



# Status of contaminated marine sediments in four Nordic countries: assessments, regulations, and remediation approaches

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## Abstract

**Purpose** Since the 1960s, pollution of the marine environment has been observed around the world, and a general awareness of the potential environmental hazards from contaminants arose. This general awareness was followed by implementation of environmental regulations at the national and international levels regarding industrial discharges, and forcing the development of management programs to improve the environmental quality. This overview focuses on the status of assessments, regulations, and remediation actions of contaminated marine sediments in four North European countries: Sweden, Norway, Finland, and Denmark.

**Results and discussion** We found that the extent of assessment surveys and the implementation of sediment remediation actions vary between the countries, with Norway the most advanced. Norway has initiated national pilot remediation tests, followed by full-scale site remediation by dredging and in situ capping in several projects along the coast. Sweden is following Norway's example, although with fewer completed projects. In Finland, the tradition of maintenance dredging is still very strong although the main purpose has not been cleanup actions. Accordingly, in Denmark, dredging is primarily used to maintain sailing depths. All four countries have implemented the Water Framework Directive in addition to national regulations that provide the authority for imposing and implementing sediment remediation measures. However, only Norway has implemented a national strategy on remediation of contaminated sediments.

**Conclusions** This overview highlights the need for enhanced communication and exchange of experiences between the four Nordic countries of concern with regard to sediment remediation strategy and management.

**Keywords** Contaminated sediment · Capping · Dredging · Nordic countries · Regulations · Remediation

## 1 Introduction

This paper gives an overview of the present status within four Nordic countries with regard to marine sediment assessments, regulations, and remediation approaches implemented, as well as a summary of recent developments related to decision tools

and remediation techniques. Sweden, Norway, Finland, and Denmark have relatively long coastlines that have been negatively influenced by industrial activities such as pulp and paper industry, metal refineries, mines, agriculture, shipyards, harbors, and shipping, as well as urban run-off, discharges from water treatment plants, and other diffuse sources of pollution.

For decades during the mid-1900s, industrial waste discharges reached water bodies with little or no treatment. Global awareness of environmental pollution started to rise in the 1960s and 1970s, due to important publications such as Rachel Carson's book *Silent Spring* (1962). This awareness motivated the implementation of national and international regulations on pollution sources such as industrial discharges. Considering that contamination of water bodies is impacted by—and impacts all—surrounding countries, international regulations are needed in order to improve the ecological status. The declaration adopted at the United Nation's

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Conference on the Human Environment in Stockholm in 1972 was the first international environmental law to recognize the public's right to a healthy environment. During the 1980s, national regulations to protect the environment against pollution followed, such as the Norwegian Pollution Control Act from 1981, followed by actions to reduce or stop regular releases. However, even after regular discharges have been reduced or stopped, contaminated sediments may continue to act as a reservoir and a source of pollutants and, therefore, can continue to impact the aquatic environment for decades.

Contaminated sediments in lakes, rivers, and marine environments have been recognized as a source for contamination in aquatic food chains for some time (Malins et al. 1985; Varanasi et al. 1985; Spadaro 2011), and persistent contaminants such as PCBs (polychlorobiphenyl) and dioxins may bioaccumulate in organisms and biomagnify up to toxic concentrations in top predators. However, the extent to which contaminated sediments represent a threat to the environment depends on both biotic and abiotic factors. For example, disturbance such as boat propellers and other physical impact to the seabed, including the activity of benthic-dwelling organisms, may cause resuspension of contaminated sediment into the water column (Davis 1993). Hence, to reduce the ecological and human risk, contaminated sediments need to be assessed and managed.

The dramatic increase of dead zones in the Baltic Sea is directly linked to human activity (primarily terrestrially derived agricultural fertilizers) (Larsson et al. 1985; Gustafsson et al. 2012) and can adversely impact biota, depending on the degree of hypoxia (Cederwall and Elmgren 1990; Diaz and Rosenberg 2008; Conley et al. 2009). The rehabilitation of such zones can probably only be achieved by lowering nutrient inputs (Conley et al. 2009; HELCOM 2018). Dead zones are not discussed in the rest of this review, because hypoxia and anoxia are secondary effects of contamination, and the remediation of contaminated sediments does not necessarily imply the recovery of an ecosystem. Lake and river sediments have historically received more attention than marine sediments, mainly because of the lower degree of dilution, implying a higher impact on the environment. However, some observations have proven the impact of contaminated marine sediments on the environment. For example, gastropods on the east and west coasts of Sweden have been affected with imposex, which is primarily coupled with TBT (tributyltin) exposure (Severin et al. 2018). This chemical was used in boat paint but has been restricted in the country since 1989, and banned by the international convention on the control of harmful anti-fouling systems on ships on a global level in 2001 (effective in 2008). The concentration of TBT in the sediments in most of the Baltic Sea is still higher than the threshold value (HELCOM 2018).

We will first present the state of the art regarding marine sediment pollution, in terms of international legislation and

also at each national scale. This review focuses mainly on marine sediments, but it is important to note the lack of distinction between lake, river, and marine sediments in most publications. Lessons learnt from a few completed Nordic projects are then presented, and recommendations for future harmonization of sediment remediation approaches within the Nordic countries are included.

## 2 State of the art

### 2.1 International regulations

To reduce environmental pollution, several countries have united to decide upon common actions, such as the Oslo Convention to regulate the dumping of dangerous substances from ships and aircraft into the sea in 1972 and the Paris Convention on land-based sources of marine pollution in 1974. Those two conventions merged into the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) in 1992. The Helsinki Commission (HELCOM) was formed in 1974 for the protection of the Baltic marine environment by all the countries bordering the Baltic Sea. The Baltic Sea Action Plan (BSAP) was adopted in 2007 with the ultimate goal to restore a good ecological status of the Baltic Sea by 2021. Currently, this goal will probably have to be postponed, despite all the efforts and improvements that have been implemented since the beginning of this plan, mainly because the environment needs more time to recover (HELCOM 2018). Within the European Union, the Water Framework Directive (WFD) adopted in 2000 contains far-reaching goals intended to secure and manage water resources, and by implication, sediments, at the river basin scale (Bridges et al. 2009). Sediment management is also directly or indirectly included in different European directives, such as the Waste Framework Directive (European Parliament, Council of the European Union 2008c) and Habitats Directive (European Parliament, Council of the European Union 1992). Guidelines for management of dredged coastal material have been developed by several international maritime conventions, including the London Convention, OSPAR (signed by all four countries), and the 1992 Helsinki Convention.

The WFD sets “good status” objectives for water bodies throughout the Member States (European Parliament, Council of the European Union 2000). The status is based on chemical and ecological criteria. A classification system has been developed to decide upon chemical status, with threshold values known as “Environmental Quality Standards” (EQS) designated for 33 priority substances and eight other pollutants, including pesticides, and metallic and organic compounds (European Parliament, Council of the European Union 2008a, 2013). An additional proposal (European Parliament,

Council of the European Union 2011) defined 15 additional priority substances, not mandatory but aiming to improve the definition of “good chemical status.” The EQS are defined as annual average concentrations (AA-EQS), as well as maximum allowable concentrations (MAC-EQS), for each single measurement and contaminant. This dual-standard measurement allows long-term and short-term exposure evaluations, respectively. The EQS are mandatory for surface water and groundwater in all signatory nations, whereas EQS for sediment and biota are optional. EQS have not been developed for sediments in Finland, whereas in Norway, Sweden, and Denmark, sediment EQS have been implemented respectively for 28, six, and 14 contaminants (or contaminant groups).

A specific maritime policy was later established and directed for marine ecosystem protection and conservation by the EU Marine Strategy Framework Directive (MSFD) (European Parliament, Council of the European Union 2008b) as well as by a communication from the Commission of the European Communities concerning the EU Strategy for the Baltic Sea Region (Commission of the European Communities 2009). These regulations highlight the problem of pollution as one of the environmental challenges in European marine waters and the MSFD specifically asks member states to implement monitoring programs for the assessment of the environmental status of marine waters based on the indicative list, including sediment contamination. These monitoring programs need to consider corrective measures to restore the good environmental status.

## 2.2 Nation-specific regulations and strategies on contaminated sediments

In this section, we present the existing national surveys of contaminated marine sediments, and the authorities responsible for leading these as well as for the remediation actions in each Nordic country. The application of relevant national and international regulations such as the WFD is also discussed. It is important to keep in mind that, in most cases, surveys of contaminated sediments are only undertaken in places where they are likely to be found, for example near decommissioned or active factories. The known degree of the contamination of marine sediments is, therefore, related to the extent and ambition of surveys undertaken by each nation.

### 2.2.1 Norway

Norway has Europe’s longest coastline (> 100,000 km including islands) and mainly saline waters, although brackish conditions are commonly found in surface waters in the inner parts of the many fjords due to the freshwater impact from rivers. The access to waterways for transport and hydropower from the many waterfalls made the sheltered inner parts of the fjords attractive places to establish power-intensive industries

throughout the 1900s, with the fjords as recipients for industrial discharges. Harbors and cities are commonly developed around these industrial areas, increasing the anthropogenic impact on the fjords. The typical Norwegian fjord is long and rather narrow, with a deep basin (> 100 m), and one or several shallow sills in the outer parts of the fjord, restricting the circulation of the bottom waters.

The Ministry of Environment (now Ministry of Climate and Environment) was established already in 1972 followed by the Norwegian Environmental Agency (Miljødirektoratet) in 1974. The agency is responsible for implementing and giving advices on the development of climate and environmental policies, including management of contaminated sediments, implementation of the WFD, and development of national strategies on contaminated sediments.

Contaminated sediments in fjords and harbors were surveyed already in the 1980s (SFT 2000). An overview of 32 seriously contaminated areas was presented in 1992 (SFT 1992), including an action plan for cleanup of these contaminated sites by 1995. However, this plan recognized the need for pilot testing studies of remediation methods before implementation. More surveys were initiated by the National Program for Pollution Surveillance (Konieczny and Juliussen 1995a, b; Konieczny 1996; SFT 1998). At the end of the millennia, at least 120 larger and smaller sub-areas were proven to have highly contaminated sediments. The main pollutants encountered were various metals, PCBs, PAHs, TBT, and chlorinated compounds. Regional action plans for contaminated sediments were prepared for 17 prioritized fjords, identified in the Norwegian White Paper No. 12 (Norwegian Royal Ministry of the Environment 2001–2002) “Protecting the Riches of the Seas.” Governmental funds have been allocated for soil and sediment remediation since early 2000s.

The implementation of the WFD in Norway (2007) has placed the responsibility for monitoring of water bodies, including monitoring of surface water, biota, and sediment, on industrial actors. In Norway, coastal water bodies are classified primarily on sediment and biota concentrations. About 2280 coastal water bodies have been classified in terms of ecological and chemical status since the implementation of the WFD, though some water bodies are lacking data to perform the WFD classification. Typically, coastal water bodies have good ecological status except for the inner parts of fjords where contaminated sediments lower the ecological quality.

To support the management and remediation of contaminated sediments, a set of guidelines have been developed by the Norwegian Environmental Agency (Bakke et al. 2011; Lone et al. 2012; Miljødirektoratet 2015, 2016a, b; Eggen et al. 2017). Traditionally, dredging has been the main remediation strategy, although in situ isolation capping is now developing as the most preferred method unless there is a need for increasing or maintaining sailing depth.

## 2.2.2 Sweden

Sweden's territorial waters are possibly the most varied of the four countries considered in this review. The 13,500-km-long Swedish coastline borders the low salinity, almost freshwater Bothnian Bay (with low biodiversity) in the north, and the brackish Baltic Proper and the fully marine Kattegat and Skagerrak (with high biodiversity) in the southwest (Sjöberg 1992; Labuz 2015). Due to the postglacial geology of the region, the northern part of the Sweden currently experiences isostatic uplift at a maximum rate of ca. 9 mm year<sup>-1</sup>, which causes the lateral position of the coastline to continuously move (reducing the size of the Baltic Sea), while some southernmost coasts are experiencing erosion due to sea-level rise (Norrman 2010). Given the current rate of land uplift, the Bothnian Bay will become isolated from the Gulf of Bothnia in approximately 2000 years. Today, the major anthropogenic impact on the coastal zones is related to the major population centers (Stockholm, Gothenburg, Malmö), which includes recreational pollution in addition to urban runoff and agriculture in the south, but it must be appreciated that large historical forestry-supported industries polluted the Gulf of Bothnia (including large estuaries) with contaminated solid and liquid waste during the 1800s and much of the 1900s, until regulation in the 1960s.

The Swedish Environmental Protection Agency (Naturvårdsverket) is the governmental agency responsible for environmental issues. It is responsible for coordinating, prioritizing, and following up the work on environmental issues at the national level. Regarding contaminated sediments issues, the Agency collaborates with the Swedish Agency for Marine and Water Management (SwAM, or HaV in Swedish), the Swedish Geotechnical Institute (SGI), the Geological Survey of Sweden (SGU), and the 21 regional County Administrative Boards (Länsstyrelsen). SGI has the national responsibility for research, technological development, and knowledge for remediation and restoration of contaminated sites. This work is undertaken in collaboration between all the different actors, and each of them has a precise responsibility. SwAM, SGU, and the county administrative boards are responsible for the implementation of the WFD. SwAM is responsible for the implementation of the MSFD, including the decision of which criteria and assessment method should be used (Havs och Vatten myndigheten 2018).

In 1998 Sweden enforced the Swedish Environmental Code (“Miljöbalken”), a legislation promoting sustainable development and including various measures such as the “polluter pays” principle. Following the political environmental goals set in 1991 (Jordbruksutskottet 1991), the government defined 15 national environmental quality objectives and several milestone targets in April 1999 (the 16th objective was added in 2005) with the overall aim of creating a sustainable environment by 2020 (Naturvårdsverket 2018). However,

today's statistics show that this deadline will have to be postponed, despite the result of efforts.

The impact of contaminated sediments was discovered in Swedish lakes and rivers when mercury and later PCB were found in fishes and in the upper levels in the food chain. Surveys of contaminated sediments have been limited, but are gradually developing. All the data on sediment samples that have been analyzed since 1986 are part of a database, managed by SGU (“Datavärdskap för Miljögifter”), which is used in a classification aiming to provide an overview of the levels of contaminant over the country, identify the biggest threats and to set priorities for remediation actions. This classification is not related to ecotoxicological effects. It is divided into classifications for metallic (Naturvårdsverket 1999) and organic (Josefsson 2017) compounds. In 2016, a White Paper (Jersak et al. 2016a) was published to review the main sediment contamination problems in the country and the remediation efforts that have been performed. It identified contaminated areas in at least 19 of 21 counties. In 2017, the government decided to allocate special funds for soil and sediment remediation, which is taking place between 2018 and 2020 (Severin et al. 2018). All information about identified contaminated sites is available in the database EBH-portal, where restricted information is available to the public. The most problematic substances in contaminated sediments in Sweden are mercury, TBT, dioxins, and PAH.

Dredging has been performed in most remediated areas, and in situ capping in some others. A recommendation guide for dredging and handling dredged material has been published by SwAM (Vattenmyndigheten 2018). It does not include any specific concentration levels but gives advices for the remediation process and examples of past experiences.

## 2.2.3 Finland

All marine waters in Finland are brackish waters, along the coastline of the Baltic Sea. The shores are typically rocky and fragmented into numerous islands. The archipelago is a product of glacial erosion during the Ice Age and has resulted in uplifting of the land. The uplifting is especially strong in the Gulf of Bothnia, rising for up to 9 mm year<sup>-1</sup>. The coastline in the island zone is shallow; therefore, sedimentation is restricted to wind-protected deeps. Erosion of sediment is common. The rivers bring sediments in addition to associated anthropogenic substances from the catchments. Estuaries reflect the catchment properties and human actions therein. For example, dioxins enter the seabed from the River Kymijoki and heavy metals from the acid sulfate soils of the rivers at the western coast. The Baltic Sea is the most important transport route for trade and there are several active harbors where sedimentation and dredging are common issues.

The leading environmental administrative body in Finland responsible for setting guidelines and policy for the



implementation of European directives and national legislation is the Ministry of Environment (Ympäristöministeriö). The Finnish Environmental Institute (SYKE) is a national expert body responsible for advising and guiding monitoring, survey, and research programs. The practical work is done by the Regional Centers for Economic Development, Transport and the Environment (ELY) or even at city or municipality level. ELY centers follow and classify the chemical status of water bodies according to the WFD and amendment directives. The Finnish Water Way (Ministry of Agriculture and Forestry, Ministry of Economic Affairs and Employment, Ministry of the Environment, Ministry for Foreign Affairs, Ministry of Social Affairs and Health 2018) is an International Water Strategy which boldly announces the goals and means for protecting the waters. This follows the examples of United Nations SDG 6: “Ensure availability and sustainable management of water and sanitation for all.” However, the practical actions protecting environment mainly stem from the EU legislation.

There is no national systematic survey plan in Finland regarding contaminated sediments. Some areas have been identified and monitored but not many have been remediated, especially concerning marine sediments. Jaakkonen (2011) presented a preliminary national survey of contaminated sediments in inland waters. She identified 28 known and suspected sites, mainly located south of the country. Typical contaminants were metals, PAHs, PCBs, oil, and organic tin and chlorinated compounds. In the worst cases, PCB concentrations were at parts per million levels. Since then, some other sites have been identified and related to mining activity and heavy metals. Considering the fact that no EQS have been set for sediment values within the WFD in Finland, the focus is mainly on water and biota thresholds. The trends in sediment concentrations are sometimes surveyed but they are not necessarily leading to remediation actions. It is frequent to perform dredging, even though the main motivation is usually not the environmental remediation itself, but the use of waterways for navigation or construction purposes. To our knowledge, capping has only been performed in one site, and it was not a marine site. A guide was published in 2015 to support decision for handling and relocating dredged sediments as a function of their contamination levels (Ympäristöministeriö 2015). The guide includes concentration levels for the most common contaminants (PAHs, sum PCBs and dioxins, metals, TBT).

#### 2.2.4 Denmark

Denmark is located in Northern Europe and consists of the Jutland peninsula and several islands in the Baltic Sea, referred to as the Danish Archipelago. Denmark has a long coastline compared with the size of the country, and borders both the Baltic and North Seas along its 8750-km tidal

shoreline. The general shoreline (excluding most of the offshore islands and the 180-km-long Limfjorden) is 1701 km. Most of the coastal areas are shallow, and the physical, chemical, and biological conditions are very diverse with more saline waters on the west side facing the North Sea and less saline water on the east side facing the Baltic Sea. The Danish coastline varies from steep shoreline profiles with cliffs of chalk, limestone, and quaternary deposits, to gentler profile slopes and sandy beaches (Aagaard 2010; Łabuz 2015). The longshore sediment transport is large with a maximum net annual drift of 2.3 million m<sup>3</sup> year<sup>-1</sup> at Nymindégab (KDI 2001), leading to erosion and hence accreting and progradation of the different areas. Strong lee-side erosion occurs south of all harbor entrances along the central west coast. Parts of the west coast are thus protected by engineering structures. Due to the negative consequences of hard coastal protection, beach and shoreface nourishment was introduced in the mid-1970s and is now used to combat coastal erosion in Denmark. Annual nourishments along the central west coast amount to about 3 million m<sup>3</sup> year<sup>-1</sup>. Erosion problems disappear south of Nymindégab where the longshore sand transport gradient is negative (Aagaard 2010).

The WFD was originally implemented in Danish legislation by the 2003 Act on Environmental Objectives. Following a highly contested river basin management plan (RBMP) process, a new Act on River Basin Planning was adopted in 2013, establishing a new process for the second generation of RBMPs which took effect from 2016. The 2013 Act represents a significant shift regarding the legal status of RBMPs in Denmark from being legally binding upon the authorities, to being informative documents with no legal effect. The environmental objectives and the program of measures are issued as separate, legally binding documents in the form of Statutory Orders, effective from 2016 (Jacobsen et al. 2017; European Commission Environment 2019).

The (Danish) Ministry of Environment and Food (Miljø- og Fødevareministeriet) is responsible for water planning and monitoring of the condition of surface water, groundwater, and protected areas. The Ministry implements specific environmental goals for the different water districts, regarding both groundwater and surface waters, including artificial and heavily modified surface water areas.

Water bodies in Denmark are heavily impacted by anthropogenic activity, such as aquaculture, agriculture (including pig farming), shipping, and industries. All Danish fjords and coastal waters are classified as “eutrophication problem areas” and all Danish marine waters are classified as being moderately to significantly impaired with respect to marine biodiversity (Naturstyrelsen 2012). Contaminants in Danish marine waters have been monitored at the national scale since 1998 through the Danish National Monitoring and Assessment Program for the Aquatic and Terrestrial Environment, NOVANA (Hansen 2016). Hazardous substances in

sediments are analyzed every 5 years through the NOVANA program. National EQS for 14 contaminants or contaminant groups in sediment have been developed (MFVM 2017). A review of sediment data in Denmark by Andersen et al. (2016) showed that 36% of the assessed areas have a good or high chemical status, 55% have a moderate chemical status, and 9% have a poor chemical status. The offshore waters in the North Sea, Skagerrak, and Kattegat are generally classified as non-problem areas, while many of the fjords and coastal waters are contaminated (Andersen et al. 2016). As in other Nordic countries, heavy metals are one of the main groups of contaminants in sediment. In Denmark, Hg, Pb, Cd, and Cu typically account for 50–75% of the total toxic contribution from metals in dredged material. In addition, organic contaminants like PAHs and tributyltin (TBT) contribute substantially to the total toxicity of sediments (Stuer-Lauridsen et al. 2005).

Mapping of relative impact of multiple human stressors in the Danish marine waters showed that highly impacted areas were found in the Wadden Sea, open parts of the Skagerrak, Limfjorden and other estuarine systems, the Danish Straits, and along shipping routes in the Kattegat and western Baltic Sea, while areas with low estimated impacts were found in some offshore parts of the North Sea and Kattegat. The top five stressors for the entire study area are nutrients, climate anomalies, non-indigenous species, noise, and contaminants (Andersen et al. 2019).

Due to shallow water depths and heavy boat traffic, dredging is often used to maintain an appropriate sailing depth in harbors and fairways. The guidance document for handling of dredged material (MST 2005) defines lower and upper action limits (concentration) for more than 20 contaminants or contaminant groups. The concentrations of contaminants in the dredged material are compared with these action limits, which is an essential element in the evaluation of how the dredged materials should be handled. Dredged materials with contaminant concentrations above the upper action limits should in principle be deposited on land. Interestingly, the action limits are different from the EQSs values, and some contaminants have a national EQS but no action limits. The national EQSs are generally higher than the lower action limits.

A pilot-scale conventional isolation-capping project was conducted in the port of Copenhagen. The site was polluted with heavy metals, among which mercury was the most critical. Three different cap designs were tested. To our knowledge, final results and follow-up decisions are not available to the public.

### 2.3 Sediment remediation approaches

Historically, dredging, excavation, and disposal and/or treatment off-site have been the most frequently applied methods for the remediation of contaminated sediments. This approach

is widely used in Finland and Denmark; the main purpose often being technical reasons such as navigation or construction work, rather than remediation itself. In many cases, dredging leads to the remediation of a contaminated area, even if it was not the primary goal.

Dredging, however, is typically an expensive method that requires dewatering and land space for landfills, sometimes including transport of sediment over long distances, and most often inducing resuspension and recontamination (Bridges et al. 2008; Perelo 2010). Hence, dredging often must be followed by capping to reach pre-set environmental standards and prevent recontamination. For example, capping of dredged areas was done in the Oslo harbor in 2010 due to recontamination (Pettersen 2014). For these reasons, there is a need for alternative methods that are less costly and/or more environmentally friendly.

Depending on the future site use and site characteristics (in particular sea depth), contaminated sediments can sometimes be remediated in situ. Such remediation can involve treatment by physical or chemical methods, or physical isolation. In addition to lowering the bioavailability of the contaminants, some other advantages when compared with dredging are (typically) lower costs (depending on the method and material used), no transportation of the contaminated material, and no need for landfill sites. The most common in situ method yet applied is capping, and it has been used worldwide since the 1970–1980s. Various capping methods exist and have different remediation goals, fitting different degrees of contamination (Perelo 2010; Jersak et al. 2016b). Isolation capping consists of placing several layers of clean material, built up to a thickness that is greater than the benthic bioturbation zone. It aims to isolate the contaminated sediment, physically and chemically, from the aquatic environment. When applying the more recently developed thin-layer capping method, a thinner cap is placed, often in combination with chemically reactive materials (Cornelissen et al. 2012; Schaanning and Allan 2012; Zhang et al. 2016). Both types of capping can involve the use of geotextiles, active materials (activated carbon, organoclay, apatite, etc.) and/or inert materials (crushed stones, sand, etc.). Capping can also be combined with dredging, by relocating the contaminated sediments where no disturbance will damage the cap.

After the USA, Norway is one of the world leaders in terms of pilot studies and completed capping projects. To our knowledge, between 20 and 30 projects have been completed using both isolation and thin-layer capping, and using both active and inert materials (Laugesen et al. 2016). In Norway, the first sediment cleanup project was the in situ capping of Eitrheimsvågen in Odda carried out in 1992. During the period 2001–2002, five pilot projects were performed in Tromsø, Trondheim, Sandefjord, Kristiansand, and Horten. Several full-scale projects have been subsequently conducted including the following: (I) dredging of contaminated sediment in

Haakonsvern in Bergen with establishment of near-shore confined disposal sites; (II) several sediment remediation projects in the Kristiansand harbor area, including dredging and excavation, and capping with sand and gravel and in some places with geotextiles and gravel; and (III) dredging of contaminated sediments in the Oslo harbor area and deposition of contaminated sediment in deep deposits (70 m deep) outside the dredged area followed by capping with sand. In addition, a pilot study on thin-layer capping with activated carbon based on a large field experiment was conducted in the Ornefjorden and Eidangerfjorden (Cornelissen et al. 2012; Schaanning and Allan 2012). In Sweden, at least five sites have been remediated using either isolation or thin-layer capping, without the use of active material (also called conventional capping) (Jersak et al. 2016a). One of the sites is located on the river Vanån, two on lakes (lake Turingen and lake Tollare), and two on different parts of Gothenburg's harbor (Lundbyhamnen and Sannegårdshamnen) (Jersak et al. 2016a). In Finland, one project of conventional isolation capping has been performed, in lake Jämsänvsi (Hyötyläinen et al. 2002). To our knowledge, only one pilot-scale project has been conducted in Denmark, in the Port of Copenhagen. Techniques involving biological processes such as bioremediation and phytoremediation have been developed and tested at the pilot scale (Perelo 2010; Sun et al. 2010; Gomes et al. 2013; Huang et al. 2013; Zhang et al. 2016), but no site has yet been remediated (to our knowledge) using these methods in the four studied countries.

Monitored natural recovery (MNR) consists of a close monitoring of the contaminated system, in a context where the pollution is predicted to naturally attenuate. This can happen by oversedimentation, mixing, biodegradation, dispersion, dilution, etc. (Gomes et al. 2013). Enhanced natural recovery (EMNR) consists of adding various substances to boost the natural processes. Several places in Norway are being monitored to observe recovery, but MNR has not been officially accepted in any of the four Nordic countries as a remediation strategy for any project where remediation action plans have been developed.

### 3 Lessons learnt from Nordic remediation projects

In the aim of improving remediation technologies, experiences and results from completed projects have to be understood, compared, and shared. However, such information is not always available, rarely published in scientific journals, and often only published in a national language. As a first step, a common database and/or website for the Nordic countries containing information on the success of completed and ongoing sediment remediation projects could be a useful resource for future remediation actions. Some relevant

experiences from selected remediation projects are presented for illustration.

#### 3.1 Suitable planning and site characterization

The characterization phase of the site is important in order to develop an adequate remediation plan. It includes a thorough assessment of the pollution level, of the water depth, and other site-specific factors. In the case of Oskarshamn's harbor in Sweden, this step was not well performed. The remediation of this very industrially active harbor is the largest remediation project in Sweden. The technique chosen was dredging and deposit in landfill because capping was not feasible due to the intense boat traffic (Liedberg Jönsson et al. 2018; Van Renterghem et al. 2018). A few months after the start of dredging, the operations had to be stopped because many large rocks were found on the seafloor, preventing the suction dredging process. Divers had to be employed to remove the rocks, and mechanical dredging was instead performed (Van Renterghem et al. 2018). It induced additional costs and a slight delay, that could have been avoided with a better characterization of the area and suitable planning.

Many other similar examples can be found in the history of remediation of sediments, illustrating the importance of suitable planning and environmental characterization. We recommend therefore the use of various methods such as hydroacoustic and hydrographic methods for characterization of the seafloor.

#### 3.2 Monitoring before and after remediation

The monitoring part, before, after, and ideally during remediation actions, is as important as the remediation itself (Gustavson et al. 2008); one of the main knowledge gaps identified by the Norwegian Council on Contaminated Sediments (Miljødirektoratet 2006) was related to long-term monitoring. It is essential to assess the efficiency of the remediation actions, potential recontamination, and secondary effects (which can be positive or negative effects) of the method applied on the environment for the project itself and future remediation projects.

Long-term effects should be monitored and sampling must be consistent in time, space, method, and analytical methods (Gustavson et al. 2008). In the Oslo harbor, monitoring after a large dredging and capping operation showed that contaminant concentrations were reduced, though some recontamination was observed. Recolonization and recovery to acceptable biodiversity indices occurred within a few years after the operation (Alve et al. 2009; Slinde et al. 2015). Recent studies have reported potential harmful secondary long-term effects of low-impact approaches like activated carbon (AC) amendment on benthic organisms and submerged vegetation (Jonker et al. 2009; Beckingham et al. 2013; Janssen and Beckingham

2013; Samuelsson et al. 2017). In a pilot study in the Grenlandfjords area, a reduction up to 90% of the abundance, biomass, and number of species was observed after capping thin-layer capping with AC (Samuelsson et al. 2017).

Following the large remediation of Oskarshamn harbor, a plan was made for a long-term recovery. According to Denmark's national monitoring program, sediments are monitored every 5 years. However, information specifically related to remediation projects is not easily found. No information on long-term monitoring of Finnish sites was found. There is a need for monitoring, together with the need for scientific communication.

### 3.3 Residual contamination after dredging

Completed dredging projects that have been thoroughly monitored showed that residual contamination is to be expected (Bridges et al. 2008). If the residual contamination is higher than the required contamination level, further measures have to be taken. In Oslo harbor, Trondheim, and Sandefjord in Norway, a protecting capping layer was applied after dredging (Miljødirektoratet 2006; Pettersen 2014). Thus, the required level of concentration of contaminants was then obtained by combining dredging and capping.

### 3.4 Control of discharges

Control of active discharges is crucial to maintain cleanup levels. Recontamination after remediation has been reported in several sites, such as the early remediation site Eitrheimsvågen (1992), Kristiansand harbor (2001), and Oslo harbor (2006) in Norway (Walday 2002; Næs and Håvardstun 2010, 2013; Slinde et al. 2015). In Eitrheimsvågen, the recontamination was ascribed to insufficient control of discharges and run-off (Walday 2002). In Kristiansand, recontamination was explained by nearby dredging (Næs and Håvardstun 2010, 2013). Run-off from Oslo, sediment resuspension from non-remediated areas, and erosion from boat traffic were the suspected causes for the recontamination of the Oslo harbor (Slinde et al. 2015).

### 3.5 Spatially extended remediation actions

One of the lessons learned from the five Norwegian pilot projects performed in Tromsø, Trondheim, Sandefjord, Kristiansand, and Horten during the period 2001/2002 was that remediation actions should not be overfocused on hot spot areas (small highly contaminated areas) if the area is surrounded by contaminated sediments, unless the hot spot area is clearly identified as the main source of contamination (Miljødirektoratet 2006). The interrelationship between a local remediation site and the environmental situation in the surrounding area must be understood and clarified so that

realistic assessments can be made when evaluating the measure with respect to the environmental targets for the whole area.

## 4 Suggestion of strategies for decision support

As the decision-making process for remediation actions is often motivated by the need to secure human health, many other factors are usually considered to insure the protection of ecosystem services. Traditionally, dredging and isolation capping have aimed at reducing concentrations of hazardous substances in the sediments without taking into consideration the potential adverse effects of the remediation action. A more balanced evaluation can be achieved by broadening the decision context to include several relevant factors such as short- and long-term ecological impacts and benefits, residual impacts, and performance. Such an assessment could also involve a comparative life cycle assessment (Ghosh et al. 2011). Here, we suggest four main categories of criteria: efficiency, benefits, adverse effects, and costs.

### 4.1 Efficiency

The first aim of a remediation action is its efficiency to improve local environmental conditions. The measurement for securing environmental quality within the WFD is, as explained before, mainly focused on specific contaminant concentrations. However, some techniques such as capping using active materials, or chemical methods induce the immobilization of the contaminants. Therefore, the substances' concentrations are not decreased, but their mobility and bioavailability are. We suggest using the bioavailability of contaminants, as well as total sediment concentrations, for assessing environmental risks and efficiency.

The combined ("cocktail") effects of several contaminants should also be taken into account (Stafoggia et al. 2017). Indeed, it is well known that contaminants affecting the same endpoint in the same direction (e.g., growth inhibition or mortality) can be concentration additive (Loewe and Muischnek 1926) or response additive (Bliss 1939), meaning that they contribute to the same effect. In such cases, the combined effect of the contaminants will be higher than the effect of the individual contaminants.

### 4.2 Benefits

The benefits of a remediation action are linked to the objectives defined for the measure. They include ecological, chemical, and physical, as well as societal and economical, aspects that include recreation and tourism. These benefits are central



to the concept of ecosystem services (Boyd and Banzhaf 2007).

### 4.3 Adverse effects

Benthic fauna and flora are crucially disturbed during remediation operations such as dredging and capping, whereas thin-layer capping and MNR are considered low-impact approaches (Ghosh et al. 2011). Adverse effects can also be due to habitat destruction or the introduction of a new substance, disturbing physical, chemical, and/or biological conditions. Other adverse effects such as the use of resources, energy consumption, and land use have to be considered in order to use the most sustainable technologies.

### 4.4 Costs

The cost of remediation has traditionally been the primary criterion for deciding upon remediation actions. The size of the contaminated area, the availability of remediation material, and the solutions for treatment of dredged material will strongly influence the costs. Often, the combination of infrastructure projects can give opportunities for synergies that may lower costs. This combination has been the case in several remediation projects in Norway, where material from road construction has been used as capping material (e.g., in Kristiansandfjorden), or dredged material that has been stabilized and used for land extension (e.g., at quay 2 in Trondheim harbor) or utilized for harbor extensions (e.g., in Tromsø, Sandvika). Dredging is typically considered the most expensive method though capping can also be very expensive, in particular when using geotextile or active materials.

## 5 Conclusions

This study is the first compilation of Nordic experience from sediment remediation actions. It has revealed a need of characterization surveys for a better assessment of the level of pollution and the importance of monitoring of long-term effects after remediation operations, and suggests a common Nordic database of remediation projects to improve the exchange of knowledge between the Nordic countries and the international community. Subsequently, harmonized guidelines for handling of contaminated sediment and for future remediation projects would be beneficial. We propose multi-criteria analyses to decide upon remediation strategy, considering various factors affecting efficiency, benefits, adverse effects, and costs. A risk-based approach is beneficial to identify potential remediation sites and prioritize between sites, and can also be used to decide cleanup levels, though research and method developments are needed for the development of risk assessment tools for sites with multiple contaminants.

Further, we recommend that low-impact approaches such as monitored natural recovery should be given more consideration as alternative remediation strategies.

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### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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