion, sand transport, and dune mobility, potentially affecting long-term dune evolution. High salinity levels or other physicochemical characteristics may additionally delay natural colonization by dune-building vegetation such as *Ammophila arenaria*, resulting in different successional trajectories and potentially requiring delayed or staged planting strategies. Because spontaneous establishment of dune-building species can be highly variable and context dependent, vegetation management should therefore be considered an integral component of sediment-source selection and NBS design.

SUSANA results indicate that visitors generally prefer sand characteristics that resemble familiar beach conditions, such as lighter color. At the same time, alternative sands can still be used in dune construction if the design has limited direct negative effects on recreational perception. This means that the choice of sand should be made in relation to the intended bundle of ecosystem services rather than in relation to a single criterion. For NBS primarily designed to increase coastal robustness, sediment stability and dune-building capacity may be decisive. For NBS located in highly visited coastal zones, recreational perception and landscape integration become more important. The use of alternative sands should therefore not be evaluated solely on the basis of availability or technical feasibility. Instead, sand suitability should be assessed in terms of the ecosystem services that the NBS is expected to deliver.

The use of alternative sands in NBS should be supported by a careful assessment of several boundary conditions. First, the sediment must comply with the applicable environmental and sanitary quality standards, such as VLAREBO for use in beach and dune environments, and the relevant OSPAR and Marine Environment Act requirements for NBS on the foreshore. In addition to these quality requirements, the broader sustainability assessment should also consider the specific characteristics of the alternative sand source and the associated sand chain. Relevant aspects include potential sediment dispersion near sensitive marine areas, possible changes in maintenance needs when finer sediments become more compacted or respond differently to erosion, additional CO₂ emissions related to transport, and the spatial footprint associated with sorting, storage or pre-treatment. Not all of these aspects were assessed in SUSANA, but they are essential to include in the decision-making

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process. Decisions on alternative sand use should therefore be based on a full-chain evaluation that compares the avoided impacts on natural sandbanks with the ecological, logistical and operational implications of sourcing, handling, transporting and maintaining alternative sediments. At the same time, this assessment should explicitly recognize that high-quality marine sand remains a finite strategic resource. Continued reliance on this resource for NBS will create increasing pressure on sectors that also depend on it, including the construction sector. This broader resource perspective should therefore be part of the assessment, alongside ecological, logistical and operational considerations, when comparing alternative sand sources with continued reliance on high-quality marine sand.

Recommendation 2. Build public trust in alternative sand use through transparent quality assurance, communication and demonstration of the societal benefits of reuse

The success of NBS in coastal environments depends not only on their biophysical functioning but also on societal acceptance. Beaches and dunes are highly valued recreational landscapes, and changes in sand color, texture, shell content or walking comfort can influence public perception. SUSANA highlights that recreational preferences should be considered when evaluating alternative sands for NBS, particularly in intensively used coastal zones.

Public hesitation towards alternative sand may arise from visible differences, such as a darker color or a higher shell content, or from an association with dredged material and contamination, for example from port areas. People cannot assess ecological quality or health safety by looking at the sand. This creates a risk that environmentally sound reuse options are rejected because they are visually unfamiliar or perceived as unsafe.

The use of alternative sand therefore requires more than technical approval. It requires transparent environmental guarantees, clear quality testing, and communication that explains why the sand is being reused and how it contributes to reducing pressure on marine sandbanks, where it comes from, how safety and environmental quality have been assessed and how it can support the desired ecosystem services. Demonstration cases can play an important role in making alternative sand use more acceptable.

Integrate recreational perception and social acceptance into the planning and design of NBS using alternative sands. Where alternative sands differ visibly or physically from the sand found on conventional beaches and in dunes, communication should be used to align public expectations with the functional objectives of the NBS.

Recommendation 3. Improve the operational availability of alternative sand via early planning, sediment mapping and quality differentiation

SUSANA reveals that beneficial reuse is technically feasible, but constrained by fragmented governance, timing mismatches, regulatory complexity, and insufficient knowledge of sediment quality. Alternative sand sources often become available through dredging or disposal processes, but they are not always available at the right time, in the right place or with sufficiently documented health and environmental quality for NBS use. An umbrella authority should coordinate all activities at sea. Postponing certain activities by a few months could result in a win-win situation, both for the activities themselves and for NBS (e.g. shared costs, smaller/shorter storage).

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A key opportunity is to consider beneficial reuse from the earliest stages of project planning, before major design and logistical choices have been fixed. At this stage, however, specific matches between sediment sources and receiving projects may remain uncertain because detailed information on sediment quality, available volumes, timing, logistics and receiving-site requirements is often not yet available. Assessment frameworks should therefore follow a phased approach. Initial strategic screening should use general principles, sediment-quality classes and clear boundary conditions to identify potentially compatible sediment streams and intended uses, while transparently excluding options that are unlikely to be feasible. As more detailed project information becomes available, the material can be characterized and its suitability for the intended use validated. Such an approach would facilitate rather than centrally organize the matching of sediment supply and demand. It would support timely permitting and logistical planning, reduce unrealistic expectations and help distinguish genuine missed opportunities from pathways that were never feasible. Where a suitable direct match can be achieved, it may reduce the need for temporary offshore storage and avoid an additional transport stage, thereby limiting sediment losses, dispersion and associated indirect effects. Assessing the potential for beneficial reuse could become a standard requirement in the planning of NBS projects and could also be incorporated into the dredging and disposal plans required under current permits.

Sediment from different sources should not be treated as a single, undifferentiated material stream. Characterizing and, where feasible, separating sediment according to grain size and quality at designated disposal or storage sites would prevent potentially reusable sand from being mixed with less suitable material and would preserve its value for future NBS applications. Responsible authorities, scientific experts and industry should jointly identify locations where such differentiated storage and handling can be accommodated. Because offshore space in the BPNS is extremely limited, the spatial requirements for these activities should be explicitly considered in future Marine Spatial Plans.

Quality variability and contamination risk remain important constraints. A dynamic sediment quality database, repeated testing and application-oriented quality labels are needed to increase confidence in reuse decisions. Temporary storage zones, or alternative sand resources, should be managed and monitored in the same way as offshore sand and gravel extraction, in order to gain a better understanding of the available quantities and quality standards.

2.2. On the reduction of sand extraction impacts on ecosystem functioning and ecosystem services

Recommendation 4. Avoid extraction practices that are likely to cause long-lasting habitat changes or undesirable increases in organic-matter retention. Technical, economic and social considerations should be assessed within these ecological constraints.

The ecological effects of sand extraction are not limited to the removal of sediment. Previous research shows that extraction can alter seabed morphology, sediment composition and benthic communities and SUSANA reveals that this in turn can affect organic matter cycling, carbon mineralization and nitrogen transformations. Long-lasting depressions, exposure of finer or older geological layers, and increased retention of organic material can change ecosystem functioning beyond the immediate extraction event.

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Mitigation to avoid changes in ecosystem functioning should therefore focus on avoiding extraction practices that create persistent morphological or sedimentological change. This includes avoiding deep or poorly oriented depressions that trap fine material or organic matter, preventing the exposure of clayey or silty layers, avoiding screening for certain grain sizes and stopping extraction before substrate changes lead to irreversible habitat alteration.

Permitting and extraction planning for NBS could include design rules that minimize persistent seabed alteration. Depth limits based on knowledge of available sand volumes and local geological context together with proper orientation of extraction activities and rotational extraction schemes should be used as operational mitigation measures. Furthermore, if screening is applied, it should be carried out in a controlled manner, with the impact on the seabed sediment being monitored and adjustments or mitigation measures implemented where necessary.

Recommendation 5. Include cumulative pressures in decisions on extraction and beneficial reuse.

SUSANA dispersion modelling shows that seabed-disturbing activities can affect areas well beyond the direct disturbance footprint. Sediment dispersion from extraction, dredging, disposal and fisheries differs in intensity in space and time, and far-field effects may occur in ecologically relevant areas outside the immediate project zone. This means that the direct extraction footprint alone is not sufficient to evaluate impact.

A long-term strategy should therefore account for cumulative pressures at sea, including the interaction between sand extraction, maintenance dredging, disposal, fisheries and offshore wind development. This is particularly important because local extraction effects may interact with broader patterns of organic matter deposition, sedimentation, or habitat change. Historical extraction data and evidence of recovery should be used to determine the site's pre-existing or legacy pressure load. This avoids considering a previously intensively exploited area as available for renewed extraction merely because its current annual extraction pressure is low.

Decisions on the extraction of sand, either from sandbanks or from alternative sources such as disposal sites, should include both near-field and far-field effects. Cumulative impact assessments should preferably be embedded in a broader planning framework rather than being addressed separately by individual projects. Such a framework would provide a common understanding of existing pressure levels, the newly proposed and future sand demand, and recovery capacity of the marine ecosystem. This is particularly relevant where several seabed-disturbing activities overlap or where repeated extraction may progressively reduce the recovery capacity of the seabed.

Recommendation 6. Select sand extraction sites based on ecosystem services sensitivity - as part of an integrated more sustainable assessment - not solely on sand availability, technical suitability and economic feasibility.

SUSANA, in combination with previous studies, shows that the impacts of sand extraction are dependent on intensity and extraction regime as well as the location. Some extraction areas show stronger changes in sediment characteristics, organic matter retention, benthic communities, carbon and nitrogen cycling, and food-web functioning. This means that the ecological cost of extracting the same volume of sand may vary depending on the area and its local environmental context.

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A long-term strategy should therefore move beyond a purely volume-based or quality-based view of sand reserves. Marine aggregate extraction should be spatially planned to avoid, both in the near- and far-field, areas with high ecosystem service value or sensitivity, ensuring that ecological considerations carry equal weight to economic and technical criteria. The “right” extraction area is not only the one with suitable sand, but also the one where extraction causes the lowest avoidable impact on ecosystem services and ecosystem functioning.

Marine sand extraction for NBS should be guided by a spatial prioritization framework that combines sand quality, available volume, extraction feasibility and ecosystem service sensitivity. Areas with lower expected impacts should be preferred, while sensitive or already heavily impacted areas should be avoided or used under stricter conditions.

Recommendation 7. Design extraction strategies according to site-specific ecosystem characteristics, rather than applying a one-size-fits-all approach.

SUSANA, together with previous research, indicates that geological context, extraction volume and intensity are key determinants of ecosystem impact. Higher annual extraction volumes, especially on small surface areas, lead to stronger changes in ecosystem functions and thus ecosystem services, incl. in the far field (see Recommendation 5). However, for near-field impacts the ecosystem service model indicates that small extraction volumes evenly phased in time may have a larger impact than a single, large-scale extraction event over the same period of time and surface area. The model assumes that the ecosystem fully recovers within eight years after extraction has ceased (Lopez Lopez et al. 2025), so that the larger initial impact of a single intensive extraction event gradually declines to zero over the recovery period. Over the 2050–2100 implementation period of *Kustvisie*, this results in a lower net impact than continuous lower-intensity extraction.

However, these model results are subject to considerable uncertainty as it remains highly unsure whether full ecosystem recovery will occur after very large-scale extraction volumes such as those required for the implementation of the *Kustvisie* scenarios. Furthermore, the recovery rates implemented in the model are based on observations in areas that are characterized by high natural sediment dynamics. Recovery times differ in other extraction zones, and in some areas full recovery of the benthic ecosystem may not occur. Moreover, SUSANA and previous research also show that extraction effects, both in the near- and far-field, differ depending on the location (see Recommendation 6).

For NBS programs requiring large sand volumes, alternative sands should be systematically included in the assessment of possible sand-use options. This assessment should consider their suitability for the intended NBS functions and ecosystem service delivery, while also accounting for environmental and sanitary quality requirements, ecological effects, logistical and operational feasibility, and the finite nature of high-quality marine sand as a strategic resource (see Recommendation 1). Where high-quality marine sand is nevertheless required, extraction should be preceded by an effect assessment based on the local ecosystem context in and around the extraction area. This will enable inclusion of site-specific mitigation measures, while making sure that all above recommendations are considered as well. Given the uncertainties, scenarios that require very large-scale sand volumes at once should be critically assessed against alternatives that spread extraction over time.

2.3. Integrated decision support and governance for sustainable sand use

Recommendation 8. Use the ecosystem services framework as a strategic screening tool contributing to integrated cost-benefit assessment, not as a stand-alone decision rule.

The ecosystem services framework provides a valuable tool to compare trade-offs and synergies between benefits of alternative sands in NBS and sand extraction impacts. It can help evaluate how different sand sources, extraction volumes, extraction locations and mitigation options affect ecological and economic sustainability. However, the output of ecosystem services assessment should not be used as an automatic decision rule. Some impacts are not yet fully captured, including intrinsic biodiversity value, ecological effects of turbidity on food webs, impacts of deep extraction, and long-term cumulative effects. These values are typically insufficiently represented in marine ecosystem services assessments because they are difficult to capture through economic valuation alone (Addamo et al., 2024). A valuation based only on monetized ecosystem services can provide an incomplete picture of the consequences of sand extraction.

Ecosystem services should be embedded in a broader decision process. The framework should be used to structure scenario comparison, reveal trade-offs, identify robust options and support transparent dialogue between authorities, researchers and practitioners. Final decisions should also include biodiversity considerations, precautionary reasoning, governance and economic feasibility.

Recommendation 9. Establish long-term monitoring to evaluate whether NBS and sand extraction outcomes match expected ecosystem service performance.

The performance of NBS and the recovery of extraction sites are dynamic processes. Ecosystem services such as dune development, sand nuisance prevention, habitat formation, carbon cycling and nutrient regulation evolve over time and may respond non-linearly to environmental conditions and management interventions. A long-term strategy should therefore not rely only on ex-ante modelling, but should combine modelling with adaptive monitoring.

For NBS in particular, full or intermediate-scale (e.g. wave flume) pilot projects are needed to bridge the gap between small-scale experiments, modelling results and operational implementation. SUSANA and related initiatives have provided important insights into the potential use of alternative sands, dune vegetation establishment, recreational perception and ecosystem service delivery, but several key uncertainties can only be resolved under real coastal conditions and at a relevant spatial scale. The success of nature-based coastal protection depends not only on the immediate technical suitability of a sediment source, but also on its capacity to support dune growth, ecological development and adaptive performance over time. Small-scale experiments can demonstrate whether vegetation can germinate or establish on alternative substrates, but they cannot fully capture the coupled interactions between wind-driven sand transport, vegetation growth, sediment supply, storm erosion, recreational pressure and maintenance interventions. These interactions may behave differently at field scale than in controlled experiments and are decisive for whether alternative sediments can deliver the expected ecosystem services in operational NBS. Addressing this gap requires long-term monitoring and full-scale pilot projects in which alternative sediments are tested under real coastal conditions. Pilot projects should be considered as risk-reducing preparatory investments rather than as stand-alone research activities. Such pilots would also provide an operational setting to align monitoring, permitting, communication and governance arrangements before wider implementation.

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For extraction sites, monitoring should include sediment characteristics and thickness of the available layer, benthic communities, organic matter content, biogeochemical functioning and food-web indicators. Nearby sensitive species should be incorporated in a far-field monitoring plan following a risk-based approach.

An adaptive monitoring framework for both NBS sites and sand extraction sites should be established. Monitoring data should be used to update model assumptions, refine sand suitability criteria and improve future decision-making.

Recommendation 10. Strengthen governance for sand reuse and impact mitigation through a shared vision, clear responsibilities and coordinated planning.

A sustainable sand strategy for NBS requires coordination across institutions and sectors. The barriers to beneficial reuse are not only technical; they also concern regulation, timing, responsibilities, data access, permitting and public trust. Similarly, mitigation of extraction impacts requires coordination between authorities responsible for coastal safety, marine spatial planning, sand extraction, nature conservation and environmental monitoring.

SUSANA supports the need for a governance framework for strategic sand use in NBS, in which alternative sand use and extraction mitigation are considered together. This should include clear roles for government authorities, port authorities, contractors, dredging companies, research institutions and consultants. Governments should create a harmonized framework between land and sea, support centralized sediment quality data, and introduce incentives for reuse. Port authorities should integrate reuse into tendering and master planning. Contractors and dredging companies should adopt techniques to minimize impact and preserve sediment quality. Research institutions and consultants should support quality labels, environmental guarantees and decision-support tools. Governance arrangements should be tested through pilot cases and progressively formalized into standard procedures for NBS planning, permitting and implementation. A clear, harmonized governance framework should be established across the responsible authorities to coordinate sediment-quality assessment, determine suitability for beneficial reuse and streamline permitting. This governance framework should provide clear strategic guidance and common assessment principles within which individual projects can evaluate and justify their sediment-use choices.

A more robust long-term approach to the management of finite marine sand resources also requires strategic planning beyond individual projects and beyond the time horizon of successive Marine Spatial Plans. This calls for a dedicated long-term perspective on sand resource use in the Belgian Part of the North Sea, informed by sufficiently detailed projections of future sand demand from large-scale programmes such as *Kustvisie*, and supported by adequate scientific knowledge on resource availability, ecosystem impacts and recovery. Such a long-term perspective would help ensure that project-level sediment-use decisions are taken within a broader understanding of cumulative demand, future scarcity and ecological constraints.

Recommendation 11. Establish long-term financing mechanisms and investment frameworks for large-scale NBS.

Large-scale NBS for coastal safety require substantial upfront investment, while many of their benefits emerge over longer time horizons and are distributed across different policy domains, including coastal safety, nature development, climate adaptation, recreation and environmental quality. As a result, costs and benefits are not necessarily borne by the same actors or governance levels. A long-term implementation strategy should therefore not rely solely on project-based funding but should provide mechanisms that enable sustained investment across planning, construction, monitoring, adaptation and maintenance phases.

SUSANA also shows that financing is closely linked to the need for learning on an operational scale. Existing experiments and small-scale pilots provide essential process knowledge, but they cannot fully capture the coupled geomorphological, ecological, technical and societal dynamics that determine NBS performance at larger scales. Full-scale demonstrators should therefore be regarded not only as implementation projects, but also as strategic investments in risk reduction. They can provide the empirical basis needed to validate models, test the long-term performance of alternative sediments, refine monitoring strategies, assess maintenance requirements and improve the reliability of subsequent investment decisions.

Financing frameworks should consequently allow resources to be combined across relevant policy domains and should explicitly recognize the broader societal value of NBS. They should also provide sufficient continuity to support baseline monitoring before construction and long-term follow-up after implementation, as many relevant processes, including vegetation development, dune growth, storm response and ecosystem service delivery, only become apparent over time. Embedding demonstration projects within a stable financing framework can reduce uncertainty, improve cost-effectiveness of later applications and support more robust scaling-up of coastal NBS.

3. Key knowledge gaps

3.1. Understanding long-term ecological and geomorphological trajectories of alternative sediments in nature-based solutions

What SUSANA has already shown

SUSANA demonstrated that alternative sand sources can successfully be used to construct dune-in-front-of-dike systems and contribute to multiple ecosystem services, including coastal safety, habitat development, recreation, and sand nuisance prevention. The project showed that sediment properties such as grain size, color, organic matter content, salinity, and moisture-retention capacity influence vegetation establishment, aeolian dynamics, and public perception. Results further indicate that alternative sediments do not necessarily prevent dune development but may alter the pathways through which dunes and associated ecosystems develop.

What the remaining knowledge gap is

The long-term ecological and geomorphological consequences of using alternative sediments remain insufficiently understood. Alternative sediments may initially create different conditions for vegetation establishment and sand transport than native beach sands. For example, coarse or organic-rich

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sediments may provide a relatively stable substrate that facilitates early plant establishment, while subsequent deposition of naturally transported beach sand gradually shifts the system towards more typical dune conditions. Conversely, when alternative sediments are applied over the entire coastal profile, they will also alter marine and aeolian transport rates, sediment supply, dune mobility, and long-term morphodynamic development. Differences in salinity, nutrient content, or organic matter may also affect succession trajectories, potentially delaying or changing the establishment of characteristic dune-building species such as *Ammophila arenaria*.

Why it is important for decision-making

The success of nature-based coastal protection depends not only on the immediate technical performance of a sediment source but also on its long-term ability to support dune growth, ecological development, and adaptive capacity. Decisions based solely on short-term engineering suitability may overlook delayed ecological responses or unintended effects on sediment dynamics. Understanding these trajectories is particularly important when alternative sediments are used at larger scales, where their influence on dune evolution, vegetation succession, and maintenance requirements may become more pronounced. Uncertainty about colonization processes also affects practical management decisions, such as whether vegetation establishment can be left to natural recruitment or requires active planting.

What is needed to address the gap

Long-term monitoring and experimental pilot sites are needed to evaluate how alternative sediments affect dune development, vegetation succession, and ecosystem functioning over decadal timescales. Monitoring should combine geomorphological indicators (aeolian transport, erosion and accretion patterns, dune growth rates) with ecological indicators (species establishment, vegetation cover, habitat development, and biodiversity trajectories). Process-based modelling should be further developed and used to explore how sediment characteristics influence sediment transport, vegetation development and dune evolution under different climate and management scenarios. In addition, field experiments should evaluate different vegetation establishment strategies, including natural colonization, immediate planting, and delayed planting, to determine under which conditions characteristic dune-building species can be expected to establish and contribute to long-term system resilience. Digital twins could play an important role by linking real-time monitoring, process-based coastal models, and ecological development trajectories, thereby supporting prediction of long-term ecosystem and geomorphological responses to alternative sediment use under climate-change scenarios.

3.2. Understanding contaminant risks and sediment quality

What SUSANA has already shown

SUSANA demonstrated that alternative sediment sources can support dune development and ecosystem-service delivery under suitable conditions. The project primarily assessed physical, ecological, and societal performance dimensions relevant to NBS implementation.

What the remaining knowledge gap is

The long-term implications of potential contaminants associated with alternative sediment sources remain insufficiently understood. Depending on origin, dredged or reused sediments may contain elevated concentrations of metals, organic pollutants, nutrients, microplastics, or emerging

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contaminants. Whether existing sediment-quality assessment frameworks are sufficiently suited for the specific ecological and functional context of NBS remains uncertain. Criteria developed for conventional soil or sediment management may not automatically capture the environmental pathways and ecosystem-service objectives that are relevant for NBS applications. As an example, concentrations may comply with existing regulations, though uncertainty remains regarding their long-term behavior after placement in dynamic coastal systems.

Why it is important for decision-making

Concerns regarding contamination are among the most important barriers to the acceptance and permitting of sediment reuse projects. Potential impacts on vegetation establishment, soil development, groundwater quality, food webs, and public perception may influence both environmental and social acceptability.

What is needed to address the gap

Research is needed to evaluate whether existing quality standards and assessment frameworks adequately address the ecological, functional and societal objectives of NBS applications, and to identify where additional assessment criteria or context-specific guidance may be required.

Long-term monitoring of sediment chemistry, groundwater quality, contaminant mobility, and ecological responses is needed to support evidence-based permitting and implementation, as well as site-specific risk assessments and harmonized sediment-quality criteria for NBS applications. . When reusing old disposal grounds, a top-down risk characterization is required.

3.3. Understanding cumulative impacts across activities and over time

What SUSANA has already shown

Regarding cumulative impacts, SUSANA focused on sediment-dispersion modelling bringing awareness on the far-field footprint of bottom-disturbing activities, such as extraction, dredging, disposal and bottom-contacting fisheries. Outcomes showed differing spatial extents and exposure durations. Related research further showed that extraction effects depend on geological and sedimentary context, cumulative extraction intensity and the persistence of disturbance. Cumulative pressure therefore has both a spatial dimension, the overlap and interaction among activities, and a temporal dimension, the accumulation of repeated disturbance and (in)complete recovery.

What the remaining knowledge gap is

Although cumulative physical pressures can increasingly be reconstructed and modelled, their translation into cumulative ecological effects remains limited. It is unclear when successive or overlapping pressures produce additive, synergistic or antagonistic responses, and how much recovery is required between disturbances to prevent irreversible habitat change. The influence of the pre-existing pressure load on the response to new extraction is unknown. For the extraction of finer alternative sand resources, the associated plume footprint, far-field deposition and resulting ecological exposure have not yet been modelled and assessed. Hitherto, regardless of several EU environmental legislations requiring cumulative effects to be considered, no assessment methods, data inputs and effect thresholds are yet harmonized across sectors and countries, limiting the consistent treatment of cumulative and cross-border pressures.

D5.3 Recommendations for sustainable use of sand in NBS

Beyond scientific uncertainty, there is also a governance challenge. It remains unclear at which decision-making level cumulative effects should be assessed and managed when multiple sediment-producing and sediment-consuming projects interact over time.

Why it is important for decision-making

Project-level assessments cannot be fully understood or managed through project-level decision-making alone. It may be concluded that individual activities are acceptable, while overlooking broader system-level interactions. Strategic planning frameworks are therefore needed to ensure that individual permitting decisions are informed by system-wide environmental objectives and pressure levels. Cumulative-impact information is needed to determine where and how much sand can be extracted, whether extraction should be phased, and which recovery periods are required.

In addition to improved ecological assessment methods, governance mechanisms are needed that allow cumulative effects to be evaluated across projects and sectors. Such mechanisms could fulfil a role comparable to strategic environmental assessment by providing a broader framework within which individual project decisions are made.

What is needed to address the gap

Multi-year sediment-dispersion should be combined with risk-based monitoring along gradients of cumulative pressure. Proxies are needed to enable linking observed seabed properties to specific pressure histories while distinguishing anthropogenic effects from natural variability. In sensitive areas, the significance of change and particularly its irreversibility should be assessed to aid decision making. This may entail adaptive permit conditions, including spatial limits, extraction phasing allowing for recovery, and stopping rules.

3.4. Understanding ecosystem responses to future large-scale sand extraction for NBS

What SUSANA has already shown

Current evidence demonstrates that extraction volume and intensity are key drivers of ecological impact. Higher extraction volumes are usually associated with stronger changes in benthic and fish biodiversity, ecosystem functioning and ecosystem service delivery. However, these relationships have been established based on the extraction intensities currently occurring in the Belgian Part of the North Sea, typically up to approximately 3 million m³ per year for industrial purposes and ca. 0 -1.5 million m³ (year dependent) for coastal defense purposes (website FOD Economie).

What the remaining knowledge gap is

It remains unclear whether the observed relationships between extraction volume and ecological impact remain valid under the substantially larger extraction volumes that may be required to support future large-scale Nature-based Solutions. Near and far field potential threshold effects, non-linear ecosystem responses and recovery limitations at higher extraction intensities are currently poorly understood. As the transition towards Nature-based coastal protection is expected to increase demand for marine aggregates, understanding the ecological consequences of extraction volumes beyond current operating conditions is essential for defining environmentally sustainable extraction limits.

Why it is important for decision-making

D5.3 Recommendations for sustainable use of sand in NBS

Future coastal protection strategies may require considerably larger volumes of marine aggregates than those extracted today. Without a sound understanding of ecosystem responses at these higher extraction levels, decision-makers face significant uncertainty when assessing environmental impacts, defining sustainable extraction limits and evaluating trade-offs between coastal protection benefits and the conservation of marine ecosystem services. This uncertainty may lead either to underestimating ecological risks or to overly precautionary restrictions that unnecessarily limit extracting available sand resources.

What is needed to address the gap

This requires long-term monitoring and predictive modelling across a wider range of extraction intensities than currently observed, combined with scenario analyses of future sand demand for Nature-based Solutions. Particular attention should be given to identifying ecological thresholds, cumulative impacts and recovery potential under high-volume extraction scenarios, enabling the definition of scientifically robust and environmentally sustainable extraction limits.

3.5. Broadening valuation beyond monetary use values

What SUSANA has already shown

SUSANA developed a coupled modelling framework that quantifies benefits of using alternative sand sources both in the dune-in-front-of-dike system and in the marine ecosystem affected by sand extraction. Key strength is that both submodels are largely based on local, empirical data, allowing to quantify impacts across the NBS impact zone. Changes in ecosystem functioning were translated, where possible, into societal value through monetary valuation.

What the remaining knowledge gap is

SUSANA also showed that monetary valuation does not capture all relevant ecosystem values. This is particularly important for marine ecosystems, where valuation still focuses strongly on use values and monetary approaches, while a wider range of methods is more commonly applied in terrestrial systems (Van Schoubroeck et al., 2024). Non-use values, option values and intrinsic values remain insufficiently represented because they are difficult to capture through economic valuation alone (Addamo et al., 2024).

Why it is important for decision-making

A valuation based only on monetized ecosystem services can provide an incomplete picture of the consequences of sand extraction. Ecological impacts for which no monetary value is available may receive too little weight. In SUSANA, this could in some cases result in a seemingly more favorable assessment of increased extraction for specific ecosystem services (increased biomass production of some commercial fish species), while important ecological and societal values remain outside the comparison.

What is needed to address the gap

Future work should complement monetary valuation with methods that can capture non-use, option and intrinsic values, such as participatory valuation, deliberative approaches and multi-criteria analysis. These methods should be tested in combination with the SUSANA model outputs to determine how they affect the comparison of alternative sand-use and extraction strategies.

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