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Best practice for boulder reef restoration

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Colophon

Title: Best practice for boulder reef restoration

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Front page photo: Placement of quarry stone from Norway when establishing the boulder reef near Livø in the Limfjord. Photo: Torben Bramming Jørgensen.

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Summary: This report clarifies what boulder reef restoration includes and describes the recommended process for designation and implementation of restoration projects. The report also provides an overview of relevant regulations, licences and authorities in relation to boulder reef restoration in Danish coastal waters. It also provides recommendations for monitoring reef development as well as examples of boulder reef design and costs associated with boulder reef restoration.

Contents

Preface

Restoration of boulder reefs in Danish waters has received a lot of attention in recent years. A few reefs have been restored and many restoration projects are underway. To promote the likelihood of future projects being successful and support the ambitions of restoring boulder reefs in areas where reefs have been impacted by past extraction, we here provide best practice guidelines that are recommended to be used in future restoration projects.

The report has been submitted for technical consultation to the Danish Coastal Authority and the Danish Environmental Protection Agency. The Danish Coastal Authority has only carried out a professional control of information about its practices.

Summary

The report describes six phases that should be included in the designation of areas suitable for nature restoration of boulder reefs. Initially, a screening (Phase 1) should be carried out, which includes: a) clarification of the purpose of site selection; b) delineation of an initial screening area; c) analysis of sediments, depth conditions and historical boulder extraction; d) initial conflict analysis; e) analysis of ecological framework conditions. Based on an overall assessment of these six factors, an initial designation of an overall project area is made. The initial screening should be supported by preliminary studies of the carrying capacity of the bottom and biological and cultural-historical conditions (Phase 2), from which a detailed project plan (Phase 3) specifying the selection of reef restoration material is prepared and submitted for approval by the authorities (Phase 4). Once a licence has been obtained, the reef must be established (Phase 5) and, finally, thorough documentation (Phase 6) must be elaborated of whether the placement plan was followed, and it is recommended to document the biological development on the reef in relation to the stated objectives of the restoration. The report provides an updated overview of relevant regulations, data, licence requirements and authorities in relation to nature restoration of boulder reefs in Danish coastal waters. It also provides recommendations for monitoring reef development as well as examples of the design and costs associated with boulder reef restoration.

1. Introduction

The report is aimed at municipalities and organisations with an interest in restoring boulder reefs.

The report clarifies what boulder reef restoration includes and describes the recommended process for designation and implementation of restoration projects. The recommendations are based on experience from several restoration projects and in-depth knowledge of the occurrence of natural boulder reefs that have not been exposed to extraction. The report also describes which authorities will be involved in the application processing.

The guidelines go through the various practical and management considerations that should be taken into account when restoring boulder reefs in Danish waters. Alongside the guidelines, a report "Conditions of importance for nature restoration of boulder reefs" (Stæhr et al., 2024a) has been prepared, which describes in more detail the biological and environmental conditions that should be taken into consideration in connection with a restoration project.

In English terminology, boulders are larger than 25.6 cm. Stable reef structures in Danish waters may consist of cobbles (6.4-25 cm) or even minor stones. For simplicity, we used the term boulder reef in this report if the substrate is considered stable.

The purpose of the report is to:

- Describe the different phases of designating areas suitable for boulder reef restoration.
- Provide an overview of relevant regulations, licences and authorities in relation to boulder reef restoration in Denmark.
- Communicate knowledge about the design, selection of materials and establishment of the reefs.
- Provide recommendations for monitoring and documentation of reef development.
- Create a platform for knowledge exchange and knowledge building as more experience is gained with boulder reef restoration.

2. Boulder reef restoration

Definition of boulder reef

In relation to the designation and management of protected areas under the Habitats Directive, the Danish Ministry of the Environment has developed a definition of the boulder reef habitat type. According to this definition, a core area must contain a deposit of stones with at least 25% coverage of the seabed. Where this is the case, the reef is delineated outwards, reducing the stone coverage to 10% (Al-Hamdani et al., 2019, in Danish). A boulder reef is characterised by stable stones that can provide a habitat for perennial organisms that grow on the surfaces of the stones. The size of stones that are stable depends on the physical environment of the area. Experience has shown that the size of stable stones varies between 5 and 30 cm in Danish waters.

Boulder reefs can be divided into different geomorphological types. Some reefs are well-defined, either with sharp transitions from stones to softer sediments, while others have a smoother transition where the stones gradually become rarer and typically smaller. Finally, there are also reef areas where the stones are placed in a mosaic structure, where denser stone deposits are replaced by bottom types with finer sediments. If the reef structures with 25% coverage are not too far apart, the reef habitat type is mapped as the entire mosaic area including the sandy areas in between. An example of mapping this type of reef can be found in appendix 1. A more detailed description of factors that are important for life on boulder reefs can be found in Stæhr et al. (2024a).

Boulder extraction

Boulders on the seabed have historically been utilised for the construction of coastal structures such as fortifications, harbours, dykes for coastal protection and as erosion protection for other marine construction projects. The utilisation of boulders along coasts and in very shallow water can be traced back to Stone Age burial monuments, but the possible Stone Age impact of today's boulder reefs is limited to the south-west of the country, where there has been no subsequent land uplift.

The need for boulders grew significantly with the expansion of the Danish coastal infrastructure during the 1900s when a very large number of harbours were built along the Danish coasts and even on smaller islands. Later in the 1900s, many more marinas were also added.

In the latter half of the 20th century, sand and pebbles (gravel) began to be extracted from the seabed in earnest. This type of extraction is done with suction. The size of the stones removed with this method is limited by the diameter of the pipe. In areas protected from waves and currents gravel banks on the seabed can fulfil the same biological function as reefs consisting of larger stones.

Actual boulder extraction was banned with the amendment of the Mineral Resources Act in 2009, but already from 1999, the industry was heavily regulated with regard to a small number of designated boulder extraction areas and a restriction to only carry out repair work on existing structures (Helmig et al.,2020). Boulder extraction from ships has primarily taken place at water depths shallower than 10 metres, most often between 4 to 7 metres depth, corresponding to the surf zone in many areas (Helmig et al., 2020). Boulder extraction first took place from fishing boats in very shallow water, where you could see the stones and guide a claw down from the deck of the ship to grab them. With the increasing demand for boulders, the industry became more specialised. Larger boats came into use, mechanisation was introduced, and divers were used to guide the boulder claw on the seabed to reach stones that could not be seen or grabbed from the surface. However, the use of divers and the technology of the time also limited where the exploitation of boulders took place, how intensive the exploitation was, which stone sizes were exploited and the fact that the extraction of raw materials was limited to a depth of around 10 metres.

The way in which boulder extraction was carried out provides a good insight into which areas were potentially exploited and how the bottom was left after exploitation. The stones of interest to the industry were larger boulders that could create stable structures along the coastline. Locally, you can find out about the popular boulder sizes by looking at the stones used for, e.g., harbour piers.

When grabbing the boulders, the ship was at anchor and you could only reach the stones that were directly under the boat. Once they had been grabbed, or if there were none of the right size, the crew pay anchor line out and tried a new spot to where wind and current took the ship. Once the anchor line was used up, the ship sailed forward and extraction was resumed. If a diver was used, they would go down on the seabed and push around a very large stone plier. Here, too, there was very limited mobility. The work of extracting boulders from the seabed is well described by former crew members on the vessels. Descriptions of boulder extraction can be found in Appendix B in Helmig et al. (2020) and heard in an interview with a person who, among other things, worked on establishing Hundested Harbour. The interview can be viewed at the following link: https://www.youtube.com/watch?v=cMQKFE_IwMk

Considering the practical challenges and limitations of boulder extraction, it is reasonable to assume that the extraction did not leave a site completely devoid of stones. This is also the message from the interviews found in Helmig et al. (2020). Boulder reefs exposed for extraction have therefore been impoverished and left with fewer stones, especially fewer large boulders, and its depth distribution may have been reduced as stones at shallower water depths were easier to remove.

The effect of an impoverished reef can be that many of the remaining stones are no longer stable in the prevailing physical environment of waves and currents. This will lead to further erosion of the site as was observed at Læsø Trindel (Dahl et al., 2009). Fewer stones will also reduce the total stone-covered area, resulting in fewer habitats for attached animals and macroalgae and a corresponding impoverishment of the seaweed forest. Unstable substrates favour opportunistic algae species and benthic animals and do not support the same amount of animals and plants. Finally, a lowering of the reef's top will cause a reduction in available light and physical impact.

The Centre for Marine Nature Restoration works with historical maps and collects information on boulder extracted sites to improve knowledge about those localities. The best overview in the form of maps and data can currently be found at https://data.dtu.dk/articles/dataset/Stenrev_som_gyde-_og_opv_kstomr_de_for_fisk_Revfisk_/24117225/1.

Today, information is available on many locations where boulders have been extracted and in some cases also on the quantities of stones brought ashore by individual ships. It is expected that more information will be added continuously with the interest in boulder reef restoration, and everyone is encouraged to submit new information to the Centre for Marine Nature Restoration. There is already information on many reef sites that may be restored.

Definitions of boulder reef restoration

The concept of boulder reef restoration refers to the restoration of reefs that have been formed by natural processes. Unfortunately, there is no historical knowledge of how large areas the individual boulder reefs covered the seabed and how large and dense the stone deposits were before the extraction of raw materials took off. In some cases, however, it is likely that boulder extraction over the years lowered the water depth at a site. The accuracy of the boulder extraction information that has been preserved for posterity is centred on a location name and not a specific area. Restoration of a boulder reef should therefore be seen as a restoration at a site with a stony seabed where it is likely that boulder extraction has taken place. The restoration will add more and larger stones to the area and possibly restore the historical depth range of the reef.

To the extent that documentation of boulder extraction on a stony seabed can be obtained, it will be an actual restoration. This approach is in line with a recent EU decision in relation to the Marine Strategy Framework Directive taken in spring 2023 (Descriptors under the Marine Strategy Framework Directive (europa.eu)). It was decided that maximum 2% loss of each habitat type will be allowed relative to the conditions decades ago. Reef restoration will not contradict this decision, quite the opposite. Establishing reefs at a site where no reefs have previously existed, on the other hand, would not be compatible with the intention of the Commission's decision to preserve original habitats.

If it is unlikely that boulder extraction has taken place in a designated area, a project involving the establishment of boulder reefs will not have the character of nature restoration but can be categorised as, for example, ecosystem engineering, a nature tool or an educational/experience reef (Petersen et al, 2023).

Interests and obligations in boulder reef restoration

Since the first major European marine nature restoration project at Læsø Trindel, funded by the Danish Ministry of the Environment and the EU LIFE programme, the restoration of boulder reef habitats has for many years been driven by local interests funded by private foundations. In recent years, however, government funds have been allocated in the "nature and biodiversity package" and in the Finance Act for the establishment of boulder reefs. And most recently, marine restoration, including boulder reefs, has received attention in the EU Nature Restoration Regulation, which defines binding targets for restoring lost nature on land and sea.

Documentation on placed stones at Læsø Trindel (Blue reef project). Photo: Karsten Dahl.

3. Phases of a restoration project

Experience has shown that restoring a boulder reef involves various phases, including the collection and interpretation of existing knowledge, citizen involvement, authority processing, construction and field-based monitoring. The timeline of a restoration project (hereafter referred to as the project) and its individual elements are described in more detail in the following sections.

A project can be divided into six phases:

1. General designation of a potentially suitable area or areas (screening) based on a review of existing knowledge.
2. Preliminary surveys to delineate the exact site(s) for stone placement. Parts of the survey can advantageously be designed so that it forms a monitoring baseline (point 6) for initial assessment of the biological effects of the project and for subsequent comparison of the results obtained.
3. Detailed project planning including comprehensive design of the boulder reef's shape, size, timing of placement and stone selection.
4. Authority application and approval.
5. Reef establishment with placement of boulders.
6. Follow-up documentation of biological effects/ecosystem services using standardised monitoring methods.

In each phase, there are a number of sub-elements as listed in Table 1.

In addition, it is recommended that an assessment be made in collaboration with relevant authorities to determine whether there is a need for a change in the future management of the selected site. A large increase in the abundance of, e.g., cod on a restored reef can lead to a greater fishing pressure and thus end up having a negative effect on a species that is already under a great pressure in the inner Danish waters. Therefore, it should be considered whether the future management of the restored boulder reefs should include fisheries protection.

It is recommended to promote citizen involvement throughout the project to ensure local support and to gain valuable local knowledge. The course of the designation process and subsequent surveys as well as the detailed planning and documentation is shown in Table 3 and follows the overall recommendations for nature restoration projects described in Stæhr et al. (2024a).

The first three phases can typically take up to a year or more to complete as they involve preliminary studies prior to placing the stones. Good preliminary studies, on the other hand, create the potential for successful restoration of boulder reef habitats. The six phases are elaborated on below.

Phase 1: Screening of suitable areas

The screening part qualifies, based on existing knowledge, the designation of optimal areas for stone placement to avoid resource-intensive nature restoration failures. The following guideline will be updated as experience is gained.

Formulating the project's goals

The basic purpose, of course, is to carry out reef restoration in order to re-establish the physical and biological structure and function of a boulder reef. However, since we cannot expect to obtain detailed knowledge about past stone densities or precise information about the working places of stone fishermen and perhaps not even about changed bottom conditions, it is useful to formulate a

***Table 1**. Overview of the expected process of designation (screening) and subsequent preliminary surveys, detailed project planning, authority approval, establishment and final documentation of a boulder reef project.*

Phases:	**Activities**	**Approximate duration**					
		1	2	3	4	5	6
1: Screening	Clarification of the purpose						
	Delineation of the screening area						
	Analysis of sediments, depth conditions and boulder extraction						
	Initial conflict analysis						
	Analysis of the ecological framework conditions						
	Overall initial assessment and delineation of the project area						
2: Preliminary surveys	Investigation of seabed composition (stone cover and possibly carrying capacity) and depth conditions						
	Biological baseline study						
	Cultural heritage survey						
3: Detailed project planning	Selection of placement material (boulders from the sea, boulders from agricultural fields or land construction sites or quarry boulders)						
	Preparation of a detailed georeferenced plan including the overall project area, specific areas with average boulder densities after placement, quantity estimates as well as indications of changed depth conditions						
4: Authority approval	Submission of application to the Danish Coastal Authority						
5: Establishment	Purchase, transport, shipping and placement of boulders						
	Deploying of marker buoys, if required						
	Construction supervision						
6: Documentation	Depth measurements and other control of the placement						
	Use of standardised monitoring methods to document reef development						

more specific purpose for the project in question to optimise the delineation of the screening area, the specific placement plan and costs. The goals set should also influence any future management and the development of a monitoring programme.

Typical specific purposes of boulder reef restoration:

- Restoration of the stability and physical complexity of a reef.

- Re-establishment of specific habitat types. These can be 1) seaweed forests in the photic zone (i.e. where there is light at the seabed), 2) fauna-dominated reefs at depths with little or no light or 3) reefs where both algae and flora are present.
- At Natura 2000 sites, reef restoration will support the achievement of favourable conservation status for the “reef” habitat type if it is included in the site's designation basis.
- Preservation or restoration of the species richness of seaweeds, benthic animals and fish.
- Strengthening of marine food chains including fish and marine mammals.
- Strengthening of blue corridors for the spread of organisms between areas.
- Socio-economic interests. For example, promoting diving or angling tourism or commercial fishing by boosting local fish stocks.

It may be necessary to adjust the purpose during the planning phase as a result of the information and data collected about the site and the original boulder reefs.

Delineation of the screening area

Delineating a screening area can be considered a first step in prioritising the collection of a range of available data that can support the development of a specific project proposal. The delineation of the screening area can be politically motivated or driven by local interests within an area. Either way, there should be some form of professional documentation for the need to restore a specific boulder reef. Examples of two very different areas of interest include reef restoration in the Øresund region, which was formulated by the Danish Ministry of the Environment as part of the Danish Parliament's nature and biodiversity package, and Roskilde Inderbredning, formulated by National Park Skjoldungernes Land.

Analysing sediments, depth conditions and boulder extraction

A restoration project should include an initial analysis after which a potential restoration site is designated based on a review of available knowledge about seabed sediment conditions, depth conditions and old nautical charts.

There are three different map types that describe the sediment composition of the seabed. One map is GEUS' seabed sediment map, which provides an overall description of the sediment conditions in the top ½-1 metre of the seabed. This map covers the entire Danish marine area. Areas with boulder reefs or stony areas are not explicitly shown but are included along with sand, gravel and clay in a broad type that includes moraine deposits, which can also be referred to as diamict. The seabed sediment map relies on modelling based on available point sediment surveys and various acoustic surveys. The data density varies considerably, and for shallow coastal areas it is often very scattered. This uncertainty must be considered in the analysis. Areas shown as moraine deposits on the seabed sediment map can be a good starting point for narrowing down a project area, but there are and have not necessarily been boulder reefs in the area. Conversely, there may be moraine deposits in an area that has not been mapped, and these are therefore shown on the map as sand or mud. GEUS seabed sediment maps can be accessed online or downloaded (https://data.geus.dk/geusmap/?mapname=marta#baslay=baseMapDa&optlay=&layers=havbundssediment).

The second map is a substrate type map, which only describes the top layer of the seabed (approx. ½-1 metre). The substrate type map provides a much more detailed description of the substrate composition in the seabed surface. This map type has been created for Natura 2000 areas, many mineral resource areas and areas with completed or potential infrastructure projects such as wind farms, bridges and tunnels. The maps are based on acoustic surveys and numerous sediment samples at selected points and describe the substrate types in great detail (Table 2). Substrate type maps are also used as a starting point to describe (map) marine habitats such as boulder reefs. The boulder reef habitat type consists of substrate type 4 and additionally substrate type 3, but only if substrate type 3 occurs together with substrate type 4.

Table 2. Substrate types used in the substrate type map. The substrates represent the top layer of the seabed (from the surface to about 1 metre depth). The substrate map is used to describe the habitat types and for mapping raw materials (see Figure 1) (Al-Hamdani et al., 2021.)

Substrate type	Definition
1a. Soft seabed	Soft seabed. Homogeneous silty sandy seabed or silt where the seabed is not dynamically influenced and where the sediment consists of silt and silty sand or mud.
1b. Sand	Homogeneous firm sandy seabed (sand is defined as grain sizes from 0.06-2.0 mm) characterised by some form of dynamics with wave ripples, etc. This substrate type may also hold varying amounts of shells, gravel and silt.
c. Patterned sandy seabed with clay	Areas consisting of clay or larger relict clay blocks on a silty to sandy seabed, where the highly reflective clay gives the seabed a patterned appearance. These clay patterns can have very distinctive current stripes.
2a. Sand, gravel and pebbles	Highly variable substrate type dominated by sand and coarse sand with varying amounts of gravel and pebbles. The substrate consists of a mixture of sand, coarse sand and gravel with a grain size of approx. 0.06-20 mm and pebbles with sizes of approx. 2 to 10 cm.
2b. Sand, gravel and pebbles as well as dressing (<10%) with stones >10 cm	Highly variable substrate type, dominated by sand and coarse sand with varying amounts of gravel and pebbles and scattered large stones. The substrate consists of a mixture of sand, coarse sand and gravel with a grain size of approx. 0.06-20 mm and pebbles with sizes of approx. 2 to 10 cm. The substrate type can also contain larger stones >10 cm, but only up to 10% coverage.
3. Sand, gravel and pebbles as well as dressing (<10%) with stones >25 cm	Area consisting of mixed substrates with sand, gravel and pebbles and with a dressing of larger stones >10 cm. The substrate type contains a larger number of stones >10 cm, most often with a coverage of 10-25%.
4. Stones >10 cm covering >25%.	Area dominated by stones >10 cm but also with varying amounts of sand, gravel and pebbles. The stones are either scattered on the seabed with a coverage >25% or occur as a dense layer of stones

Examples of the three map types are shown in Figure 1 from the same area off Gilleleje in North Zealand. In this case, the detailed substrate type mapping is incorporated into parts of the seabed sediment map. The outer framework of the moraine/diamict class, for example, reflects the use of interpolations with the use of straight lines.

At shallower water depths in coastal areas, georeferenced aerial photos (also known as orthophotos) can be used to get an idea of whether an area is interesting for further investigation. How deep you can see in the images depends on the clarity of the water at the time when the photo was taken. Sandy seabed stand out, while it can be more difficult to distinguish eelgrass, mussels and stones from each other. It is common for all three types to appear together at a site. Orthophotos from the spring can be downloaded from Dataforsyningen (https://dataforsyningen.dk/data/981). Summer orthophotos also exist, but they are not publicly available. Summer orthophotos of the

Seabed sediment map (Leth, 2020).

Substrate type maps based on sidescan sonar surveys (GEUS, pers. communication).

Habitat type map based on an interpretation of the substrate type map Natura 2000 plans 2022-27, https://mst.dk/erhverv/tilskud-miljoeviden-og-data/data-og-databaser/miljoegis-data-om-natur-og-miljoe-paa-webkort/hent-data-udstillet-paa-miljoegis

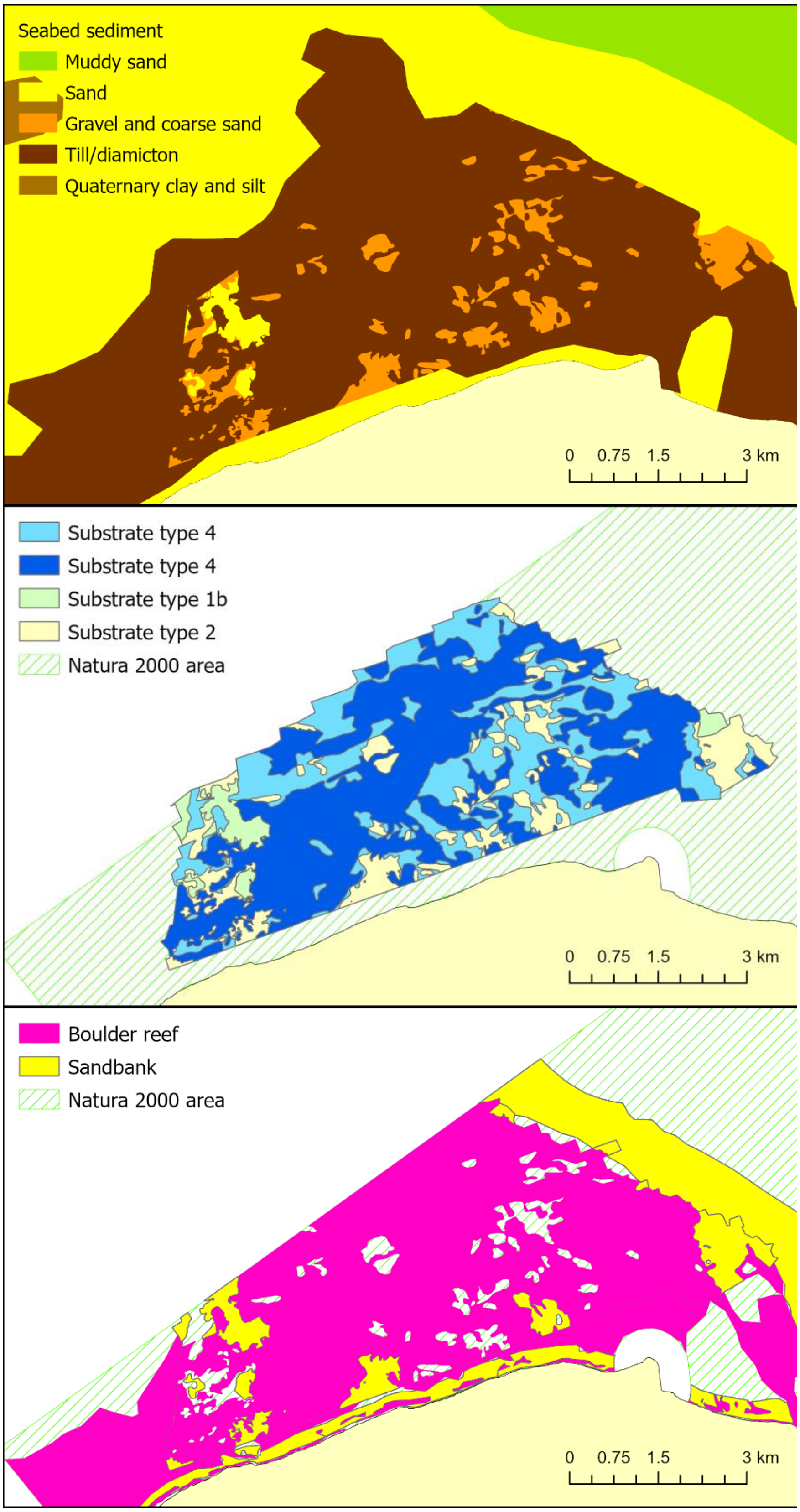

Figure 1. Three types of seabed mapping in the area north of Gilleleje.

coastal sea areas are regularly taken with high coverage, most recently in 2012 and 2018. Orthophotos can be found for most coastal sections with less precision back to the 1940s [(https://maps.flyfotos.dk/)](https://maps.flyfotos.dk/). Seabed depth maps are also available from the Danish Geodata

Agency (Geodatastyrelsen, 2022). The mapping along shipping lanes is highly accurate and done with multibeam.

Shallow areas that are dangerous to navigate have also been a major focus of marine depth measurements in the past, but here it was first done with a plumb line and later with single beam echo sounder. In both cases, these are point measurements along shipping lanes. In shallow coastal areas and areas without commercial interest, measurement is extensive and the depths shown are based on interpolations between measurements. This means that mapping is rarely very accurate.

Preliminary analysis based on knowledge of sediments, depth conditions and possible boulder extraction

An analysis of areas suitable for boulder reef restoration can be made based on existing data as shown in Figure 2. Initially, you can exclude areas where the presence of stones and reefs is unlikely. For example, you can exclude areas that are mapped as pure sand or mud and completely exclude areas significantly deeper than 10 metres where boulder extraction has not been possible due to the methods used.

Mapping of substrate types 3 and 4 in existing substrate type maps combined with knowledge of boulder extraction and changes in depth conditions indicate that the area can be designated as a suitable nature restoration area with a high degree of certainty.

If only a seabed sediment map is available with information on moraine/diamict combined with information on boulder extraction in the area, the certainty of the assessment of the site's suitability for nature restoration should be set as medium with a clear need for further mapping to delineate a suitable restoration area.

An example of a low certainty assessment is a combination of a seabed sediment map with information on moraine/diamict and lack of information on boulder extraction, but with harbours in the vicinity made with so-called sea stones grabbed from the sea.

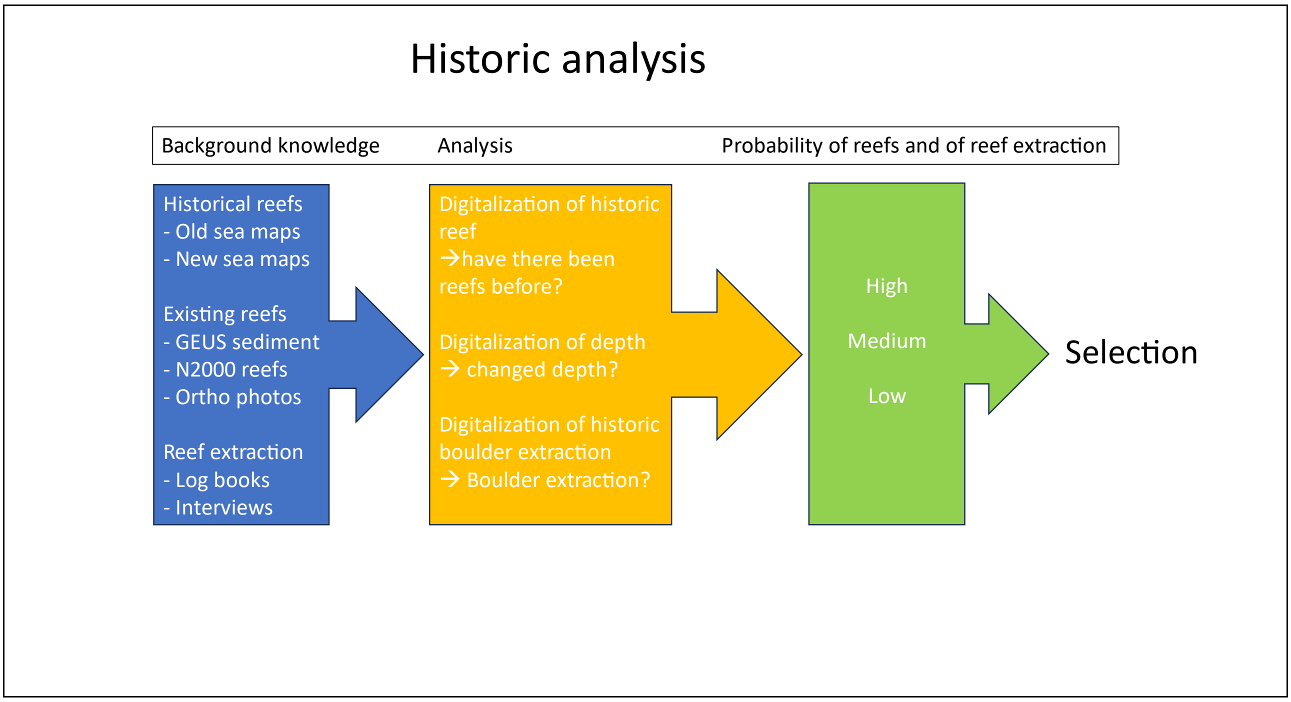

***Figure 2**. Background knowledge included in an historical analysis of changes in the distribution of boulder reefs to provide historical documentation of boulder extraction in a local area. The certainty of the documentation contributes to the overall designation of areas suitable for boulder reef restoration. In many cases, it can be difficult to obtain all the background knowledge.*

In addition to maps, knowledge from boulder extraction logbooks can be utilised (see Helmig et al., 2020). Logbook information from vessels conducting boulder extraction is general in terms of where the stones were grabbed at a given site but may indicate the amounts that the vessel in question has fished. The logbook information should be considered a reliable indication that an area has been used for extraction and possibly give a minimum amount that has been taken up. Local citizens may also have relevant knowledge about boulder extraction. This was the case, for example, in the designation of areas suitable for boulder reef restoration in Roskilde Fjord (Dahl et al., 2019, in Danish). By analysing historical nautical charts, it is possible to identify sites where stones and stone deposits have been observed over time. Any differences in local depths compared to contemporary maps can also contribute information that makes boulder extraction likely as historically there has been a particular focus on surveying boulder reefs that could be a hazard to navigation. It is also possible to assess the need for, and thus the likelihood of, boulder extraction in the local area by reviewing the distances to potential boulder extraction sites in relation to constructed harbour piers and coastal protection structures.

In Dahl & Göke (2021) you can see an example of an analysis of potential reef restoration areas in the Øresund region. The analysis combined current sediment and bathymetry mapping with historical nautical charts of sea depths indicating named reef sites. Differences between the historical and current records were used to delineate areas of likely boulder extraction. However, although the approach was quite thorough, the delineation is uncertain. Reefs may well have been spread over a larger area in the past. The main purpose of nautical charts was originally to map navigational safety. Therefore, only those parts of the reefs that had the most relevant depth for shipping traffic were indicated on the nautical depth charts.

More detailed information on seabed mapping and various types of point surveys of seabed sediments can be found in the GEUS Marta database:

https://data.geus.dk/geusmap/?mapname=marta#baslay=baseMapDa&optlay=&extent=80081.01851851854,5989834.104938271,1034918.9814814815,6460165.895061729

Analysing the ecological framework conditions

A wide range of environmental conditions affect the development of life on and near the placed boulders and thus which ecosystem services and purposes a new reef can be expected to fulfil. Environmental conditions include:

- Light
- Salinity
- Temperature
- Oxygen
- Physical exposure
- Sediment stability/distribution of large-sized stable stones

The relevance of and minimum requirements for these environmental conditions for the suitability of an area for boulder reef restoration are described in Stæhr et al. (2024a). An initial designation (screening) of areas suitable for boulder reef restoration should therefore include a review of existing environmental data. If such data are not available, new data should be collected on the local area.

The impact of a new boulder reef on the connectivity with the surrounding nature should also be considered as restored boulder reefs will be much more likely to act as donor areas with the potential to promote the local and regional distribution of species.

Initial conflict analysis

Restoration activities in the coastal zone should be coordinated and delineated in relation to the many other requirements for marine area use. For example, there are areas designated for shipping lanes, military training areas, dredging, submarine cables and recreational activities (e.g. sailing) or allocated for the expansion of commercial or recreational harbours. Even if a plan for area use exists, more activities, including reef restoration, may be added. The Danish Maritime spatial plan (https://havplan.dk/da/om-havplanen/data-og-gis) provides a good overview of both the planned utilisation zones and the background data used, compiled in the nautical chart of Denmark, but there is no portal where all relevant data is updated, so other relevant sources may include the coastal atlas (https://kms.maps.arcgis.com/apps/webappviewer/index.html?id=8669133b3f4842b7a9a19fb24b08ffd5) or environmental GIS (https://mst.dk/erhverv/tilskud-miljoeviden-og-data/data-og-databaser/miljoegis-data-om-natur-og-miljoe-paa-webkort).

Special conditions may be associated with a potential restoration site located in a Natura 2000 area. It makes sense to restore boulder reefs in Natura 2000 areas, but it can also require a lot more administrative work on behalf of the applicant if boulder reefs are not already included as part of the designation for the Natura 2000 area in question. If reefs are not included in the existing designation because boulder extraction has meant that there are no areas with 25% stone cover left, there may be a conflict with other habitat types (most likely "sandbanks") or species on which the designation is based. An example of this paradox is described in a memo for a restoration project for Roskilde Fjord in Dahl & Palner (2019 in Danish).

Information on which Natura 2000 areas have boulder reefs as part of the designation and their location can be found on the Danish Nature Agency's website: https://mst.dk/erhverv/rig-natur/naturindsatser/natura-2000 . Among the general objectives for the habitats listed under the Habitats Directive is that "The total occurrence of habitat types in the Natura 2000 area, regardless of whether they are mapped or not, shall be stable or increasing". This applies even if the action programme does not include specific targets for the reef habitat type.

As a starting point, an appropriate assessment must be prepared for all projects that are carried out in or in the immediate vicinity of Natura 2000 areas, regardless of whether it is a matter of nature restoration or not. If a significant negative impact on the habitat types and/or species underlying the Natura 2000 designation cannot be ruled out, the developer must prepare an impact assessment. In addition, the impact of the project on any Annex IV species under the Habitats Directive must be assessed.

The above investigation must be carried out, even if it can be argued that such a situation is solely due to a lack of knowledge about the need for restoration at the time of designation. The geographical location of Natura 2000 areas and their designation basis according to both the Habitats and Birds Directives can be found on the Danish Environmental Protection Agency's website: https://mst.dk/natur-vand/natur/natura-2000/

Other issues that should be investigated in Phase 1 are the risk of presence of ancient monuments in a project area, also known as cultural heritage, or cables and pipelines placed on or in the seabed. The Danish Agency for Culture and Palaces maintains a comprehensive database of findings and ancient monuments and a website with information (Slots- og Kulturstyrelsen, 2022). It is recommended to investigate whether there is a potential problem already in Phase 1 and whether the conflict can be limited to the part of the area that is of interest. The Danish Cable Protection Committee (https://dkcpc.dk/) collects data on cables. Additional cables and pipelines may be marked on the nautical chart. Cultural heritage studies are further described under Phase 2.

Overall initial assessment (screening)

The key elements (historical analysis, environmental analysis, support of nature and marine area management) and possibly screening for existing cultural heritage findings contribute to an initial assessment of the suitability of areas for boulder reef restoration. Together, these elements form a screening process that must be supported by a subsequent thorough feasibility study, after which the actual detailed plan can be elaborated. Attention should also be paid to areas where high water temperatures can occur. Temperatures up to around 24ºC, are detrimental to a species like sugar kelp and fatal if the temperature rises even higher. Similarly, warm waters can affect fish species, and there are likely to be effects on other fauna organisms adapted to cool marine areas.

In addition to environmental issues, there are several other issues concerning the existing maritime area management and other interests/activities that may conflict with or create synergy with/benefit from the restoration of boulder reefs in an area. Overlap between the project area and areas of, e.g., navigation interest does not necessarily exclude that an area is suitable for restoration of boulder reefs but may trigger requirements for temporary or permanent marking with buoys. Authorities may also require that a given minimum depth is maintained after project completion.

The overall initial designation (prioritisation) of the suitability of areas for boulder reef restoration is carried out by combining information on the different types of environmental requirements and area interests with available data and maps. Areas where all minimum requirements are met should be prioritised highest in the first overall designation.

Phase 2: Preliminary studies

Once the screening process has identified a potential high-priority project area, the next step is to conduct feasibility studies. A feasibility study should include a geomorphological survey, a survey of biological habitats and, possibly, a survey of ancient monuments. Only when all relevant preliminary studies have been completed, the final detailed designation can take place and detailed planning of the nature restoration can begin.

Geomorphological surveys

The purpose of the geomorphological survey is to prove that the site is stony and, to a certain extent, to substantiate that the seabed can support the placement of new boulders. With great advantage, a survey of existing (remaining) stone deposits can be carried out using sidescan sonar and/or multibeam echo sounder. Mapping of existing hard bottom conditions in shallow areas can also be done using orthophotography, satellite imagery, Underwater Viewer (Bathyscope), an underwater robot (ROV) and by diving or a by combination of methods. Geophysical surveys generally require a licence in Denmark according to the Coastal Protection Act.

The carrying capacity of the seabed should be investigated before the stones are placed. If there are moraine deposits of plastic clay or mud deposits beneath the surface layer of the seabed, there are likely to be problems. Of course, the risk is greatest if you place many layers of stones on a bed that has sunk due to mining and erosion. A detailed investigation of the carrying capacity of the seabed requires interpretation of powerful sonar system results and expert knowledge and can be done in parallel with acoustic mapping of the seabed surface. More impractical and uncertain is an assessment based on the use of metal spears combined with the presence of large stones on the seabed. However, metal spears can only be used in the upper part of the seabed.

Biological baseline study

It is also relevant to describe what existing habitats there are in areas beyond the stones left behind after boulder extraction. It is important to investigate whether there are eelgrass beds, blue mussel banks, horse mussel banks or gravelly sandy sediments between the remaining stones where in-fauna communities dominate.

Experience has shown that the scope and thoroughness of a preliminary study can vary considerably. Working with re-establishing the Taarbæk reef in Øresund, a detailed mapping of habitats and species was carried out using underwater video (ROV), diver mapping (Dahl et al., 2022) and eDNA (Stæhr et al., 2024b). ROV and possibly diver surveys also provide essential knowledge for acoustic mapping of seabed sediment conditions. In comparison, the citizens' group behind the establishment of Hou Stenrevene (STENREV-HOU project) carried out preliminary studies using underwater cameras to map species and habitats. A thorough preliminary study can subsequently be used as baseline to document the biological effects of the restoration project, see chapter 9.

When selecting specific restoration areas in Roskilde Fjord, an area with a large mussel bank was rejected (Dahl et al., 2019). Areas with eelgrass were avoided as much as possible, but eelgrass meadows with scattered stones are today widespread in Roskilde Fjord at shallower water depths, unlike reef areas. As a result of the completed restoration project, there is now a small shallow area with a complex habitat consisting of eelgrass and placed boulders.

Cultural heritage survey

The Danish Agency for Culture and Palaces, which is the responsible authority for ancient marine monuments, may require the project to carry out an archaeological survey in connection with the authority approval, as described in Phase 4. If an archaeological survey is required, it must be paid for by the organisation/authority responsible for the construction work/activity.

When it comes to marine archaeology, Moesgaard Museum is the contact address for Jutland and Funen, while Vikingeskibsmuseet covers Zealand and the islands (Slots- og Kulturstyrelsen, 2023a). The Danish Agency for Culture and Palaces assesses the probability of encountering cultural remains in coastal areas as high (Danish Agency for Culture and Palaces, 2023b).

In connection with the authority processing (Phase 4), there will be a consultation phase where the Danish Agency for Culture and Palaces must decide on the specific project. If a study is needed and has not already been completed during Phase 2, it could lead to a delay of the construction phase and incur costs that could affect the scope of the planned and applied-for project.

Phase 3: Detailed project planning

Only when all relevant preliminary studies have been completed, the final detailed designation can take place and detailed planning of the nature restoration project can begin. The project description must include an account of the planned execution of the project with associated maps, methodology, etc. The Danish Coastal Authority is responsible for the primary case processing and subsequent consultation with relevant bodies and stakeholders. The application form can be obtained from the Danish Coastal Authority at kyst.dk (Apply for a licence at kyst.dk). It is important to read the relevant sections of the Danish Coastal Authority's administrative basis for the maritime territory and the instructions for the application form when preparing the project application. In general, be aware that the process of obtaining the necessary authorisations can be time-consuming and take months.

During the detailed project planning, there are a number of risks and potential benefits that should be considered:

The seabed:

- It is crucial that the seabed can support the restored boulder reef so that it neither collapses nor is buried in the sediment.
- At sites where stones have been removed, it is highly likely that the ground can support the stones that are placed.
- If heavy erosion is suspected in the area, or if there is evidence of sand and gravel suction in the area, a geological survey should be considered before making a restoration decision.

Sediment transport:

- The restored boulder reef can affect current conditions and thereby sedimentation and erosion in the area around the boulder reef. It should therefore be considered if model calculations should be carried out to determine whether there is a problem. The problem is assumed to be relevant for reefs located near the coast and in shallow water.

Risk of "oxygen trench":

- Establishing or re-establishing boulder reefs in brackish environments or at water depths with reduced light will favour the colonisation of benthic fauna. If the reef is established with the purpose of producing oxygen in the bottom water, dominance of fauna organisms rather than well-developed macroalgae vegetation will give the opposite result and create a site that has a net consumption of oxygen. A careful study of salinity, oxygen content and light levels at the bottom or a study of the biology at existing stones should be carried out to determine what organisms can be expected on the placed stones under the present conditions.

The effect of seasonality:

- Massive attachment of *Balanus* or possibly mussels can affect and delay the migration of the species expected on a newly established boulder reef. For example, you can explore if mussels are abundant in the area and avoid placing stones during the period when the larvae typically find a hard surface to settle on.

Material for boulder reef construction

Selection of stone type:

Natural boulders should generally be used for the restoration of reefs (see also Box 1 under Phase 4). This ensures a surface structure for which benthic animals and algae have optimised their attachment structures during more than thousands of years through evolution.

There are several possible sources of natural stones:

- Reusing so-called "sea boulders" from disused piers in connection with harbour expansions is the best solution. These stones originally come from boulder reefs, are typically very rounded in shape and have the highest degree of originality. This solution is the optimal (most original), but such stones rarely occur in large quantities.
- Another possible source is "boulders collected from farmers field" or stones from infrastructure projects. They can be obtained from construction works or collected from farmers. These stones are also typically somewhat rounded in shape. This solution was used for reef restoration at two sites in Roskilde Fjord. Boulders from land can be dirty and need to be cleaned. Stones retrieved from piles collected over decades from fields can also provide habitats for lizards, snakes, etc. on land.

- The third alternative is to purchase "quarry stone" from, for example, quarries in Sweden or Norway. Quarry stones are often angular and sharp compared to boulders transported and dropped by glacial processes.

Combined solutions with quarry stones placed as a base layer and field stones on top can be considered.

Attention should be paid to the quality of the boulders to be placed. There may be stone types with limited durability in the marine environment over time. Shale is made up of compressed sediments, typically clay, and is known for its layered structure. Here, the individual layers can be separated if necessary. Lime and chalk also have less strength than granite, for example. Experience from the NOVANA monitoring programme clearly shows that chalk is not a suitable substrate for hard-bottom organisms in general.

If natural boulders from land in Denmark are used in the restoration project, these are stone types that also occur naturally on the seabed. The same applies, of course, to re-placement of sea boulders. However, blasted stone from abroad may have a different mineral composition than boulders brought to Denmark during the last ice age. When enquiring at quarries, you should obtain information about the type of stone and then seek guidance from geological experts before purchasing. Attention should be paid to the possible need for cleaning of field stones (see Box 2)

Selection of stone size:

The stone sizes used should reflect the physical environment but also the purpose and economy.

- It is important that the placed boulders are stable. At very exposed sites, it may be necessary to use large boulders. In the southern Kattegat at exposed sites, stones of about 30 cm in diameter form a stable substrate at a depth of 4 metres. A good rule of thumb is to examine the size of the existing stone sizes with fouling in the depth range of the restoration.
- At very sheltered sites, a boulder reef can be stable and serve as an excellent habitat for hard-bottom organisms with even very small stones down to 4-5 cm if the light conditions only favour the growth of smaller organisms.
- Cavernous reefs at shallower water depths with lots of light can harbour higher biodiversity as fauna organisms can establish themselves in dark crevices where they are not outcompeted by seaweeds. This has been observed on Læsø Trindel. More cave formation is achieved by using larger similar-sized stones, placed densely or possibly in several layers. Multi-layered, cavernous reefs are thought to only occur naturally in locations without sand migration, such as shoals and shallow waters in open areas where erosion processes over millennia have washed sand and gravel into deeper water and without the possibility of sand migration bringing in new sand.

Design and detailed plan

It is important to develop geo-referenced design plans. The plans will initially be used in relation to the authority processing but later also for the contractor who is responsible for the actual construction work. The drawings should indicate planned placement areas, heights of the different structures and, possibly, average placement densities. It is also a good idea to establish a space on the seabed that functions as a stock for boulders during the construction phase. Appendix 2 describes an example of a detailed plan for the restoration of Tårbæk Reef. If you plan to construct a sea stock, a licence is required in accordance with the Coastal Protection Act. It should therefore be included in the application. As a starting point, the Danish Coastal Authority can accept the inclusion of extra buffer areas of 20-25% relative to the extent of the reef within the project area in connection with an application.

In relation to boulder reefs, the reef design ought to further the purpose of the reef as the effects of boulder reefs are to some extent defined by the design of the reef (Wilms et al., 2021). It is therefore possible to optimise boulder reef projects through advantageous reef designs. In the following, there are some examples of this.

Purpose: Protection or restoration of a specific habitat type such as seaweed forests

In general, boulder reefs that are located at a water depth where sunlight can penetrate (the photic zone) and have a large surface area are a good habitat for seaweed forests (macroalgae). It is important that the size of the stones in the top layer is matched to the expected size of the individual macroalgae as stones that are too small can become mobile when seaweed grows on them. For example, large leaf-bearing brown algae can move stones up to 7-10 cm in very exposed areas (Dahl et al., 2009).

Purpose: Preservation or increase of biodiversity and well-functioning food chains

A boulder reef with high biodiversity should theoretically have many microhabitats where individual species can establish themselves. This is ensured by having bottom conditions that alternate between different stone sizes and gravel/sand and that have a large vertical distribution (large depth range). Areas with very dense stone deposits will, together with the macroalgae vegetation in the photic zone, create crevices and caves that can favour many species of invertebrates (small animals) and fish.

Purpose: Production of food for fish

Studies on reefs in the photic zone have shown a positive correlation between the area of hard bottom and epifauna (animals that live on the seabed) in general and mussels, snails and polychaetes specifically, species that are all food sources for fish (Svendsen et al., 2022). An in-depth study of the photic zone at Hatter Barn (Dahl et al., 2015) found a positive correlation between seaweed biomass and sessile fauna biomass in general, but particularly pronounced between red algae biomass and fauna. There was also a specific correlation between crustaceans and red algae biomass. The essence of these studies is that the greatest amount of food for many fish species and the greatest biomasses of fauna and macroalgae are generally achieved by placing stones that provide large surface areas in contradiction to multilayer.

Purpose: Restoration of the stability of a reef

Stable boulder reefs are characterised by a layer of stones that is sufficiently large in diameter and density so that both the larger and smaller stones remain stable even under extreme wave and current events.

Purpose: Strengthening of blue corridors

A better quality of boulder reefs (higher density and possibly vertical spread of the reef) can strengthen the dispersal potential and thus also the dispersal pathways for hard-bottom organisms with pelagic dispersal stages. Modelling studies that combine water movement with information on pelagic dispersal dynamics can quantify the exchange of biological material between different sites with similar living conditions (light, salinity, etc.)

Purpose: Improvement of water quality

A boulder reef can influence physical conditions such as currents, sediment transport and turbulence and can be positioned to create local upwelling (i.e. the bottom water, which is often nutrient rich, is forced to the surface). If the reef is placed at depths at the interface with an oxygen-poor bottom layer, the position of the reef can influence the oxygen transport to the bottom water (Stæhr et al., 2024a).

Boulder reefs with kelp forest in bottom waters and in areas with frequent stratification of the water column and problems with oxygen depletion can supply oxygen to the bottom water at critical times in late summer, potentially reducing the release of nutrients from the bottom. However, there is a critical balance between when a reef is overall net oxygen-consuming or oxygen-producing, which should be clarified by thorough studies before choosing restoration based on this (Stæhr et al., 2020, Dahl et al., 2020). When restoring boulder reefs, some additional nitrogen and carbon are sequestered in the biomass of macroalgae and benthic animals that build up at the site.

Purpose: Restoration of fish populations

In general, some fish are attracted to complex habitats where plants or bottom structure provide cover for predators and shelter from currents. The many niches in a boulder reef can provide space for many species of fish, which is why fish biodiversity at reefs is often high (Wilms et al., 2021; Svendsen et al., 2022). Small fish are important food items for many fish species, including those that are important commercially and recreationally.

In addition to typical reef fish (e.g. goldsinny wrasse) that reside in and around boulder reefs, there are often increased abundances of cod fish at seabeds with topographic variations (Kristensen et al., 2017; Wilms et al., 2022; Flavio et al., 2023). Boulder reefs have the potential to promote herring spawning because herring often spawn near stones and vegetation (Svendsen et al., 2022) as well as growth rates for cod (Schwartzbach et al., 2020).

The greatest amount of food for a given amount of stones is achieved by placing stones in a single layer. Caves and crevices can be created by placing stones close together in some areas. In the photic (illuminated) zone, macroalgae vegetation, which primarily grows on the upper half of the stones, will contribute to the number of hiding places for the fish.

Phase 4: Authority application and approval

In all cases, the Danish Coastal Authority, in addition to decisions under the Coastal Protection Act 16 a, also makes decisions according to the Coastal Habitat Order (654 of 19/05/2020, which implements the Habitats and Birds Directives).

The "Administration basis for the marine territory" forms the basis for the management of the sea in relation to facilities and activities covered by section 16a of the Coastal Protection Act. This also includes nature restoration projects. The administration is handled by the Danish Coastal Authority on whose website the administration basis can be found (see Administrationsgrundlag_rk_avi_tilrettet_23_03_15_endelig.indd (kyst.dk)). In connection with the case processing, the Danish Coastal Authority involves a number of authorities and stakeholders listed in Table 3, and the application is published on the Coastal Authority's website. Depending on a specific assessment in each individual case, the consultation circle can be expanded.

There is a specific chapter on nature restoration of boulder reefs, under which three separate sections have been prepared for the benefit of both the initial work and specifically for the preparation of the concrete application.

The first section (A) defines and describes the facility (i.e. the boulder reef) and explains the Danish Coastal Authority's practice within the area (Box 1). The second section (B) describes what the applicant must explain in the application and the requirements and conditions associated with a restoration project (Box 2), and the last section (C) describes the assessment criteria that are included in the processing of the application (Box 3).

Table 3. The Danish Coastal Authority's consultation and information partners in relation to nature restoration of boulder reefs.

Consultation and information partners
Danish Maritime Authority
Danish Environmental Protection Agency
The Agency for Culture and Palaces
Moesgaard Museum/Vikingeskibsmuseet
Danish Fisheries Agency
The Danish Transport Authority
The Danish Ministry of Defence – Property Management
Plan- og Landdistriktsstyrelsen ("Planning and Rural District Agency")
Municipalities
Danish Society for Nature Conservation
BirdLife Denmark
The Outdoor Council
Ejendom Danmark ("Real Estate Denmark")
The National Association of Holiday Home Owners
Danish Geodata Agency

Please note that examples of relevant legislation are referenced in section A) Description.

What you should be particularly aware of is that section B states that "the facility" (i.e. the boulder reef) must not be placed in marine archaeological areas without the consent of the Danish Agency for Culture and Palaces". Similarly, section B states that, as a starting point, a appropriate assessment must be prepared for all projects that are carried out in or in the immediate vicinity of Natura 2000 areas or where Annex IV species of the Habitats Directive are present. The requirement will be determined based on a specific assessment (screening). An example of input for such a screening can be seen in a memo prepared for the Danish Environmental Protection Agency in connection with a restoration project in Roskilde Fjord (Dahl and Palmer, 2019).

The Danish Coastal Authority further states that an application must also include an assessment of the project in relation to the impact on the water body in question (Water Framework Directive) and the various descriptors of the Marine Strategy Directive. In cases of boulder reef restoration, the Marine Strategy Directive's descriptors "seabed integrity" and "biodiversity" will both be improved. Only in cases where stone placement at depths characterised by oxygen depletion will a negative effect on the status of the water body under current environmental conditions be foreseeable.

In all cases, the Danish Coastal Authority, in addition to decisions under the Coastal Protection Act 16 a, also makes decisions according to the Coastal Habitat Order (654 of 19/05/2020, which implements the Habitats and Birds Directives).

The "Administration basis for the marine territory" forms the basis for the management of the sea in relation to facilities and activities covered by section 16a of the Coastal Protection Act. This also includes nature restoration projects. The administration is handled by the Danish Coastal Authority on whose website the administration basis can be found (see Administrationsgrundlag_rk_avi_tilrettet_23_03_15_endelig.indd (kyst.dk)). In connection with the case processing, the Danish Coastal Authority involves a number of authorities and stakeholders listed in Table 3, and the application is published on the Coastal Authority's website. Depending on a specific assessment in each individual case, the consultation circle can be expanded.

There is a specific chapter on nature restoration of stone reefs, under which three separate sections have been prepared for the benefit of both the initial work and specifically for the preparation of the concrete application.

The first section (A) defines and describes the facility (i.e. the stone reef) and explains the Danish Coastal Authority's practice within the area (Box 1). The second section (B) describes what the applicant must explain in the application and the requirements and conditions associated with a restoration project (Box 2), and the last section (C) describes the assessment criteria that are included in the processing of the application (Box 3).

Please note that examples of relevant legislation are referenced in section A) Description.

What you should be particularly aware of is that section B states that "the facility" (i.e. the stone reef) must not be placed in marine archaeological areas without the consent of the Danish Agency for Culture and Palaces". Similarly, section B states that, as a starting point, a materiality assessment must be prepared for all projects that are carried out in or in the immediate vicinity of Natura 2000 areas or where Annex IV species of the Habitats Directive are present. The requirement will be determined based on a specific assessment (screening). An example of input for such a screening can be seen in a memo prepared for the Danish Environmental Protection Agency in connection with a restoration project in Roskilde Fjord (Dahl and Palmer, 2019).

The Danish Coastal Authority further states that an application must also include an assessment of the project in relation to the impact on the water body in question (Water Framework Directive) and the various descriptors of the Marine Strategy Directive. In cases of stone reef restoration, the Marine Strategy Directive's descriptors "seabed integrity" and "biodiversity" will both be improved and only in cases where stone placement at depths characterised by oxygen depletion will a negative effect on the status of the water body under current environmental conditions be foreseeable.

Box 1 Definition and description of reefs from the Danish Coastal Authority's administration basis, as defined at the time of publication of this report.

A) Description

The Danish Coastal Authority will only recognise stone as a material in connection with the establishment of a reef.

Submerged breakwaters for coastal protection, offshore wind turbine foundations, bridge piers, oil rigs, etc. can have a reef-like effect, but they are not considered reefs because their primary purpose is different.

Boulder reefs can take many different forms, from dense deposits of stones rising abruptly from the seabed, to mosaic-shaped stone banks or more diffuse structures with scattered stones on a sandy or gravelly seabed. The reef should be at a depth so that it avoids desiccation as the reef's primary purpose is considered to be enhanced marine biodiversity.

Boulder extraction has removed many reefs, especially in shallow water and coastal areas (<10 m water depth). Here, entire reefs or large parts of them have been removed and used for harbour construction and other construction works. Removing a reef's larger stones contributes to make the remaining reef unstable, whereby erosion spreads the reef's remaining smaller stones across the area.

As boulder reefs are important for marine biodiversity, nature restoration can be an important tool for the conservation and distribution of marine animals and plants. The term nature restoration refers to the re-establishment and restoration of naturally occurring boulder reefs. Where almost all stones have been removed, the restoration will have the character of re-establishment of the physical and biological structure of a reef. The original boulder reef should, as far as possible, be re-established as to stone types, stone sizes, depth ratio, etc. However, lack of knowledge of the original structure and depth conditions or lack of access to stone material may result in the original boulder reef being re-established with different stone types and sizes as well as a different depth ratio. If there is still an existing reef, the re-establishment will have the character of a restoration. Here, several larger stones are added to preserve the reef from erosion and improve its biological structure and function.

Reefs can help to increase biodiversity and thus the production of living marine resources in an area. This can benefit commercial interests such as commercial fishing or recreational interests such as scuba diving and underwater hunting. It can also have a socio-economic impact in terms of tourism.

In connection with the establishment of reefs, there have been considerations about whether reefs can influence the nitrogen turnover in coastal waters. However, the magnitude of the nitrogen effect is yet to be seen. It also requires very specific conditions to achieve the desired effect, including placing the reef under the thermocline and plenty of light.

It should be noted that after a reef has been established, the affected area must always be measured.

Relevant legislation that should be considered:

- Executive order 267 of 11 March 2009 on coastal protection.
- Executive Order no. 874 of 2 September 2008 on the administration of international nature conservation areas and the protection of certain species with regard to installations and extension of harbours and coastal protection measures as well as the construction and extension of certain facilities in the maritime territory.
- Executive Order no. 579 of 29 May 2013 on environmental assessment of certain constructions and measures in the maritime territory.
- Act no. 1606 of 26 December 2013 on water planning.
- Act no. 522 of 26 May 2010 on marine strategy.
- Executive Order no. 963 of 2 July 2013 on the protection of the marine environment.
- Executive Order no. 32 of 7 January 2011 on the dumping of occupied seabed material (dredging).
- Executive order no. 568 of 21 May 2014 on fishing and fish farming (Fisheries Act).

- Executive order no. 72 of 17 January 2014 on safety at sea.
- Executive Order no. 1351 of 29 November 2013 on safety of navigation in connection with construction work and other activities, etc. in Danish waters.
- Executive Order no. 45 of 22 January 2015 on marking in Danish and Greenlandic marking areas, etc.

1) The Danish Coastal Authority must refer to the fact that there may be other relevant legislation that applies within the area. It is the applicants' responsibility to familiarise themselves with the legislation in force at any given time. The Danish Coastal Authority must furthermore remind the applicants that legislation changes over time. All Danish legislation can be found here: www.retsinformation.dk.

Box 2 describes the conditions that an application for a reef restoration project must account for as well as the requirements and conditions that are generally associated with the project. The description is valid at the time of publication of this report.

B) Elucidation of conditions

In order for the Danish Coastal Authority to process an application, the following conditions, among others, must be clarified.

Purpose:

- Justification for the project and its scope.

Project description:

- The structure of the reef must be sketched and described. Reefs should generally be made of natural stone.
- Description of materials, including, for example, stone size.
- Description of the origin of the stones. If stones from fields, construction work or similar are used, they must be cleaned of any environmentally hazardous substances (e.g. pesticides) before being placed.
- If it is a research project, you must explain the project purpose, including any impacts of the project and expected conclusions.
- Description of the placement. The placement of the stones must be controlled so that the reef is located at the applied-for site. The Danish Coastal Authority must approve the placement plan.
- Description of the expected construction period.

Site:

- The reef site must be given in geographical coordinates in degrees, minutes and decimals of minutes, in datum WGS 84 with 3 decimals.
- Indication of the dimensions of the project area.
- Indication of the water depth in the project area.
- An assessment must be made of oxygen conditions, light conditions, temperature conditions, depth, salinity, nutrient supply and current conditions, etc. of the desired site to determine whether the site is suitable for the purpose.
- An assessment of sediment conditions, sediment transport, seabed slope and carrying capacity, etc. must be carried out to determine whether it is suitable for the purpose.
- Mapping of the relevant benthic fauna and vegetation in the area must be carried out.
- If the purpose of the reef is nature restoration, a historical analysis must be carried out that confirms or substantiates that a reef has existed at the site.
    - The Danish Coastal Authority recognises that this can be difficult to document and, therefore, the carrying capacity of the seabed is also emphasised in the Danish Coastal Authority's assessment.

<u>Consider the following factors when selecting a site:</u>

- The reef must not be placed within a restricted area, e.g. reserves, shooting ranges, etc. Official Danish nautical charts can provide further guidance on restriction areas in Danish waters.
- The reef must not be placed within a distance of 500 metres or in areas used for dredging of sediment or extraction of raw materials. This also applies in areas where companies have been granted a licence for mineral exploration.
- The reef must be placed so that it does not obstruct or interfere with already established facilities such as bridges and mooring systems, etc. Consideration must be given to distance to other facilities and activities, including compliance with distance restrictions. Thus, the reef must not be placed within a 200 metre radius of cable lines and pipelines without the consent of the cable line or pipeline owner.
- The reef must not interfere with navigation or navigational safety. When selecting a site, shipping routes (including fast ferries), general shipping traffic and traffic separation systems must be taken into account. If the reef is to be located in areas with a lot of sailing, you will be expected to prepare a sailing safety risk assessment.
- The reef must be placed so that it causes as little inconvenience as possible to the recreational use of the marine area, including rowing, swimming, etc.
- The reef must be placed so as to minimise interference with commercial fishing. If the reef causes losses to commercial fishing, compensation must be paid for the lost earnings, cf. the Fisheries Act.

- If the reef is to be constructed in or in the immediate vicinity of a Natura 2000 area and/or there are Annex IV species, an impact assessment is likely to be required. The requirement for an impact assessment will be determined based on a specific assessment (screening) of whether the project applied for will significantly affect the designation basis for the Natura 2000 area and/or Annex IV species.
- The reef must not be placed in marine archaeological areas without the consent of the Danish Agency for Culture and Palaces.

Anchoring and marking:
- Any marking must be approved by the Danish Maritime Authority, which may set requirements for additional marking on an individual basis.

Financial conditions
- An explanation of the estimated cost of removing the reef.

Information for use in EIA screening:
Descriptions of the reef's
- dimensions,
- cumulation with other projects,
- use of natural resources,
- waste generation, pollution and nuisance, and
- risk of accidents, especially taking into account the materials and technologies used.

Descriptions of the impact of the reef on the environmental vulnerability of the area, particularly in relation to
- current area use,
- the relative richness, quality and regeneration capacity of the natural resources present, and
- the carrying capacity of the natural environment, with particular attention to coastal areas, areas protected or subject to national and international nature and environmental protection, densely populated areas, areas of particular importance from a historical, cultural or archaeological point of view.

Descriptions of the potential impacts of the reef, including
- the extent of the impacts (geographical area and number of people affected),
- the transboundary nature of the impacts,
- impact levels and complexity,
- the likelihood of impacts and
- the duration, frequency and reversibility of the effects.

Appendices:
- Latest nautical charts at the relevant scale with the site and extent of the reef marked
- Overview map/photo with the reef marked
- Sketch of the reef structure

Box 3 Description of the assessment criteria used by the Danish Coastal Authority when processing an application for a reef restoration project. The description is valid at the time of publication of this report.

C) Assessment criteria
The following assessment criteria will be included in the Danish Coastal Authority's processing of an application. There may be other criteria than those mentioned that the applicants consider important and therefore want to highlight in their application.

The criteria are included in the Danish Coastal Authority's overall assessment of the specific project.

3.12 Evaluation criteria

- Purpose
- Nature restoration
- The carrying capacity of the area
- Environmental improvement
- Protected areas and species
- Research and communication
- Synergies
- Infrastructure and related facilities
- Safety

The Danish Coastal Authority will always prioritise the restoration of vulnerable nature. Special attention will be paid to whether historical data or similar can document prior existence of reefs at the desired site. Emphasis is also placed on association of biologists or similar with knowledge of marine ecosystems with the project.

The carrying capacity of the area will also be included in the assessment. Thus, it would not be appropriate to establish a reef at a site where the biological and physical conditions are not optimally suited for the purpose. This also includes whether there are other reefs in the vicinity from which immigration of species can be expected. Emphasis will be placed on the importance of the reef to the marine environment in terms of increased biodiversity on and around the reef.

Emphasis will be placed on whether the flora and fauna of the area will be affected by the project, including whether the project can be realised without damaging the designation basis for Natura 2000 areas or breeding and resting areas for Annex IV species.

Furthermore, great emphasis will be placed on utilising the reef for research, teaching and communication. Projects with direct links to research and dissemination institutions will be weighted favourably.

The project's interaction with other activities in the area will also be prioritised. Positive weight will be given to the applicant's ability to demonstrate that the project will not significantly conflict with other recreational interests.

The project's impact on the local community will also be stressed. Here the focus will be particularly on the impact on fisheries as the reef can contribute to increased occurrence of fish on and around the reef. Importance will be given to whether the applicant can account for the expected positive impact on fisheries.

If the reef is to be used for diving, the onshore infrastructure will also be prioritised. The Danish Coastal Authority will include the municipality's assessment of access conditions and parking options in the evaluation of the project.

Phase 5: Establishing the reef

Once you have received license and funding to carry out boulder reef restoration in a local area, the next phase is to plan the detailed design of the actual construction. This results in a detailed project plan, which includes a clarification of the approved project outline for use in any tender documents for contractors with technical work descriptions, dimensional overview and sectional maps, tender lists, tender letters and a timetable for the construction work.

Purchase and placement of stone material

The purchase and placement of stone material will typically be by far the largest project cost, and the organisation of this is of great importance for the project's economy and the quality of the boulder reef.

- The cost of shipping and placing stone is less during periods of calm weather. In open, exposed areas, this can have a significant impact on the overall cost.
- The stones must be placed with high precision according to the applied-for plan. This requires the use of a vessel equipped for such a task.
- Reef establishment at depths of more than about 3 metres can typically be carried out using a larger barge/ship. Boulder reefs in very shallow water require specialised technology and a barge/raft and perhaps the possibility of establishing part of the reef from the shore. In general, construction costs in shallow water are likely to be higher per cubic metre than in deeper water.

Work area – buoy marking and bans.

While the project is being carried out, it may be a requirement from the authorities or simply expedient to mark the work area and ban boating and fishing.

When communicating with stakeholders, marking and possible bans should be discussed with all groups, and these issues should be known while discussing the location of the boulder reef.

Construction supervision

The entrepreneur should carry out technical supervision and control of the contractor's execution of the construction work to ensure compliance with the terms of the license. In Roskilde Fjord, this was done by visiting the placement vessel, using a drone, submitting documentation of the vessel's work positions and subsequently using diving and ROVs.

In addition to the above, a number of rules apply to works in Danish territorial waters, tendering, contractual matters, safety and environmental conditions of ships and vessels, etc. A detailed review of these rules is beyond the scope of this report.

Phase 6: Documentation/monitoring of a boulder reef project

Hydrographic survey and navigational safety at the end of the project

Stones placed in shallow areas can pose a risk of grounding if the water depth is significantly reduced. The risk is greatest near shipping lanes and other trafficked areas, and one should also be aware of the existence of any traditional recreational boating routes.

As a general rule, it is a requirement in connection with the licence for the restoration that a final hydrographic survey is carried out (Box 1). The hydrographic survey should be carried out immediately after the boulder reef establishment is completed to update nautical charts. The Danish Geodata Agency is the authority responsible for hydrographic survey and the production of nautical charts. Hydrographic surveying requires a licence, and there are special requirements for data delivery. Relevant information can be found here: https://gst.dk/soekort/soeopmaaling/privat-soeopmaaling#fem

There is an obligation to inform about the placement of boulder reefs well in advance through "Navigational information" (https://www.dma.dk/safety-at-sea/navigational-information). Accidents occurring without this information may result in claims for damages. It is also recommended to minimise the risk of grounding by providing thorough information to sailing clubs, diving associations, etc., preferably over a number of years, and possibly marking of the reef.

Biological monitoring

From the start of the project, resources should be prioritised to document the development of the restored area with the aim to assess the degree of fulfilment of the success criteria defined at the start of the project.

The monitoring programme should be designed so that the results can be used to evaluate whether the success criteria have been met and whether the reef has had the intended effect. Monitoring should therefore optimally include a preliminary study before the restoration and one to several studies after the restoration. It is recommended to designate a control area that is surveyed both before and after at the same time as the restoration area, and which can be used to calibrate the results and account for general trends that are not associated solely with the effects of the restoration. This requires identification of a suitable reef area that can be used for the purpose.

Experience from the Blue Reef boulder reef project at Læsø shows that it can take many years before the migration of benthic animals and plants on placed stones is complete. For the Blue Reef project, the process of immigration, succession and biomass build-up corresponding to a "climax community" took around 10 years (Karsten Dahl, pers. obs.). Studies of the biological significance of boulder reefs should therefore be conducted over many years.

The documentation collected should ideally follow the NOVANA programme's technical guidelines for boulder reefs for marine flora and fauna (Dahl and Lundsteen, 2018) to ensure comparability of results between similar projects. However, there are currently no technical instructions for fish surveys, but camera methods and mapping the movement patterns of individual fish have been used in several restoration projects (Wilms et al., 2021, Rhodes et al., 2020, Svendsen, 2022, Kristensen et al., 2017).

4. Costs

When restoring boulder reefs, experience has shown that it is advantageous to involve professional assistance in the purchase, transport, shipping and placement of stones. Once the tender documents are finalised, tenders are usually requested from several contractors. Here, the client must familiarise themselves with the procurement law rules for obtaining tenders for construction works. Once the tender is finalised, a binding construction contract must be drawn up between the client and the contractor.

Table 7.1 Examples of costs for establishing different boulder reefs. The "b", "m" and "s" in the column with placed m^3 indicate quarry stones, Natural boulders from land and recycled sea boulders, respectively.

Project	Year	Amount of stones placed in m^3 or tonnes	Cost of baseline studies	Cost price for stone	Cost of placement *including stones	Total project costs
Blue Reef	2008	100,000 tonnes (b)	DKK 1.7 million		DKK 25.4 million	DKK 27.7 million
Livø Reef		12,000 m^3 mainly "b" and some "m"	DKK 2.1 million	DKK 400 per m^3 incl. placement	DKK 0.4 million	DKK 5.5 million
Roskilde Innerbredning	2022/2023	3250 m^3 "m"	DKK 0.2 million			DKK 5.2 million
Reef off Hundested	2020/2021	4300 m^3				DKK 3.9 million

5. Management

Once the reef has been restored and completed, the relevant authorities should decide on the future management of the reef and its surroundings.

If a restored reef is located within a Natura 2000 area where it is part of the designation basis, management of the habitat will automatically be part of the authorities' task.

It is relevant to consider whether the restored habitat should be protected from fishing to support the ecosystem functions of the reef. A ban on fishing was implemented at Læsø Trindel in connection with the restoration and is still in force. There is also a ban on lobster fishing at the reef in Livø Bredning.

6. Citizen engagement and knowledge sharing

It is important to gain stakeholder support for the project's purpose and realisation to ensure broad backing for the restoration. Local residents, organisations or business interests can contribute useful knowledge to the project about the identification of suitable sites, design and purpose. Typical stakeholders will be: local authorities, commercial ports, the fishing industry, recreational fishermen, scuba divers, yachtsmen, local nature and outdoor organisations and the local tourism organisation.

It is recommended to set up a monitoring group among the stakeholders who have the greatest interest in following and contributing to the project from start to finish. It should be ensured that the decision-making process is transparent and that all stakeholders can contribute their knowledge and experience before decisions are made.

It is important to provide information about the project's background and purpose as well as the status of the project. Boulder reef restoration presents a particular challenge as it takes place at sea and below the surface and is therefore not immediately visible.

Dissemination activities may include public meetings where it is possible to obtain relevant knowledge and discuss the implementation of the project and possibly consult the authorities on management plans for the restored boulder reef.

Knowledge sharing can include:

- Scientific reports
- Website with general information about the project, images, news service, posting of meeting minutes, etc.
- Films, e.g. on YouTube.
- Updates from influencers.
- Ads and articles in local newspapers and magazines.
- News can also be advertised by contacting organisations directly. An example would be yachting organisations that specifically draw attention to changing sailing conditions.
- Newsletters, leaflets, posters, etc.
- Local radio and TV.
- Various social platforms.

7. Completed boulder reef projects

Several boulder reef projects (> 40) have been completed in Danish waters. Most are quite small but there are a few larger projects. Many of the projects are defined as nature restoration, but some are rather educational reefs or artificial reefs. On the website of the Centre for Marine Nature Restoration (Marine nature - Centre for Marine Nature Restoration), you will find a list of completed projects with relevant references.

Fauna in a crevice between two large stones 13 years after the restoration of the Læsø Trindel boulder reef (photo: Karsten Dahl).

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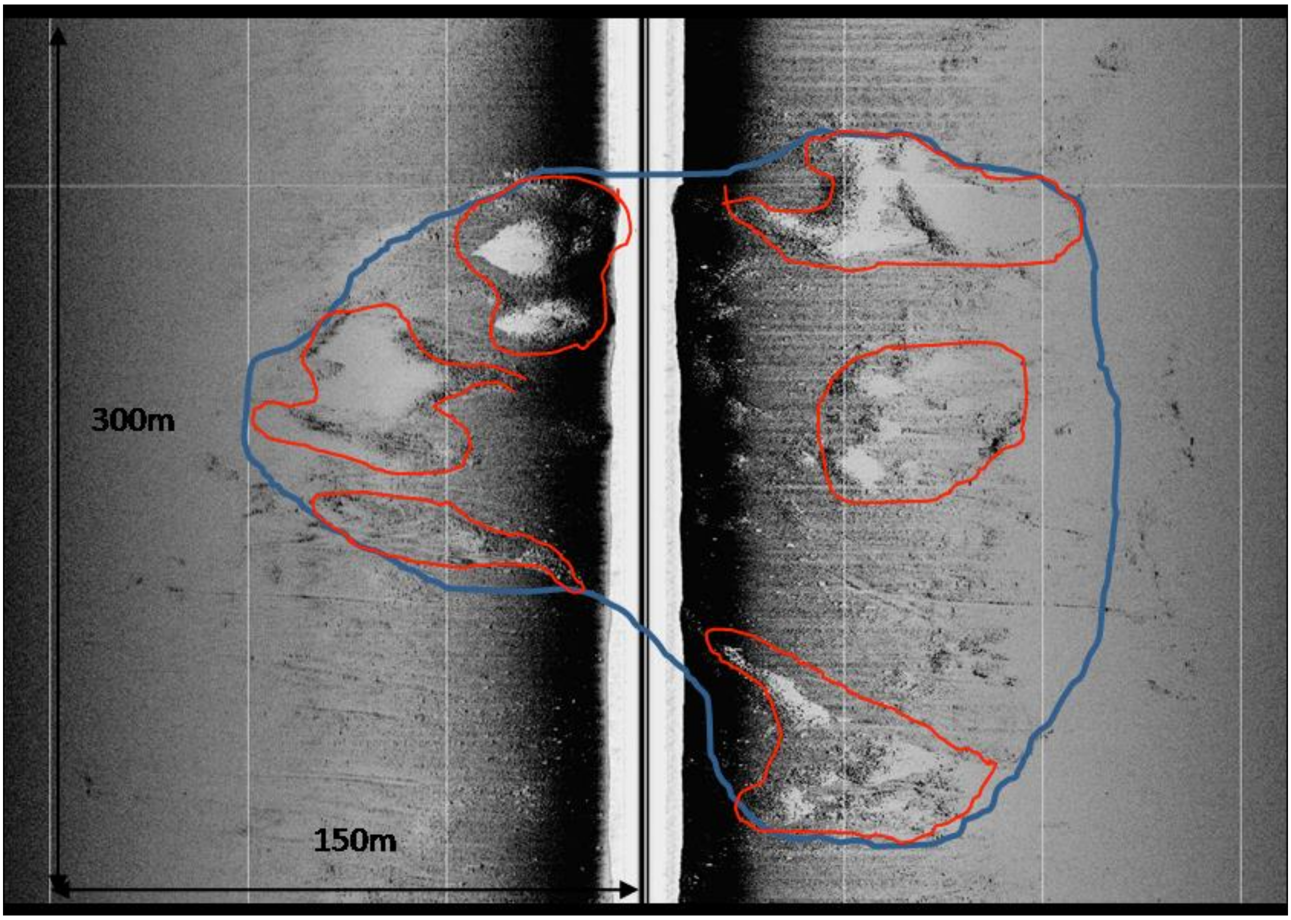
9. Appendices

Appendix 1: Example of delineation of the habitat type "Reef"

A mosaic of reefs (white patches) surrounded by gravel/small pebble seabed. Each of the red areas represents a reef with >80% stones. Due to the resolution of the sidescan-based seabed classification, the reef mosaic in the map is merged into one area (blue line) classified as reef (from Dahl et al., 2011).



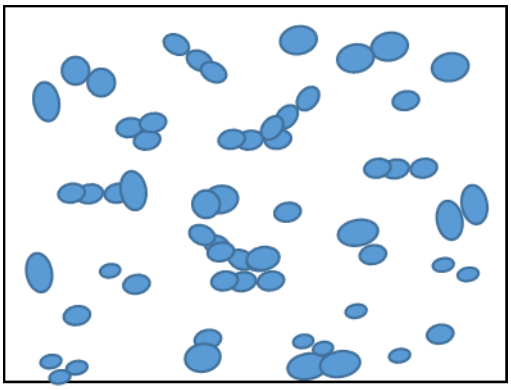
Appendix 2: Boulder reef design example

Tårbæk Reef in Øresund is an example of a project with thorough design considerations for a boulder reef (Göke and Dahl, 2022). A screening survey for the Øresund region identified a number of sites as suitable for nature restoration (Dahl and Göke, 2021). Of these, Tårbæk Rev was selected by the Danish Parliament's Green Transition Committee. A study of changing depth conditions from historical nautical charts to current conditions and a great need for large stones for coastal protection of the established road “Strandvejen” and harbours in the area made it likely that Tårbæk Reef was affected by boulder extraction. An acoustic mapping survey of the area was conducted (WSP, 2022), identifying a few dense stone deposits and a larger area with scattered larger stones. Following a complementary ROV and diver survey that identified areas with dense mussel beds and eelgrass beds, a suitable project area was designated (Göke and Dahl, 2022).

The following criteria were established as the basis for a detailed project planning:

- Areas with dense eelgrass beds and mussel beds were to be avoided as much as possible.
- The identified suitable placement area was divided into sub-areas.
- The overall goal was to increase the areal distribution of stone deposits. This meant that the majority of the stones had to be placed in one layer.
- The individual sub-areas were to have varying densities of stones.
- The stones were to be laid out in "lumps" to create varying complex habitats alternating between sand/gravel bottom and dense deposits of stones with crevices in between as potential physical hiding places for fish (figure app-1).
- The density of placed stones in the individual sub-areas was to decrease with increasing distance to existing smaller stone deposits.
- Areas with tops (multiple layers of stones) were to be established near existing tops, but only to a depth of 5 metres (navigational safety) (figure app-2).
- New stones were to be placed with a buffer zone of at least 5 metres to existing dense stone tops.

Figure app-1.
Scattered but lumpy placement of stones on the original seabed.



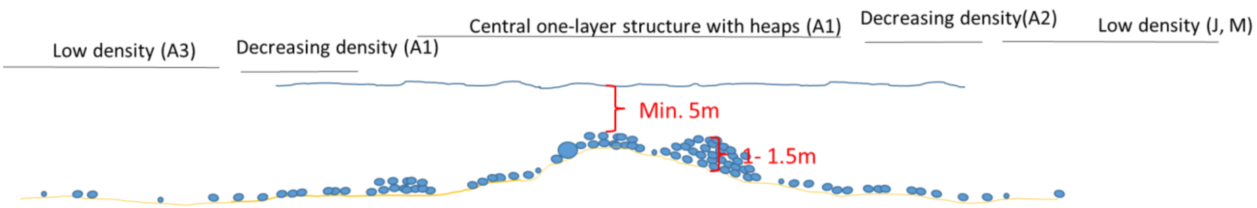


Figure app-2 Schematic sectional drawing of placed stones divided into tops and scattered stones with decreasing coverage away from the core area.

The final placement plan is shown in figure app-3, and the accepted proposal prioritised the individual sub-areas from the inner core area towards the outer areas. From the outset, the plan covered a larger area than the allocated budget was expected to cover. The proposal allowed for a flexible solution depending on the cost of the restoration project and for possible later addition of new stones without further planning and investigation.

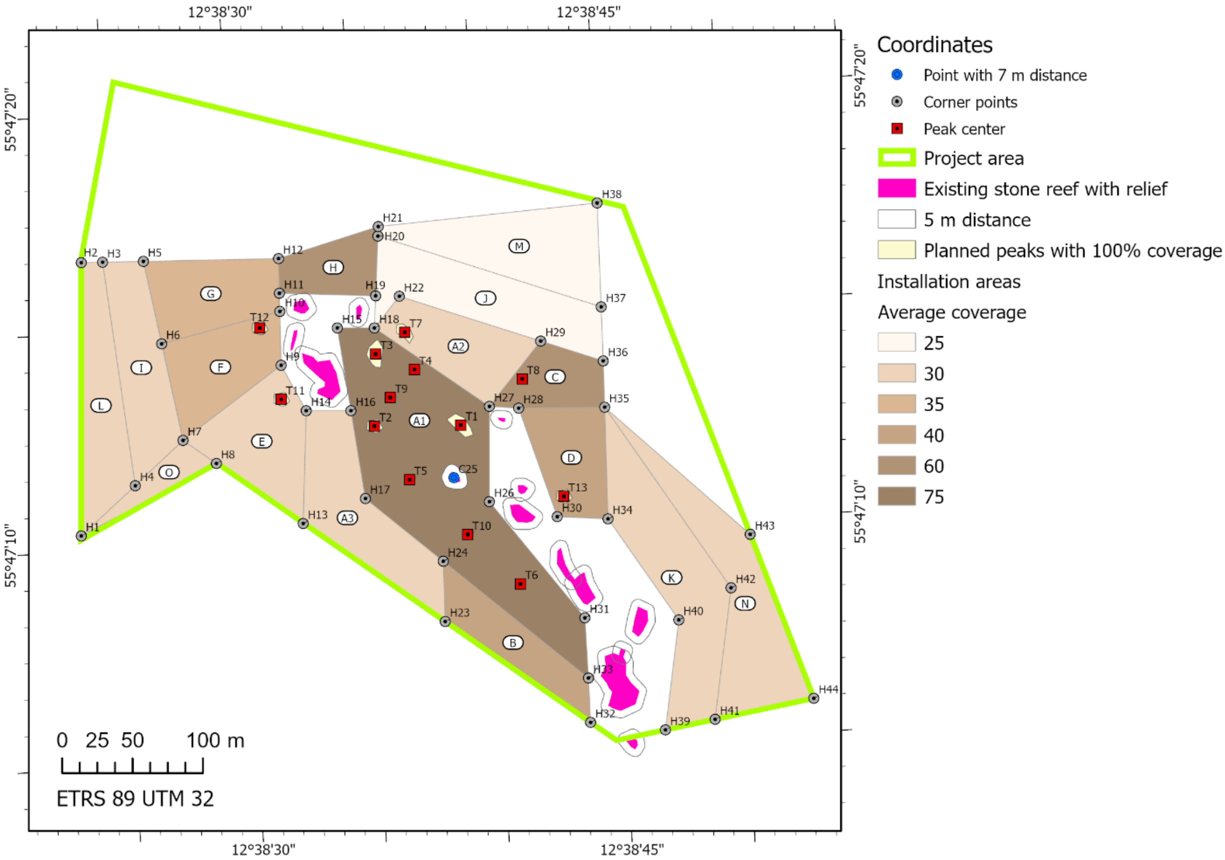


Figure app-3. Design plan for the restoration of boulder reef at Tårbæk Rev. The coverage of stones planned to be placed in the different sub-areas is shown in the legend. Exposed tops with multi-layered stones are marked in red. The existing reef formations with dense deposits of larger stones are shown in purple colour with a buffer area drawn around them.

Center for Marine restoration is a collaboration between Aarhus University - Department of Ecoscience, DTU Aqua - National Institute of Aquatic Resources, The University of Southern Denmark, and the Limfjord Council.

The main goal of the Center is to promote knowledge-based implementation of marine restoration, to strengthen the health and resilience of marine ecosystems, and enhance associated marine ecosystem services.

SDU University of Southern Denmark

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Limfjordsrådet

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Environmental Protection Agency

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