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SUSTAINABLE RISK MANAGEMENT OF CONTAMINATED LAND AND SEDIMENT - NORDROCS 2016

Multi-criteria assessment tool for sustainability appraisal of remediation alternatives for a contaminated site

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Abstract

Purpose In order to improve and support decision-making for the selection of remedial techniques for contaminated sites, a multi-criteria assessment (MCA) method has been developed. The MCA framework is structured in a decision process actively involving stakeholders, and compares the sustainability of remediation alternatives by integrating environmental, societal, and economic criteria in the assessment.

Materials and methods The MCA includes five main decision criteria: remedial effect, remediation cost, remediation time, environmental impacts, and societal impacts. The main criteria are divided into a number of sub-criteria. The environmental impacts consider secondary impacts to the environment caused by remedial activities and are assessed by life-cycle assessment (LCA). The societal impacts mainly consider local impacts and are assessed in a more qualitative manner on a scale from 1 to 5. The performance on each main criterion is normalized to a score between 0 and 1, with 1 being the worst score. An overall score is obtained by calculating a weighted sum with criteria weights determined by stakeholders. The MCA method was applied to assess remediation alternatives for the Groyne 42 site, one of the largest contaminated sites in Denmark.

Results and discussion The compared remediation alternatives for the site were: (1) excavation of the site followed by soil treatment; (2) in situ alkaline hydrolysis; (3) in situ thermal remediation; and (4) continued encapsulation of the site by sheet piling. Criteria weights were derived by a stakeholder panel. The stakeholders gave the highest weighting to the remedial effect of the methods and to the societal impacts. For the Groyne 42 case study, the excavation option obtained the lowest overall score in the MCA, and was therefore found to be the most sustainable option. This was especially due to the fact that this option obtained a high score in the main categories Effect and Social impacts, which were weighted highest by the stakeholders.

Conclusions The developed MCA method is structured with five main criteria. Effect and time are included in addition to the three pillars of sustainability (environment, society, and economy). The remedial effect of remediation is therefore assessed and weighted separately from the main criteria environment. This structure makes interpretation of criteria scores more transparent and emphasizes the importance of effect and time as decision parameters. This also facilitated an easier weighting procedure for the stakeholders in the case study, who expressed a wish to weigh the remedial effect independently from the secondary environmental impacts.

Keywords Contaminated site · Decision support · Multi-criteria assessment · Soil contamination · Stakeholder involvement · Sustainability assessment

1 Introduction

Recent estimates of the number of sites with contaminated soil in Europe by the Joint Research Centre of the European

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Commission show that there are more than 2.5 million potentially contaminated sites in Europe (van Liedekerke et al. 2014). Of these about 14% (340,000 sites) are expected to be contaminated and are likely to require remediation. Until recently, remediation of a contaminated site has been considered to be inherently green or sustainable, since it removes a contaminant problem. However, it is now broadly recognized that while remediation is intended to address a local environmental threat, it may cause other local, regional, and global impacts on the environment, society, and economy. Over the last decade, the broader assessment of these criteria is occurring in a movement toward "sustainable remediation" (Holland 2011; Hou and Al-Tabbaa 2014),

The Brundtland Report by the World Commission on Environment and Development (UN 1987) defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Harbottle et al. (2008) presented a framework for assessing sustainability of contaminated land remediation focusing only on the technical and environmental sustainability of the remediation technology. Subsequently, a number of different definitions of sustainable remediation have been proposed. A common feature is that they employ a "triple bottom line approach" addressing the three pillars of sustainability: environment, society, and economy (SuRF-UK 2010; Sparrevik et al. 2011, 2012; Rosén et al. 2015). Sustainable remediation eliminates or controls contaminant risks while minimizing negative environmental, social, and economic impacts. A well-balanced decision support processes must therefore address all three aspects (SuRF-UK 2010). In addition, the engagement of stakeholders has been stressed as an important issue for sustainable remediation. The NICOLE (2010) roadmap for sustainable remediation defines a sustainable remediation project as "one that represents the best solution when considering environmental, social and economic factors—as agreed by the stakeholders."

Table 1 provides an overview of some of the existing approaches for sustainability appraisal that have been applied to remediation of contaminated sites or contaminated harbor sediments. Only studies that describe themselves as sustainability assessment tools and consider all three pillars of sustainability were included in the overview. Some tools that describe themselves as sustainability assessment tools, however, have a skewed focus on environmental indicators and contain only few social indicators (also noted in Huysegoms and Cappuyns (2017) and Cappuyns (2016)). The above selection criteria excluded tools such as REC (Beinat et al. 1997), SiteWise (United States Navy et al. 2015) and sustainable emediation Tool (SRT, AFCEE 2010). Furthermore, we focused mainly on studies that include an application of the tool for an actual site and for which a full description (in English) is published. The commercially available tool GoldSET (Golder

Table 1 Comparison of applied approaches for assessing sustainable remediation in terms of issue addressed, type of multi-criteria assessment (MCA), total number of indicators (2 levels counted), inclusion of stakeholders and evaluation types (quantitative or semi-quantitative) used for the assessment of the environmental, social and, economic aspects is noted

Reference	Remediation issue addressed	MCA type	Total no. of indicators	Stakeholders involved in case study?	Evaluation type		
					Environmental	Social	Economic
Sorvari and Seppälä (2010)	Contaminated site	MAVT Linear additive	11	Yes	Quantitative (LCA)	Semi-quantitative	Quantitative (costs)
Sparrevik et al. (2011)	Contaminated sediment	MAVT Linear additive	9	Yes	Quantitative (Carbon footprint)	Semi-quantitative	Quantitative (costs)
Sparrevik et al. (2012)	Contaminated sediment	Outranking	4 [a]	No (3 stakeholder profiles tested)	Quantitative (LCA)	Quantitative (health risk reduction)	Quantitative (socio-economic benefit)
SuRF-UK (2013a) Case study 2	Contaminated site	MAVT Linear additive	16	No	Semi-quantitative; quantitative (carbon footprint)	Semi-quantitative	Semi-quantitative; quantitative (costs)
SuRF-UK (2013b) Case study 3	Contaminated site	MAVT Linear additive	8	No	Semi-quantitative	Semi-quantitative	Semi-quantitative; quantitative (costs and selected benefits)
Rosén et al. (2015)	Contaminated site	MAVT. Linear additive and non-compensatory	22	No[b]	Semi-quantitative	Semi-quantitative	Quantitative (cost-benefit analysis)

MAVT multi-attribute value theory, *LCA* life-cycle assessment

[a] Only one level of criteria is reported. Environmental sub-criteria are therefore not counted

[b] Stakeholders were not involved in the case study, but the method does allow for stakeholder participation

Associates n.d.) includes all three pillars of sustainability; however a complete tool description could not be provided by the supplier. The tool is therefore not included in Table 1. A more complete review of decision support tools for assessment of site remediation can be found in Huysegoms and Cappuyns (2017) and Brinkhoff (2011).

The reviewed studies in Table 1 included a total of 4 to 22 indicators divided between environment, social, and economic indicators. The evaluation types for the environmental and social criteria are mainly semi-quantitative assessments using different scoring systems. A full life-cycle assessment is employed in three of the studies for a quantitative evaluation of environmental impacts (Sorvari and Seppälä 2010; Sparrevik et al. 2011, 2012). The economic criteria are mostly evaluated using a combination of semi-quantitative and quantitative evaluations of costs and benefits. In addition to the environmental, social, and economic criteria, SuRF-UK (2013a) added additional criteria categories covering the remedial effectiveness and the practical implementation of the remediation technologies. All reviewed studies apply a multi-criteria assessment (MCA) technique to rank the assessed technologies based on their performance on the various sustainability criteria. Most of the studies apply the linear additive model, which is based on a multi-attribute value theory (MAVT) developed by Keeney and Raiffa (1976, 1993). The linear additive model (Eq. 1) calculates an overall score V, to each decision alternative, x, based on the weighted sum of each individual normalized criteria score $v_\mathrm{i}(x_\mathrm{i})$. The weights w_i reflect the relative importance of the criteria and sum to one, where n is the number of total criteria, i.

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i) \tag{1}$$

The linear additive method is *compensatory*, meaning that criteria with high scores can compensate for other criteria with low scores. Furthermore, it assumes that all criteria can be evaluated independently. In contrast to MAVT, Sparrevik et al. (2012) employs *outranking*, a different type of multi-criteria assessment method where a comparative assessment of alternatives is conducted using the PROMETHEE II algorithm which ranks the alternatives without normalization of criteria scores.

Multi-criteria assessment is an attractive tool for environmental decision-making encompassing a wide selection of decision criteria (Kiker et al. 2005; Brinkhoff 2011). Life-cycle assessment (LCA) and risk assessment are essential tools for assessing alternatives with respect to the included criteria (Linkov and Seager 2011). The assessment of secondary environmental impacts of remediation systems for contaminated sites using life cycle assessment (LCA) has been well studied (Lemming et al. 2010a, 2010b, 2012; Morais and Delerue-Matos 2010); however, available sustainability assessment tools either do not apply LCA (Rosén et al. 2015; SURF-UK 2013b) or apply a limited LCA focusing only on few selected indicators such as energy use and carbon footprint (Sparrevik et al. 2011, SURF-UK 2013a; GoldSET, applied in Beames et al. 2014). The studies that do apply a full LCA tend to focus on the environmental aspects of sustainability and social and economic impacts are only sparingly covered (Sorvari and Seppälä 2010) or concern sediment remediation (Sparrevik et al. 2012). The aim of this study is to develop a multi-criteria decision support model with the aim of comparing the sustainability of remediation options for contaminated sites. We combine the use of multi-criteria assessment with a full LCA of the assessed techniques. In addition, we include impacts in the economic and social domain, and we add topic-specific main criteria regarding the remediation efficiency and time use to address stakeholders' requests. Previous methods most often placed the effect of remediation (cleanup efficiency) as a sub-criterion under environment or Social impacts. This reduces the importance of this criterion and makes interpretation more difficult. The review of sustainability appraisal methods for contaminated sites also revealed that the number of detailed case studies published in literature is very limited. Therefore a second objective of this study was to apply the method in this paper at an actual contaminated site.

2 Materials and methods

2.1 Multi-criteria decision process and method

MCA was selected as method for the sustainability appraisal tool. Using a multi-criteria assessment allows for a joint assessment of a range of indicators which may be quantitatively or qualitatively assessed. MAVT (the linear additive model, see Eq. (1)) was applied since this model is easily understood by both decision makers and stakeholders (Marttunen et al. 2015).

The applied multi-criteria decision process is depicted in Fig. 1, showing the synthesis between decision process steps, involved groups and tools. This framework is based on the general framework for decision analysis in environmental decision-making by Kiker et al. (2005). The process steps involves: (1) definition of problem and decision alternatives; (2) identification of criteria and sub-criteria;(3) determining the relative importance of criteria;(4) assessing the performance of the alternatives on the different criteria; (5) ranking of alternative; (6) decision-making. The decision maker is active during the formulation of problem and alternatives (remediation strategies) and in the final decision-making. Stakeholders take part in the identification of sustainability criteria and the assessment of the relative importance of these criteria. Experts and consultants carry out assessments to determine the performance of the remediation alternatives on the

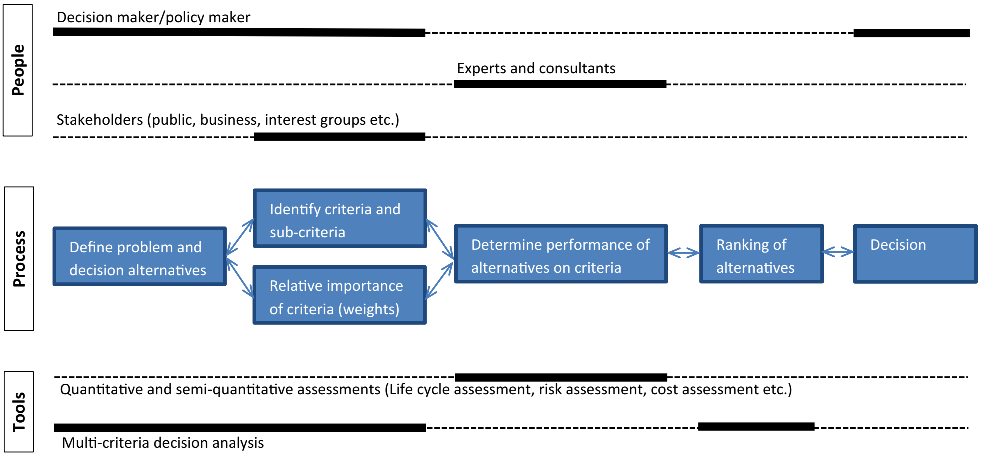


Fig. 1 Overview of the multi-criteria decision process and the synthesis between people, process and tools. Modified after Kiker et al. (2005). The dark lines mark process steps directly involving specific groups (decision makers, experts/consultants and stakeholders) and the dotted lines represent steps with less involvement. The process is iterative in each phase

different sustainability criteria. The multi-criteria decision support tool uses these assessments and the criteria weights to calculate a ranking of the assessed remediation alternatives. Based on this ranking the decision maker takes a decision on which remediation method that applies best to the problem.

To obtain an overall score, Eq. 1 is applied with weights being determined in a process involving stakeholders. Stakeholders are defined here to be individuals, groups, or organizations who can affect a decision or can be affected by a decision (Freeman 1984). Relevant stakeholders depend on the site context and include land owners, authorities, residents, neighbors, other users of the site, local industry, and non-governmental organizations (NGOs) representing certain interests. Section 2.5 explains how stakeholder involvement was employed for a specific case study site.

2.2 Identification of criteria for sustainability assessment of site remediation

In order to address all three dimensions of sustainability, Environment, Society and Economy was selected as main criteria. Based on a process involving a literature survey of sustainability indicators, existing literature surveys (Surf-UK 2010; Brinkhoff 2011), and a dialogue with decision-makers and stakeholders, Effect (cleanup efficiency) and time were added as main criteria. The multi-criteria assessment tool thus applies a hierarchical structure with a number of sub-criteria divided under these 5 criteria headings, see Fig. 2. In most reviewed studies, the remedial effect (or risk reduction) is included as a sub-criterion below environment or society. However, in contrast to other environmental criteria which consider a range of secondary impacts on the environment due to remediation (emissions, waste etc.), effect assesses the positive benefits of remediation. Were effect to be placed under the environmental criterion, then it would become difficult for decision makers and stakeholders to interpret and weight this main criterion since it would contain very different impacts in one score. In this study, both stakeholders and decision makers expressed a strong wish to separate effect from environmental criterion in order to be able to weigh these criteria separately. In addition to the 5 main criteria, a number of sub-criteria (see Fig. 2) were selected based on literature (e.g., SuRF-UK 2010; Brinkhoff 2011) and discussions with the decision maker. A hierarchical structure with main criteria and sub-criteria was employed as depicted in Fig. 2. Weights can be applied both to main criteria and sub-criteria. It should be noted that using a hierarchical structure will give less weight to each of the sub-criteria of main criteria with many sub-criteria than if a non-hierarchical structure was used. At the same time, the hierarchical structure ensures that main criteria with many sub-criteria (in this case environment and society) are not implicitly given a larger weight than main criteria with few sub-criteria. A requirement of the linear additive model is that all criteria are mutually independent, and this was a constraint on the selection of the sub-criteria. The individual sub-criteria and the procedures for criteria performance assessment are presented in Section 2.3.

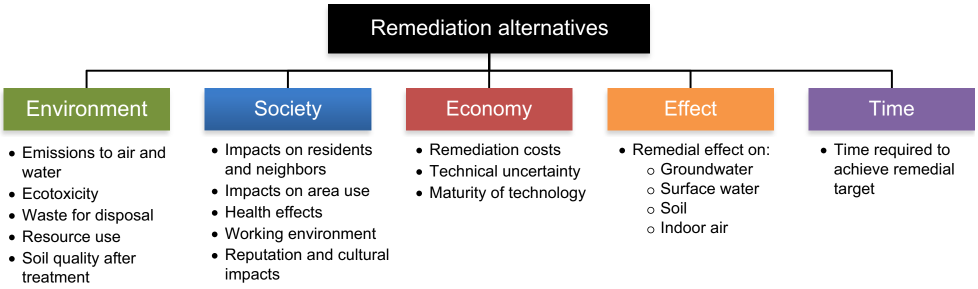


Fig. 2 Criteria structure used for the sustainability assessment of contaminated site remediation

2.3 Performance assessment of alternatives

Most of the criteria are quantitatively assessed; however, some impacts are difficult and uncertain to assess quantitatively, especially societal impacts. Therefore, a semi-quantitative assessment method is applied using a scoring system with scores from 1 to 5. An expert panel on remediation technologies has conducted a general assessment of selected semi-quantitative criteria for 17 commonly used remediation technologies (see Supporting Information, SI). An assessment of the criteria should always be completed for the actual site; however, these general criteria assessments may be used as a starting point.

The scores for each main criterion (environment, social, economy, effect and time) are normalized on a 0–1 scale. The environmental and social sub-criteria have 2nd order sub-criteria and these are also normalized. A score of zero is applied when there is no impact and a score of 1 is given to the remediation strategy which performs worst for the specific criterion. For environmental and social criteria that are evaluated qualitatively on a scale from 1 to 5, the normalization is relative to the worst possible score of 5. Time use is normalized by 30 years, so that a remediation technology requiring 30 years has a normalized score of 1. Thus if all compared remediation alternatives have comparably short-time frames, this criteria can be left out, since all the normalized values will be similar. For all criteria scores linear interpolation is used to obtain values between 0 and 1.

The total sustainability score is obtained using the linear additive model (Eq. (1)), which calculates a weighted sum of the normalized scores. In order to enhance the likelihood for decisions that gain public acceptance and create value for the community, the tool encourages criteria weights to be derived through a process actively involving stakeholders. This is further described in Section 2.4. The multi-criteria assessment method for selection of remedial techniques for contaminated sites described in this paper has been built into an Excel spreadsheet model (in Danish) and is available on sara.env.dtu.dk or on request from the authors.

2.3.1 Environmental criteria

The environmental criteria (Table 2) consider the secondary impacts to the environment caused by the remedial activities, whereas the local reduction in contaminant concentrations is part of the remediation effect criteria (see 2.1.4). The environmental criteria E1–E4 consider the environmental impacts caused by the use of energy, materials, transport etc. These are assessed in a LCA which consider emissions and resource use over the whole life of the remediation technology, including raw material acquisition, manufacturing, use, and end-of-life. The environmental exchanges (emissions and resource use) are translated to environmental impacts during the life cycle impact assessment. The more local environmental impacts of site remediation such as the soil quality changes are not covered by the LCA. Therefore an additional sub-criterion was added (E5) to qualitatively assess local impacts to the soil and groundwater environment on a scale from 1 to 5. The evaluation scale is presented in Appendix A (see ESM). The LCA method applied is EDIP2003 (Hauschild and Potting 2005) for non-toxic impacts and USEtox (Rosenbaum et al. 2008) for the toxic impact categories. Impacts are normalized to person equivalents (PE) by dividing impacts by the average impact of a European citizen in 2004 (Laurent et al. 2011a, 2011b). Resource consumption is reported as person reserves (PR) which are defined to be the person equivalent resource consumption weighted by the reciprocal supply horizon (global resource available per person) of each resource type (LCA Center 2005). The applied normalization reference and weighting factors for resource depletion are available in the Electronic Supplementary Material. Inventory data for background processes (production of electricity, production of steel, production of chemicals, transportation processes etc.) was sourced from the Ecoinvent database v.2 (Frischknecht et al. 2007).

2.3.2 Social criteria

The social impact criteria consider impacts to local society (S1, S2, S5) as well as health impacts (S3) and impacts to working environment (S4) (Table 3). The S1 criterion considers the nuisance to residents and/or neighbors experienced during remediation, for instance noise, dust and increased traffic. The S2 criterion applies to a recreational area with no residents and direct neighbors. In that case, S2 is used instead of S1, and evaluates the level of restrictions and nuisance experienced by users of the recreational area. S5 considers two sub-criteria: The first sub-criterion considers the impact of remediation activities on the reputation of the local area; while the second sub-criterion addresses the impact as a result of remediation.

The S3 criterion considers the human health impacts due to the release of toxic substances in all parts of the remediation life cycle. Finally the impacts to the working environment are assessed in criteria S4. All social impacts are assessed semi-quantitatively on a 1–5 scale except for criterion S3 which is assessed by life cycle assessment. The applied scale and the associated qualitative descriptions of the scores can be seen in Appendix A (see ESM).

2.3.3 Economic criteria

The economic criteria consider the estimated cost of remediation (EC1), and the added costs due to technical uncertainty (EC2) and the maturity (EC3) of the applied remediation technology (Table 4). The technical uncertainty EC2 considers the uncertainty in both the timeframe and effect of the method. For instance, ex situ methods often more reliably attain the desired effect in the

Table 2 Environmental criteria (E1–E5).

1st-level sub-criteria	2n- level sub-criteria	Evaluation method	Unit
E1: emissions to air and water	Global warming Acidification Eutrophication Photochemical ozone formation	Life-cycle assessment (LCA)	Person equivalents (PE)
E2: ecotoxicity		Life-cycle assessment (LCA)	Person equivalents (PE)
E3: waste for disposal (including soil)		Life-cycle assessment (LCA) or project specific evaluation	kg
E4: resource use	Crude oil Natural gas Uranium Hard coal Brown coal Aluminum Iron Chromium Nickel Copper Manganese Molybdenum Sand and gravel (high quality) Sand and gravel (other)	Life-cycle assessment (LCA)	Person reserves (PR)
E5: local soil quality after remediation	E5A: biogeochemical impact of soil E5B: impact of terrestrial environment at site	1–5 scale	–

If the remediation activity is directed at (or strongly influencing) the top ½ meter of the soil, then E5 A and E5 B should be evaluated as one joint criterion

PE person equivalents, *PR* person reserve

expected time and so are more certain, whereas in situ methods are dependent on good contact between contaminants and reactants, introducing uncertainty. The technical maturity criteria EC3 is used to assess whether the technology is ready for implementation at the site or whether more site investigations, treatability tests etc. are needed. Both EC2 and EC3 can be qualitatively assessed on a 1–5 scale and then translated into an additional cost (see Appendix A, Table A3 in the ESM).

2.3.4 Remedial effect criteria

Remedial effect is assessed via a number of sub-criteria depending on the contaminant distribution at the site, including the remedial effect on groundwater (E1), surface water (E2), soil (E3), and indoor air (E4) (Table 5). Only the relevant sub-criteria should be evaluated. The effect is evaluated in terms of the expected reduction (fraction) of a relevant metric such as contaminant concentration, contaminant mass discharge, or contaminant mass. Note that it is only relevant to compare remedial alternatives that are able to reduce contaminant risks to an accepted level. This criterion assesses the quality difference related to the remedial actions, since these may not have the exact same efficiency in reducing all contaminants at the site.

2.3.5 Time use criterion

The time use (T1) criterion considers the expected time (years) required for the remediation alternative to reach the remedial

Table 3 Social criteria (S1–S5) Note that either S1 or S2 is used. S1 is used in the case where local residents are impacted by the remediation while S2 is used if there are no residents at or near the site. S2 is applicable for recreational sites

1st-level sub-criteria	2nd-level sub-criteria	Evaluation method	Unit
S1: impact to residents and/or neighbors	Degree of impacts to residents and/or neighbors	1–5 scale	–
S2: impact to area use	During remediation After remediation	1–5 scale	–
S3: human health impact	Human toxicity (carcinogenic) Human toxicity (non- carcinogenic)	Life-cycle assessment (LCA)	Person equivalents (PE)
S4: working environment impacts		1–5 scale	
S5: reputation and cultural impacts	Impact on reputation of area Impact to landscape types or cultural sites	1–5 scale	

Table 4 Economic criteria (EC1-EC3)

1st-level sub-criteria	Evaluation method	Unit
EC1: cost of remediation	Cost estimate	MDKK
EC2: technical uncertainty	Qualitative 1–5 scale, translated into an added cost (see ESM)	MDKK
EC3: maturity of technology	Qualitative Scale 1–5 scale, translated into an added cost (see ESM)	MDKK

effects specified in EF1–EF4. The criterion only considers the time spent until the contamination has been contained or removed at the site itself, and does not consider subsequent treatment taking place elsewhere (e.g. for excavated soil).

2.4 Site description and remediation alternatives

The contaminated site "Groyne 42" is located on the west coast of Denmark. The site is one of the largest contaminated sites in Denmark and covers an area of approximately 20,000 m^2. During the 1950s and 1960s a large amount of mainly pesticide production waste was buried beneath the beach. In 1981 1200 tons of waste material was excavated from the site from areas above the water table. In 2006 a sheet pile cut-off wall was installed around the site in order to prevent discharge of contamination to the North Sea. Today is has been estimated that the site contains approximately 200 tons of contamination, mainly consisting of pesticide products and degradation products. The site is also contaminated by approximately 7 tons of mercury. The contaminated area has been divided into four subareas (Fig. 3): (I) A highly contaminated sludge layer; (II) hot spot with heavy contamination; (III) peripheral area with heavy contamination; and IV) a lightly contaminated area.

The Region of Central Denmark is the government authority responsible for the management of the Groyne 42 site. The Region of Central Denmark selected four remediation alternatives to be evaluated for the site. The alternatives include a containment method (continued capsulation using sheet piling), an in situ chemical method (in situ alkaline hydrolysis), an in situ thermal method (steam enhanced extraction), and an ex situ method (excavation and ex situ soil treatment). The remediation methods target the heavily contaminated areas (I, II, and III).

Table 6 Summarizes key data for each remediation alternative including consumables, costs, time use. and remedial effect.

2.4.1 Alternative 1: continued encapsulation (sheet pile wall)

Continued encapsulation involves maintenance of the sheet pile wall, which is already installed, for an indefinite period. This remediation alternative does not remove contamination. Groundwater is abstracted from the contaminated area to remove infiltrating water and to maintain a gradient towards the site. The abstracted water is treated by activated carbon filtration near the site. In order to calculate consumables and costs, a 100-year timeframe is assumed although the time frame is actually indefinite.

2.4.2 Alternative 2: in situ alkaline hydrolysis

The alkaline hydrolysis remediation alternative targets the pesticide contaminants with injection of a strong base (sodium hydroxide) leading to their chemical breakdown and enhancing their dissolution in water. In this scenario the most contaminated sludge layer is excavated and sent for external thermal treatment (see description under "Excavation" alternative). After 1 year the water treated with base is abstracted and sent for ex situ treatment (base treatment and heating). A new injection of base is initiated and a total of around 8 cycles of sodium hydroxide injections and subsequent abstraction are expected. Pilot tests conducted at the site shows that alkaline hydrolysis can be expected to remove around 90% of the pesticide contamination and 10% of the mercury (via the pump and treat system). A network of 84 injection wells and 12 monitoring wells are established at the site. A sheet pile wall is constructed around the central and most contaminated part of the site making it possible to treat the two areas separately.

2.4.3 Alternative 3: in situ thermal treatment

In this remediation alternative, the contaminated soil is heated in situ to 110 °C by injection of steam. The high temperatures enhance the transfer of contaminants to the vapor phase. The contaminated vapors are then removed by vapor phase

Table 5 Remedial effect criteria (EF1–EF4). Only the indicators that are relevant for the assessed contaminated site are included

1st-level sub-criteria	Evaluation method	Unit
EF1: groundwater	Reduction in contaminant mass discharge to groundwater	Fraction
EF2: surface water	Reduction in contaminant mass discharge to surface water	Fraction
EF3: soil	Reduction in contaminant mass/concentrations	Fraction
EF4: indoor air	Reduction in concentration/mass discharge to indoor air	Fraction

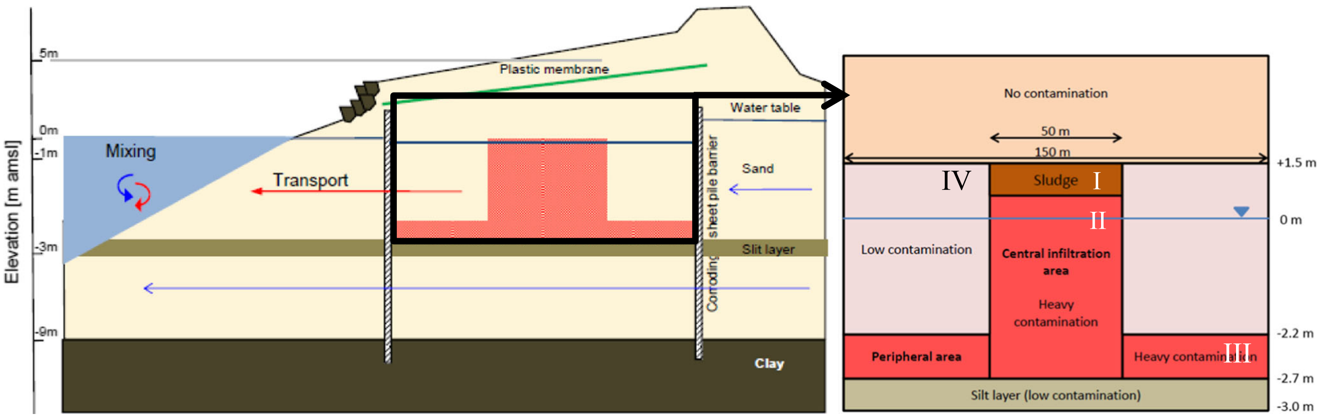


Fig. 3 Vertical transect of the site. The red area in the left hand side figure indicates the target zone for the remedial action. A detailed description of the contaminated area is seen on the right hand side: I highly contaminated sludge; II hot spot with heavy contamination; III peripheral area with heavy contamination; IV area with low contaminant levels (Figures from Fjordbøge et al. 2014)

extraction and treated in a thermal oxidizer, which incinerates the contaminants at a temperature above 1000 °C. The thermal treatment takes approximately 9 months. With installation and decommissioning the total timeframe is about 2 years. The thermal method is expected to have a high removal effect for the pesticide contaminants, but is not expected to remove the mercury. The system requires a network of 386 steam injection wells and 59 extraction wells. Prior to treatment the top 1 m is excavated from the site together with the contaminated sludge layer. The sludge layer is sent for external thermal treatment (see description under "Excavation" alternative). A concrete cover is then constructed over the site. The excavated sand is placed on top of the concrete cover before treatment starts.

2.4.4 Alternative 4: excavation, off-site treatment and disposal

In order to excavate the contaminated soil, the existing sheet pile wall needs to be strengthened and the groundwater table must be lowered by 4 m. The abstracted groundwater is treated by activated carbon. The contaminated soil is transported to an external treatment facility where a thermal treatment at 1100 °C is conducted. In this scenario, the residuals from the treatment are transported by ship to a Norwegian disposal site. The excavated pit at Groyne 42 is refilled with clean sand to reestablish the beach. The timeframe for the excavation including preparations and refilling is around 2 years.

2.5 Stakeholder participation and derivation of criteria weights

The contaminated site is a part of a recreational beach area along the west coast of Denmark used for fishing, swimming, hiking etc. The existence of the contamination has led to a local ban of swimming and fishing at the Groyne 42 site and is a general blight on the area. A stakeholder workshop was arranged with the participation of 10 stakeholders representing government authorities at different levels, local residents representing users of the site, relevant NGOs, and local industry. In addition a "reference group" of regional authorities in parallel participated in the workshop. The site and the remedial alternatives including their cost and expected remedial effects were presented in order to provide the stakeholders with a sufficient background. The stakeholders were then divided into two groups, which were each asked to rank the 5 main criteria according to the importance of the criteria. Rank order distribution theory (Roberts and Goodwin 2002), was used to transform the rankings into a set of criteria weights. Subsequently the groups used an analytical hierarchy process (Saaty 1987) to conduct a more detailed assessment of the relative importance of the main criteria. In the analytical hierarchy process, the importance of two criteria is evaluated on a 1–9 scale, where a score of 1 is given for criteria having equal importance and 9 is given if one criterion has extreme importance compared to the other. The analytical hierarchy process can also be used as a method for criteria scoring; however, here it was applied only for determination of criteria weights. Stakeholder weights were also determined for the five environmental sub-criteria and the four social sub-criteria respectively. The weighting of sub-criteria was exclusively done by rank order distribution (ranking of the criteria) and not by the analytical hierarchy process. In addition stakeholder input from the workshop was used to score the impact of the remediation alternatives on the reputation of the local area (S5).

3 Results

3.1 Criteria weights derived by stakeholders

Each of the two stakeholder groups reached consensus on the ranking of criteria. The resulting criteria weights are quite similar for the two groups (Fig. 4). Both stakeholder groups found that social impacts and remedial effect were the two

Table 6 Key data for the four remediation scenarios

	Continued encapsulation	In situ alkaline hydrolysis	In situ thermal treatment	Excavation, external treatment, and disposal
Consumables	On site - Electricity: 22 MWh/year, in total 2200 MWh - Activated carbon: 2 tons/year, in total 200 tons - Steel: 900 tons per renewal, in total 2700 tons - Diesel: 24.700 l	On site: - Diesel: 17.970 l - Electricity: 170 MWh - Sodium hydroxide: 3100 tons - Sodium sulfite: 5 tons - Polyethylene: 32 tons - Steel: 7,3 tons Off-site water treatment: - Electricity: 280 MWh - Steam: 3700 tons - Sodium hydroxide: 370 tons - Hydrochloric acid: 550 tons	On site: - Diesel: 202.400 l - Natural gas: 145.746 GJ - Electricity: 2.800 MWh - Water: 36.400 m^3 - Activated carbon: 110 tons - Steel: 32 tons - Stainless steel: 1,3 tons - High temperature grout: 130 tons - Fiberglass: 850 tons - Foam concrete: 4900 m^3	On site: - Steel: 44 tons - Diesel: 286.800 l - Electricity: 306 MWh - Activated carbon: 76 tons Off-site soil treatment and disposal and transport: - Truck transport of soil: 264 km (48.988 tons) - Shipping of soil 525 km (38.014 tons) - Energy (Fuel oil) for soil treatment: 117.570 MWh - Activated carbon: 50 tons - Diesel (for disposal of soil): 34.300 l
Costs	53 MDKK	91 MDKK	107 MDKK	216 MDKK
Time use (at site)	Indefinite, but 100 years used in the calculation of consumables and costs. Remedial effect at current time, since wall already in place	8.5 years	2.2 years	2 years
Remedial effect (percent of contaminant mass removed)	Pesticide products: 0% (100% containment effect) Mercury:0% (100% containment effect)	Pesticide products: 90% Mercury:10%	Pesticide products: 99% Mercury:0%	Pesticide products: 100% Mercury:100%

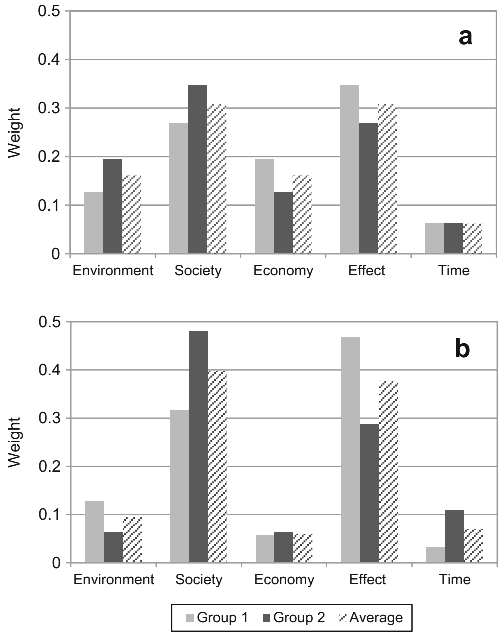


Fig. 4 Criteria weights derived by the two stakeholder groups based on **a** criteria ranking and **b** the analytic hierarchy process. The figures show the resulting weights from each group as well as the average. The weights in each set sum to one

most important criteria, whereas environmental impacts, economy, and time were less important. Two weighting methods were used, and it is evident that the analytical hierarchy process weights give a larger span in the final weights. This is due to the fact that the analytical hierarchy process makes it possible to express how much more important one criterion is than another. Resulting sub-criteria weights are available in the Electronic Supplementary Material (ESM). Average weights of the two groups (see Fig. 4) were applied in the calculation of the total sustainability score in Section 3.3. The reference group made a similar ranking, and obtained almost the same results (data not shown).

3.2 Performance of remediation alternatives

Figure 5 shows the normalized scores obtained for each of the 5 main criteria. It also shows the contribution of each sub-criteria to the total score. The specific scores for each sub-criteria are available in Table S1 to S8 in the ESM. The scores are normalized to a value between 0 and 1 as described in Section 2.3. The higher the normalized score, the worse the alternative performs on the criteria. It should be noted that the environment and society sub-criteria have been weighted according to the stakeholder derived weights.

The excavation alternative has the worst score for the environmental impact criteria. This is mainly due to the environmental impacts to air and water, the large amount of waste generated, and the large resource use. It also performs worst on the economic criteria as it has the highest cost. But the excavation option performs best on the social score partly due to the fact that stakeholders evaluate it to have a very positive effect on the reputation of the area. The two in situ options (alkaline hydrolysis and thermal treatment) are the options have the least environmental impact of the options. Continued encapsulation has the highest social impacts because it does not impact the reputation of the local area positively since it maintains the *status quo*. The encapsulation strategy also performs poorly on human health impact because of the large amount of steel required to maintain the sheet pile wall.

The remedial effect is evaluated using four sub-criteria as shown in Fig. 5. The criteria evaluate the reduction of the discharge of pesticides and mercury to the ocean and the reduction of the soil concentrations of these contaminants. The containment option, the alkaline hydrolysis option, and the thermal treatment all have normalized scores of 0.5. The containment option has the maximum score for reduction of the contaminant discharge to the ocean, but minimum scores for reduction of soil concentrations. The alkaline hydrolysis reduces pesticide leaching by 90% and mercury leaching by 10%. At the same time it reduces soil concentrations by the same percentage. In situ thermal treatment is more effective in reducing pesticides (99%), but does not remove mercury. The excavation option effectively removes all pesticides and mercury in the remediation target zone and therefore obtains the maximum score.

3.3 Ranking of remediation alternatives based on the total sustainability score

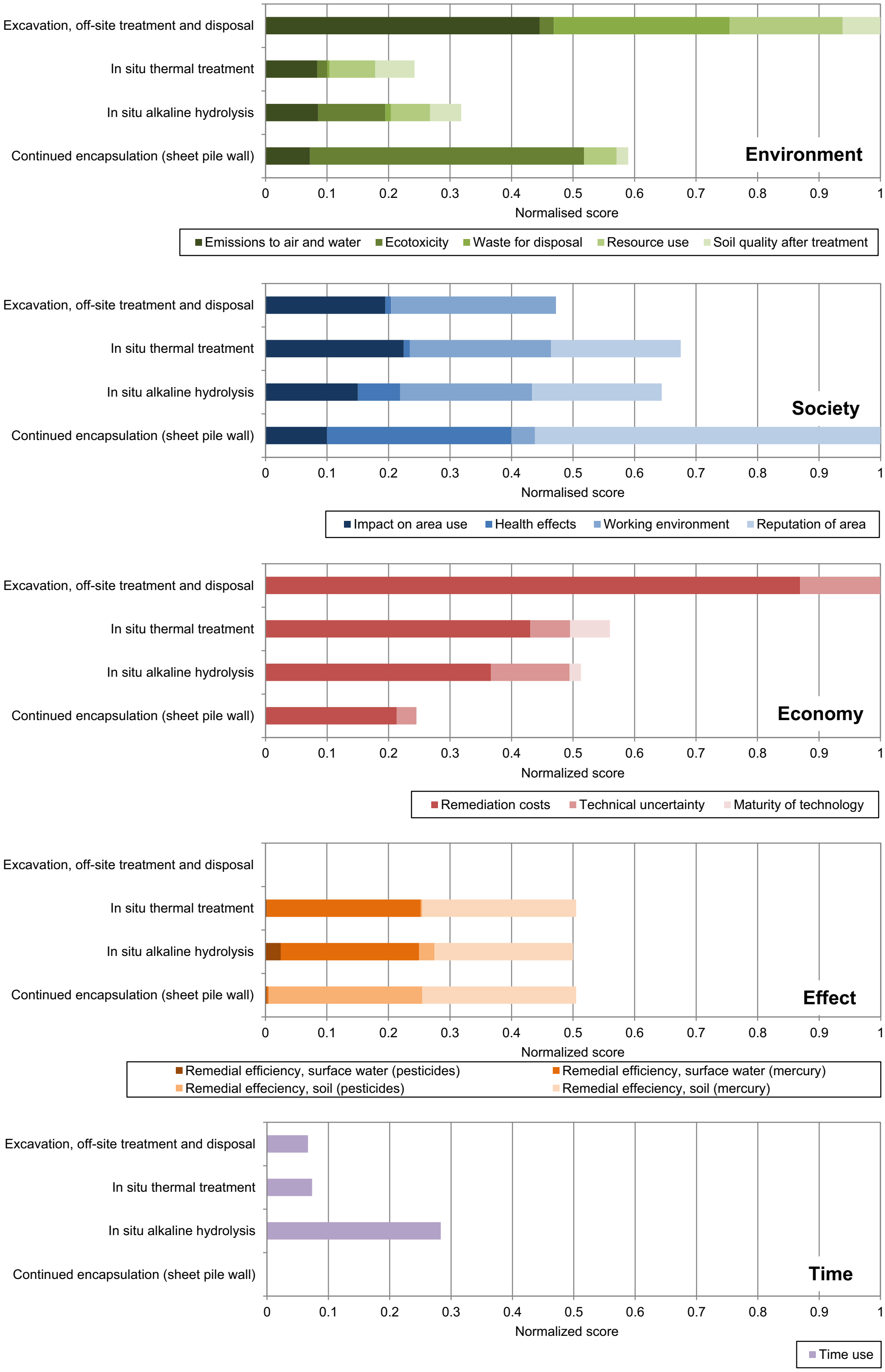
The total sustainability scores of the four alternatives were calculated as the weighted sum of the scores in the 5 main criteria. This was done using both the average weighting set established by ranking (Fig. 6b) and by the analytical hierarchy process (Fig. 6c). The unweighted total scores are shown in Fig. 6a.

The unweighted results show that all alternatives have a relatively similar performance with total scores ranging from the best score at 0.42 (thermal treatment) to the worst score at 0.52 (excavation). When the ranking-based criteria weighting is applied (Fig. 6b), the overall ranking of the alternatives shifts, with excavation now becoming the best ranked technology, and continued encapsulation ranking last. Furthermore, the difference in total scores becomes greater. This shift is even more pronounced when the criteria weights based on the analytical hierarchy process are applied (Fig. 6c).

4 Discussion

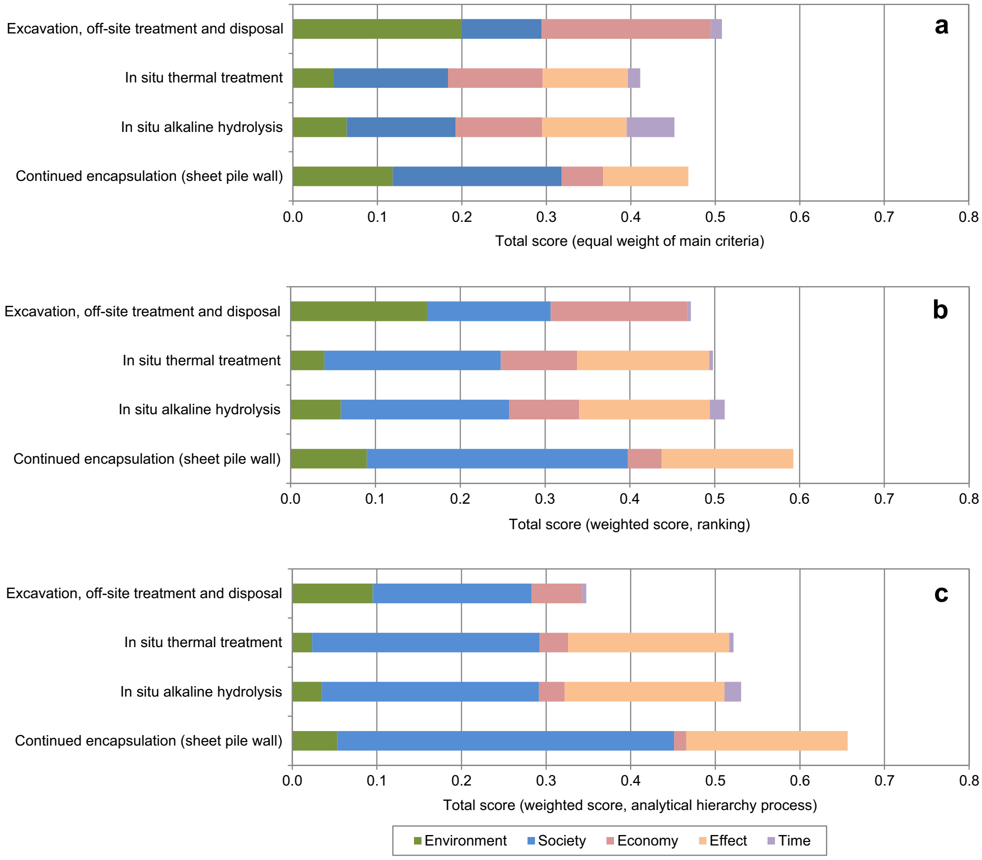
The multi-criteria method presented here for sustainability appraisal of contaminated site remediation considers a number

Fig. 5 Normalized scores obtained for each remediation alternatives



of criteria categorized under economic, social, and environmental criteria headings. In order to emphasize the importance of remedial effect and remediation time as decision parameters, the method includes these two additional criteria headings. The economic criterion in this method includes only direct costs and added costs due to uncertain aspects. Other costs and benefits were covered in the social, environmental, and effect categories depending on their type. One of the advantages of a multi-criteria assessment is that it is not necessary to quantify all impacts in monetary terms as required in a cost-benefit analysis (CBA). CBA on the other hand has the advantage that it can be used to assess whether a given

Fig. 6 Total sustainability scores obtained for the four remediation alternatives. **a** Equal weighting of main criteria; **b** stakeholder weights based on ranking; **c**: stakeholder weights based on analytical hierarchy process



remediation project has an overall net benefit in monetary terms. However, as discussed in Söderqvist et al. (2015), even if all costs and benefits can be monetized, the overall net benefit could still be questioned as decision support. This is due to the fact that welfare economics (and thus CBA) founds itself on monetization based on human preferences, which may leave out intrinsic values in nature as well as the value of people's right to a good health. Therefore, Söderqvist et al. (2015) suggests that CBA does not stand alone, but is combined with MCA for a more complete sustainability assessment.

Stakeholder views were employed in the decision process both to derive criteria weights and to assess the social criteria involving the impact on the area's reputation. The results of the sustainability appraisal for the Groyne 42 case are highly dependent on the applied criteria weights. When stakeholder derived weights were employed, a very different final ranking of the remediation alternatives was obtained than when equal weighting of criteria was applied. This has also been observed in other case studies involving stakeholders, for instance Sparrevik et al. (2011). This will of course be dependent on the composition of the stakeholder groups, and it is important to consider carefully how the members are selected and how representative they are. In this case, the stakeholder group had a local bias, because national authorities declined the invitation to participate. The local representation of stakeholders does not seem to affect results as the third group (reference group with regional authorities) obtained a similar ranking as the two stakeholder groups. Strong individuals can also affect rankings, but in this case a very similar ranking was observed in the two groups working in parallel.

Stakeholder involvement is important for gaining public acceptance and support for remediation alternatives. In accordance with previous studies (Sorvari and Seppälä 2010; Sparrevik et al. 2011), this study found that the multi-criteria decision process enables efficient communication between different stakeholders and identifies the preferred option. The stakeholder process for Groyne 42 showed that selecting of one of the methods with a lower environmental impact and cost may not be a viable solution for this site since these alternatives are less likely to gain public acceptance. The results of the stakeholder involvement process show that the cheaper remediation options might not be worth the cost since the added societal value as perceived by the stakeholders is very low. This is especially due to the fact that the cheaper in situ options does a poor job of removing mercury, which is a major concern for the stakeholders.

The excavation option is the option that obtains the lowest overall score and thereby is found to be more sustainable for this site. However, this does not mean that this method is sustainable or green. The linear additive method is a compensatory multi-criteria assessment method were low scores for some criteria may be compensated by high scores for other criteria. If the excavation alternative is selected for this site, then results indicate that it is important to investigate whether the environmental impacts of this method can be reduced by methods such as local soil treatment and recycling of treated soil. A study on optimizing the environmental performance of in situ thermal remediation technologies (Lemming et al. 2013) has shown that LCA can be used to identify and test possible environmental improvements to the remediation technology.

The economic criteria consider the cost of remediation. The estimated costs depend on whether a net present value (discounted cost) or undiscounted cost is reported. This issue is mainly relevant for the continued encapsulation option since it has a timeframe of 100 years because of on-going operation and maintenance. In the presented results, an undiscounted cost is calculated for all technologies. For the encapsulation option the cost was also calculated using a fixed discount rate of 5% and a time varying discount rate starting at 4% and ending at 2% (as recommended by the Danish Ministry of Finance, Finansministeret 2013). Results (not shown) showed that applying either of the discounting methods did not affect the ranking since the cost of the encapsulation option was much lower than remaining methods, and because the economic criterion was given a low weight by stakeholders. The potential benefit of increased employment opportunities due to remedial activities was not included in the tool. This could be added in future. For the case study in this paper, employment opportunities would be highest for the 3 active remediation scenarios and lowest for the encapsulation scenario, which already is ranked as the least sustainable choice when stakeholder weights are considered.

The Groyne 42 case indicates that stakeholders, technology developers (consultant companies, researchers), and environmental authorities may have different interests and perspectives on the remedial solutions. The stakeholders preferred a solution completely removing all contaminants, but also considered the potential for local employment (excavation, transport of soil), although this was not a criterion. Furthermore, they viewed advanced in situ technologies as complicated solutions with long-time frames and large uncertainty. This suggests that stakeholders, and in particular stakeholders with strong local interest, may prefer labor intensive solutions, and less advanced technologies compared to consultant companies and authorities which tend to prefer advanced in situ technologies and cheaper long-term solutions.

A major practical outcome of the case study was that the regional authorities recommended “excavation, off-site treatment, and disposal” as their preferred solution. This was approved by elected regional government representatives who acknowledged the involvement of the stakeholders in their handling of the case. However, the final decision has been postponed due to budget deficits and on-going political debate on the Danish policy for risk assessment and remediation of contaminated sites. The next step for the site, following the decision by the regional authorities, will be to improve the environmental foot print and the cost of the preferred solution.

This study focused on stakeholder involvement as an important aspect of assessing sustainable remedial actions. However, the outlined framework for sustainability appraisal can also be used without involving stakeholders. In this case, decision makers may do the weighting of criteria, or predefined stakeholder profiles with different preferences can be evaluated as done by Sparrevik et al. (2012).

5 Conclusions

A multi-criteria assessment method was developed in order to improve and support decision-making for the selection of remedial techniques for contaminated sites. The tool compares the sustainability of remediation alternatives by considering remedial effect, remedial time, secondary environmental impacts, societal impacts, and economy in an overall assessment. Previous multi-criteria methods typically placed the remedial effect as a sub-criterion under the environment or society heading. In the developed tool, remedial effect is one of 5 main criteria, acknowledging the fact that remedial effect is a main decision parameter for decision makers and stakeholders. This structure makes interpretation of criteria scores more transparent and allows decision makers and stakeholders to weight the remedial effect and the secondary environmental impacts independently.

For the Groyne 42 case study, the excavation option was assessed by the MCA to have the lowest overall score and was therefore found to be the most sustainable option. The low score was mainly due to the fact that excavation effectively removes both pesticides and mercury, leading to a good score on effect, a criterion given large weight by stakeholders. Furthermore, the negative social impacts of this option were lower than for the other options. However, results show that the excavation option has the highest environmental impact and the highest cost.

The MCA method can be used to both select the best remediation technology and to guide the search for improvements. For the Groyne 42 case, results show that it is very important to consider options for reducing the environmental impact of excavation, for instance by local treatment and recycling of soil. This paper has considered four remediation options for the case study site. The results of the sustainability assessment and the stakeholder participation process suggest that the continued encapsulation and the in situ options do not provide valuable outcomes for stakeholders. The next step will be to reduce costs and environmental impact of the “excavation, off site treatment and disposal” solution; however, further remedial actions are pending the final political decision on the Groyne 42 site.

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