Efficient Remediation of Contaminated Sites - A Literature Review

CHALMERS
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SUMMARY

The Swedish Environmental Protection Agency (SEPA) is concerned over the slow progress, low level of innovation, and high cost of publicly funded remediation projects in Sweden. More efficient and effective remediation of the estimated 1300 high-risk sites is needed if the national environmental objective, *A Non-Toxic Environment*, is to be met. Cleanup of contaminated sites, while reducing risks to human health and the environment, are known to have significant negative effects, including greenhouse gas emissions, disturbance to communities, and production of large amounts of waste to landfills. This has led to increased focus in the past decade on the sustainable remediation concept, accounting for the contradictory secondary effects of remediation. A number of sustainability assessment tools and methods are now available to assess the sustainability of remediation alternatives, including the SCORE (Sustainable Choice Of REmediation) method, developed at Chalmers. It is unclear, however, if sustainability assessment leads to increased remediation efficiency and effectiveness. The main objective of the literature review is to study how remediation efficiency and effectiveness are defined in literature and to map out possible indicators to be used in further study. It was found that remediation efficiency and effectiveness can be conceptualized on three levels: technical, project and national. Efficiency indicators focus on productivity in terms of outputs vs inputs, whereas effectiveness indicators focus on reaching specified goals or outcomes. Chosen indicators should include consideration of both risk reduction, time and costs, as well as project specific goals. Comparison of sites of differing size and characteristics with respect to efficiency and effectiveness is likely difficult given indicators considering diverse aspects.

Keywords: sustainable remediation, sustainability assessment, decision support tool, contaminated land management, efficient remediation, effective remediation

Contents

Preface

This literature review has been carried out at the Department of Architecture and Civil Engineering, Division of Geology and Geotechnics at Chalmers University of Technology in Gothenburg, Sweden. The work has been supervised by Docent Jenny Norrman and Professor Lars Rosén. The report is part of a PhD project within the SAFIRE research project funded by the Swedish Research Council FORMAS (Contract no 210-2014-90).

Göteborg, December 2017
Robert Anderson

1 Introduction

This literature review is performed as part of the SAFIRE research project, funded by the Swedish research council FORMAS. The main objective of SAFIRE (Sustainability Assessment For Improved Remediation Efficiency) is to evaluate if sustainability assessments can improve the efficiency of contaminated site remediation. The project stems from the Swedish Environmental Protection Agency's (SEPA) concern over the slow progress, low level of innovation, and high cost of publicly funded remediation projects, see e.g. (SEPA, 2017; SGI, 2015)

A first step is to investigate how efficiency in remediation is presently defined and measured in literature. In this literature review "remediation efficiency" is considered in a very broad sense, with consideration of different types of literature, from technical papers on specific treatment types, to national reports on remediation progress.

1.1 Background

It is estimated that there are 80,000 potentially contaminated sites in Sweden, where approximately 1300 are considered to pose substantial risk to human health and the environment (Rosén, 2014). While this may seem high for a relatively small population, it is linked to the country's prosperous industrial history over the past century. Contaminated sites in Sweden are often former industrial sites from the wood, mining, automotive and chemical goods industries, amongst others. It can be said, however, that the soil contamination situation in Sweden is mirrored in many other industrialized countries in Europe and North America.

The Swedish EPA is the national authority dealing with contaminated sites, with publicly funded remediation having begun in the 1980's (SEPA, 2014). The current funding program started in 1999, and is used on sites where there is no legally liable private owner or operator of the contaminated site. The over-arching goal of the program is to meet the Swedish environmental objective, *A Non-Toxic Environment*, one of 16 environmental quality objectives put in place by the Swedish government (SEPA, 2012a). So far only a small fraction of the identified national sites have been completed, and at a very high average cost of 40million Swedish Kronor (WSP, 2013). Reaching the 2050 target of having all sites with significant risks remediated is therefore in question.

Soil remediation reduces negative impacts from contaminants on humans and ecosystems, however the process itself often results in other negative effects, such as large environmental footprints and high costs to society. The most common remediation technique used in Sweden, as well as in many other countries, is excavation and disposal, so called “dig and dump” (SEPA, 2006). The technique is often used due to the wish for a quick and simple solution, however, it is associated with high costs, large emission of greenhouse gases and waste production, use of non-renewable natural resources, and significant noise and dust on-site. (Kuppusamy et al., 2016; USEPA, 2008a)

As a result of the known contradictory effects of remediation, increased focus on implementing sustainable remediation solutions has been seen internationally in the past decade, (see e.g. Bardos, 2014; Bardos et al., 2011; USSRF, 2009; ISO, 2017). Different frameworks, methods and tools have been proposed to evaluate remediation projects holistically, typically assessing sustainability within three dimensions; Environmental, Social, and Economic. An ISO standard has been developed to give general procedures on sustainability assessments for remediation projects. The SCORE (Sustainable Choice Of REmediation) method, developed at Chalmers, is a multi-criteria decision analysis tool for assessing sustainability of remediation alternatives, incorporating cost-benefit analysis and uncertainty analysis (Rosén et al., 2015). The SCORE method has been applied on six case study sites in Sweden to date, including both publicly-funded and private exploitation sites.

Incorporating assessment of sustainability is thought to lead to more balanced decisions on remediation options, and could be expected to be a future requirement for publicly funded remediation projects in Sweden. The Swedish EPA’s need to implement more innovative remediation solutions, completed at a lower cost and in less time in order to reach the environmental objective, should at the same time lead towards sustainable development. The goal of the SAFIRE project is therefore to see how sustainability assessments affect the efficiency of site remediation. A first required step is to see how efficiency in remediation is currently considered and how it can be assessed and measured. A question is if efficiency solely covers time and costs, i.e. more traditional metrics, or if it can be considered in other ways.

1.2 Aim and Objectives

The overall aim of this report is to provide a literature review on sustainable and efficient remediation of contaminated sites. The specific objectives are:

- To give an overview of how Swedish remediation projects are presently conducted;
- To describe sustainable remediation and its progress worldwide;
- To present how remediation efficiency is defined in literature and map out possible efficiency indicators to be used in further study.

1.3 Structure and Limitations

The report follows the structure shown in Figure 1 below. Section 2 gives background on the remediation process in Sweden and a short overview of remediation techniques in general. Section 3 covers sustainable remediation and available assessment tools and methods. Section 4 contains the literature study on efficient remediation, with associated discussion and conclusions in Section 5.

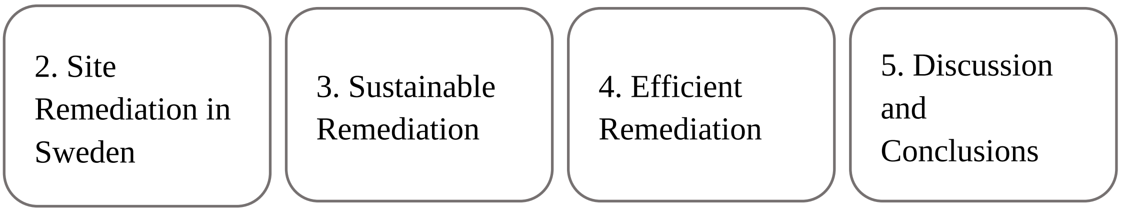

Figure 1. The structure of the report.

A number of limitations must be considered throughout the report. Sections 2.1 includes only a summary of the remediation process in Sweden. Section 2.2 includes only the most-commonly used remediation techniques. Section 3.3 lists only a number of the available decision support tools. Section 4.5 on the efficiency of national remediation programs is limited to Sweden, Canada, and the United States.

2 Contaminated Site Remediation in Sweden

2.1 The Remediation Process in Sweden

The Swedish Environmental Objectives

The Swedish EPA's generational goal, guiding environmental action in Sweden, is to hand over to the next generation (year 2020) a society in which the major environmental problems are solved and where problems are not increased outside Swedish borders (SEPA, 2012a). To accomplish this, 16 environmental quality objectives have been adopted by the Swedish Parliament. Detailed descriptions can be found on the Environmental Objectives website[1]. The main environmental objective linked to contaminated sites is *4. A Non-Toxic Environment*, which states that:

"The occurrence of man-made or extracted substances in the environment must not represent a threat to human health or biological diversity. Concentrations of non-naturally occurring substances will be close to zero and their impacts on human health and on ecosystems will be negligible. Concentrations of naturally occurring substances will be close to background levels."

Within the objective, it is specified that contaminated sites are to be remediated to such extent that they pose no threat to human health or the environment (SEPA, 2016a). The objective *A Non-Toxic Environment* will not be reached by 2020, which has led to the proposal of the following stage goals specifically concerning contaminated sites:

- At least 25% of sites with very large risk (Risk Class 1) to human health or the environment are remediated by year 2025.
- At least 15% of sites with large risk (Risk Class 2) to human health or the environment are remediated by year 2025.
- The use of other remediation techniques than excavation and disposal, without pre-treatment of masses, increased by year 2020.

These go along with the overall goal formulated by the Swedish EPA for contaminated sites that all sites with very large or large risk to human health and the environment (Risk Class 1 & 2) are remediated by year 2050 (SEPA, 2013a). An explanation of the different risk classes is provided below.

Several of the other environmental objectives also pertain to contaminated sites, including e.g. *8. Flourishing Lakes and Streams,* and *9. Good-Quality Groundwater*. It should also be noted that as there may be conflicts between objectives, e.g. traditional

[1] www.miljomal.se, Accessed 08-08-2016

remediation techniques with large emissions conflicts with the objective of reducing air pollution (*2. Clean Air)*.

The Swedish Environmental Code (Miljöbalken)

The Swedish Environmental Code (Miljöbalken) came into effect January 1st, 1999, with the purpose of promoting sustainable development and ensuring a healthy and sound environment for present and future generations (SEPA, 2016b). It is said to be a more modern, stringent, and broad legislation, replacing 15 previous environmental acts.

Section 10 of the Swedish Environmental Code deals with contaminated sites. There it is stated that the operator, who is presently operating or previously operated a site which is polluted to the extent of posing risk to human or the environment, is liable for investigation and remediation (SEPA, 2012b). A property owner may also be responsible. The above is based on what is often called the "Polluter Pays Principle".

Remediation Tracks

Depending on the situation, remediation projects are initiated by different drivers. The three "tracks" below describe the drivers for project initiation in Sweden:

1. Supervision Track – The property owner or operator has the responsibility to not contaminate. A controlling authority sets requirements for the problem owner to investigate and remediate the site if necessary. An exception is if operation ended prior to 1969.
2. Publicly-Funded Track – In cases where there is no legally liable owner or operator, public funding is used for site investigations and eventual remediation of sites that pose an unacceptable risk. This also includes sites where the government is itself responsible but the organisation that contaminated no longer exists.
3. Exploitation Track – In the case of a change in land-use, such as when a former industrial area is transformed to a residential area, risks must be reduced to levels acceptable for the new land-use. This is common in cities where available land is in high demand. Here it is common for construction companies to purchase a contaminated site and take on full responsibility for the contamination, initiating the investigation and carrying out the remediation privately, under supervision of a controlling authority.

All three tracks have different characteristics with projects completed in different ways. For instance, exploitation projects tend to be completed in much shorter time than publicly-funded or supervision projects. The investigation and risk assessment process, as well as the final result of remediation, is the same for all projects, regardless of the track. (SEPA, 2012b; SEPA 2013a)

Active Parties

A number of active parties are involved in the remediation process in Sweden, at different levels and with different responsibilities, see SEPA, 2013b. A short description of the main parties is found in Table 1 below.

Table 1. Active parties in Swedish remediation projects (SEPA, 2013b).

Active Party	*Roles and Responsibilities*
Swedish Environmental Protection Agency (Naturvårdsverket)	• Coordination, prioritization, and follow-up of remediation work on a national level • Provides guidance to County Administrations and Municipalities • Administers grants • Evaluates impact of grants • Reports to the government and the EU • Participates in European and International forum
County Administration (Länstyrelsen)	• Acts as controlling authority on supervision sites • Gives guidance to Municipalities • Overall responsibility on regional level: inventory, investigation, risk-classification, and prioritization of sites • Distribution of grants in their respective region
Municipality (Kommunen)	• Acts as responsible party on publicly-funded sites • Also acts as controlling authority on supervision sites when operator voluntarily investigates site • Carries out pre-studies and investigations
Property owner or Operator	• Obligated to notify the controlling authority if contamination is discovered on their property • Responsible for carrying out investigations and remediation work if needed
Swedish Geological Survey (SGU)	• Investigates and remediates sites where the government is itself responsible but that organisation who contaminated no longer exists. • Acts as responsible party on publicly-funded sites where the municipality can not

	• Cooperation with the Swedish EPA and SGI to achieve national objective
Swedish Geotechnical Institute (SGI)	• Responsible for research, technical development, and knowledge concerning contaminated sites nationally • Expert support on technical questions to the county administrations and municipalities • Cooperation with the Swedish EPA and SGU to achieve national objective

Inventory of Sites

Identification and inventory of the approximately 80,000 suspected contaminated sites in Sweden is a process primarily performed by the county administrations, guided by the Swedish EPA. Inventory is done according to the MIFO method (Method of Surveying Contaminated Sites), refer to SEPA (1999). The county administrations prioritize sites based on a risk classification scheme, as seen in Table 2. Sites in risk classes 1 and 2 are those prioritized for further invesitgation and potential remediation. The work with inventory of contaminated sites was finished in December of 2015. (SEPA, 2016c)

Table 2. Swedish EPA risk classification. (SEPA, 2016c)

Risk Class 1	Very high risk
Risk Class 2	High risk
Risk Class 3	Moderate risk
Risk Class 4	Small risk

Points of Departure

The Swedish EPA outlines seven points of departure to be considered in the remediation process, in-line with long-term thinking and sustainability. (Brinkhoff, 2011; SEPA, 2013a)

1. Evaluation of environmental and health risks at contaminated sites should be performed in both short and long-term perspectives.
2. Surface water and groundwater are natural resources which are always worth protecting.
3. Spreading of contamination from a contaminated area should neither result in a rise in background levels, nor a risk that the released contamination leads to reduced quality of surface and groundwater in the long term.
4. Sediment and water environments should be protected so that no disruption of the aquatic environment arise, and that species of high protection value are preserved.
5. Soil environments should be protected so that ecosystem functions can be maintained to the extent that is needed for the planned land use.
6. Equal protection levels should be aimed for within an area which, as a whole, has the same type of land use, e.g. a residential area.
7. Exposure from a contaminated site should not alone stand for the whole amount of exposure that is tolerable for a human.

Selection of a Remediation Action

The Swedish EPA provides a step by step framework of the remediation process, from initial investigation to the selection of a remedial action, see Swedish EPA (2009a). This is shown in Figure 2 below.

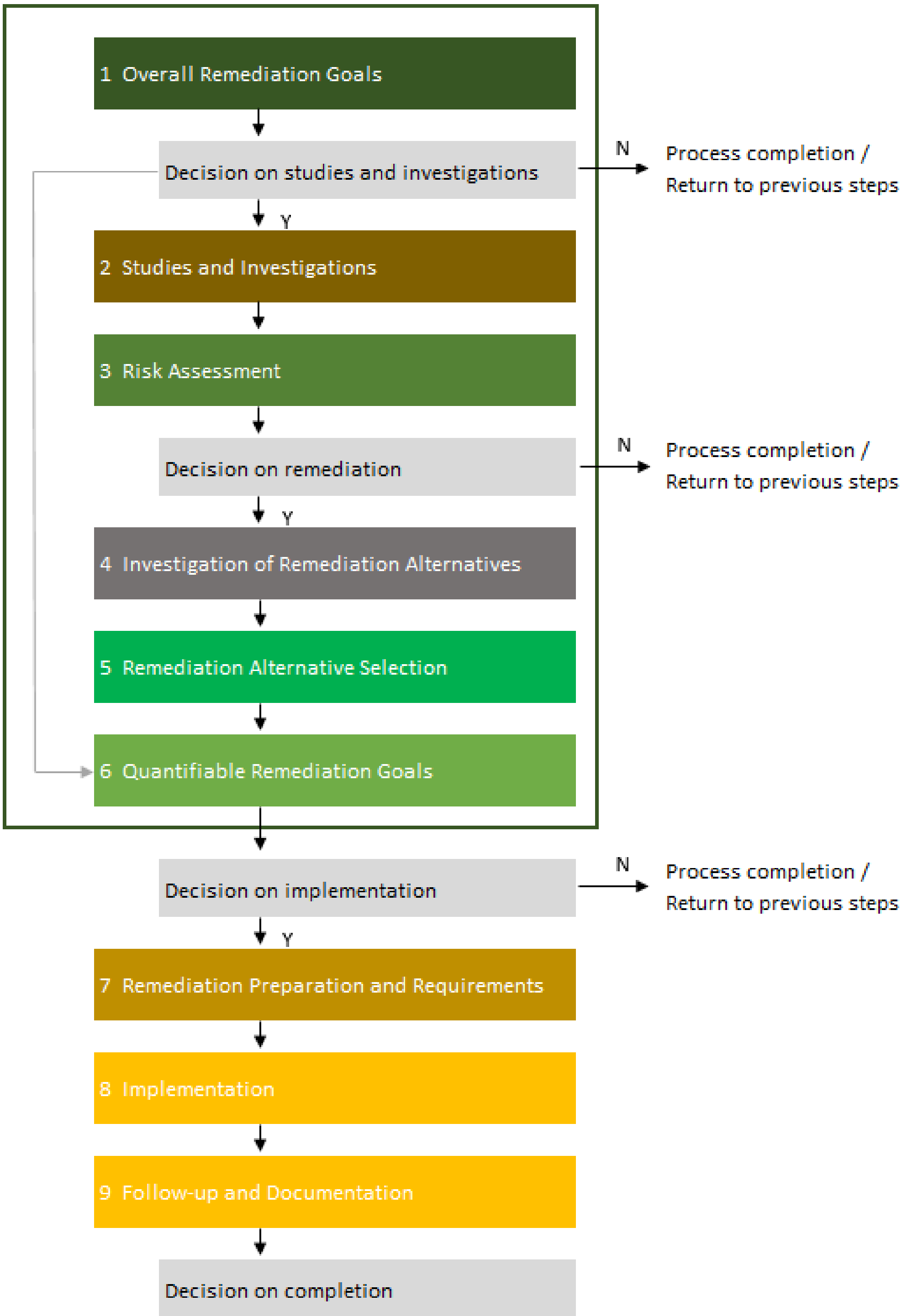

Figure 2. Swedish EPA framework for remediation. Adapted and translated from Swedish EPA (2009a) and Brinkhoff (2014).

The risk assessment step (riskbedömning) (step 3) is completed using the data and results of the investigation phase (step2) and concludes whether site remediation is required. A risk assessment identifies and quantifies the risks that a site poses presently or in the future, and how much risk reduction is required. It also describes potential requirements for remediation, and whether focus is to be placed on the contamination source, transportation and exposure pathways, or recipients, see Figure 3. (SEPA, 2009b)

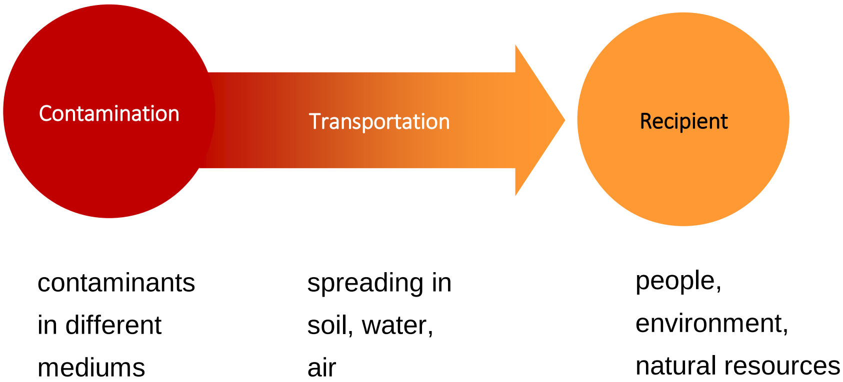

Figure 3. Visualization of contamination source, transport, and recipient. (adapted and translated from SEPA, 2009b)

Risk assessments are based on analysis results of soil sampling and/or water sampling at a site. Representative contaminant concentrations are then compared to guideline values or background levels. The Swedish generic guideline values depend on the expected end land-use for the site, with two different classifications: sensitive land use (KM) and less sensitive land use (MKM) (SEPA, 2009c). Exposure and effect analyses are then performed in order to characterize the risk at a site. Depending on the complexity of a site and its contamination situation, a more in-depth risk assessment may be required (tier 2 assessment). Detailed description of the risk assessment step is provided in a guidance report from the Swedish EPA (SEPA, 2009b).

Feasibility study and investigation of potential remedial action alternatives for a site is performed under step 4 (Åtgärdsutredning). This is based on the outlined remedial goals (Step 1) and the performed risk assessment (Step 3). The feasibility study acts as an important foundation for the selection of alternative (Step 5).

The section of a remedial alternative is performed under step 5 (riskvärdering). Alternatives are assessed based on expected benefits (primarily risk reduction) compared with costs, technical constraints etc. Assessment of alternatives is performed based on prior investigations and remediation goals. The assessment of alternatives should be conducted in close contact between the responsible party, the controlling authority, and other involved stakeholders and in some cases the public. (SEPA, 2009a)

2.2 Remediation Techniques

The choice of remediation technique or strategy at a contaminated site depends on many different factors; contamination type, soil type, site characteristics, groundwater level etc. Time and cost also greatly influence the remediation strategy. The most common remediation type in Sweden is simple excavation and disposal, so called dig-and-dump. The Swedish EPA underwent a detailed study in 2006, reviewing the techniques used on 226 projects in Sweden (SEPA, 2006).

Remediation techniques can be classified under treatment type; Physical, Chemical, Biological or Thermal treatment. Classification can also be made on whether the technique concentrates the contamination (Concentration technique), destroys the contamination (Destruction technique), or immobilizes (Immobilization technique) (SEPA, 2006). In-situ techniques refer to those where the contaminated soil stays in place. Ex-situ are those where the soil is excavated and treated, or simply disposed of. Techniques can be further classified as ex-situ on-site, where the contaminated soil is excavated but then handled at the site or ex-situ off-site where the excavated soil is transported and handled elsewhere.

The US Federal Remediation Technologies Roundtable provides detailed information on remediation technologies in a comprehensive screening matrix (2007). Table 3 summarizes the screening matrix, listing the most common soil, sediment, and groundwater remediation technologies, divided into in-situ and ex-situ techniques, and by treatment type (physical, chemical, biological, and thermal). The table is not exhaustive, with development of new innovative methods from private companies and research institutions ongoing. For the ex-situ technologies it is assumed that either the soil is excavated or that the groundwater is pumped to the surface. For detailed descriptions see the FRTR Screening matrix (FRTR, 2007) and Swedish EPA report (SEPA, 2006).

Table 3. Summary of different remediation technologies (FRTR, 2007).

Remediation Treatment Type	*In-situ*	*Ex-situ*
Physical	• Fracturing • Soil flushing • Solidification/ Stabilization • Landfill cap/ barriers • Air sparging • Directional wells • Dual phase extraction	• Separation • Soil washing • Solidification/ Stabilization • Adsorption/ absorption

	• In-well air stripping	
Chemical	• Chemical oxidation • Electrokinetic separation • Soil vapor extraction • Passive/ reactive treatment barriers	• Chemical extraction • Chemical reduction/ oxidation • Dehalogenation • Precipitation/ coagulation/ flocculation • Ion exchange
Biological	• Bioventing • Bioslurping • Enhanced Bioremediation • Phytoremediation • Monitored natural attenuation	• Biopiles • Composting • Landfarming • Slurry phase biological treatment • Bioreactors
Thermal	• Thermal treatment	• Hot gas decontamination • Incineration • Open burn/ open detonation • Pyrolysis • Thermal desorption

In Sweden, where dig-and-dump projects are so prevalent, alternatives which reduce the amount of transports made off-site to landfill, as well as limiting the amount of backfilling material should be more often considered. For example, sieving and soil washing are methods that can be performed on-site, prior to transportation which reduce secondary environmental effects (air emissions, use of fossil fuels, and production of waste), see Rosén et al. (2015) and Landström & Östlund (2011).

One of the main research goals of the Swedish Geotechnical Institute (SGI) is to focus on new, innovative solutions for remediation of contaminated sites, targeted towards fulfillment of the national environmental objective of a *Non-toxic Environment*. See TUFFO program (SGI, 2017).

Figure 2. Excavation and soil sieving at Hexion site in Mölndal, Sweden. Photo: Åsa Landström (Landström & Östlund, 2011)

3 Sustainable Remediation

The following sections provide background on sustainable development, sustainable remediation, and descriptions of available decision support tools for remediation of contaminated sites. Section 3.4 provides a summary of the SCORE sustainability assessment method, as presented in Rosén et al. (2015).

3.1 Sustainable Development

The publishing of the Brundtland report[2] in 1987 by the World Commission on Environment and Development helped push the need for sustainable development forward, and gave a definition for the concept which is most commonly used today. The first two paragraphs of the report are as follows:

"1. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two concepts:

- *the concept of ´needs´, in particular the essential needs of the world's poor, to which overriding priority should be given; and*
- *the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."*

2. Thus the goals of economic and social development must be defined in terms of sustainability in all countries – developed or developing, market-oriented or centrally planned. Interpretations will vary, but must share certain general features and must flow from a consensus on the basic concept of sustainable development and on a broad strategic framework for achieving it." (Our Common Future, 1987)

The commission was initiated by the General Assembly of the United Nations, based on the conflict seen between economic development and environmental preservation and the first and third-worlds, first acknowledged in the 1970's. The World Bank states the following:

"Sustainable development recognizes that growth must be both inclusive and environmentally sound to reduce poverty and build shared prosperity for today's population and to continue to meet the needs of future generations. It is efficient with resources and carefully planned to deliver both immediate and long-term benefits for people, planet, and prosperity.
The three pillars of sustainable development – economic growth, environmental stewardship, and social inclusion – carry across all sectors of development, from cities

[2] World Commission on Environment and Development, Our Common Future (1987)

facing rapid urbanization to agriculture, infrastructure, energy development and use, water availability, and transportation. Cities are embracing low-carbon growth and public transportation. Farmers are picking up the practices of climate-smart agriculture. Countries are recognizing the value of their natural resources, and industries are realizing how much they can save through energy and supply chain efficiency.
The question facing countries, cities, corporations, and development organizations today is not whether to embrace sustainability but how." (The World Bank, 2017)

The three pillars of sustainable development, or the three dimensions of sustainability are often seen under two models: the Venn diagram model, and the "bull's eye" model (See Figure 5). The Venn diagram model implies that each of the dimensions are equally important and overlapping, while the bull's eye model implies that the economy is a part of human society, which is itself a part of the environment (see e.g. Scott Cato, 2009).

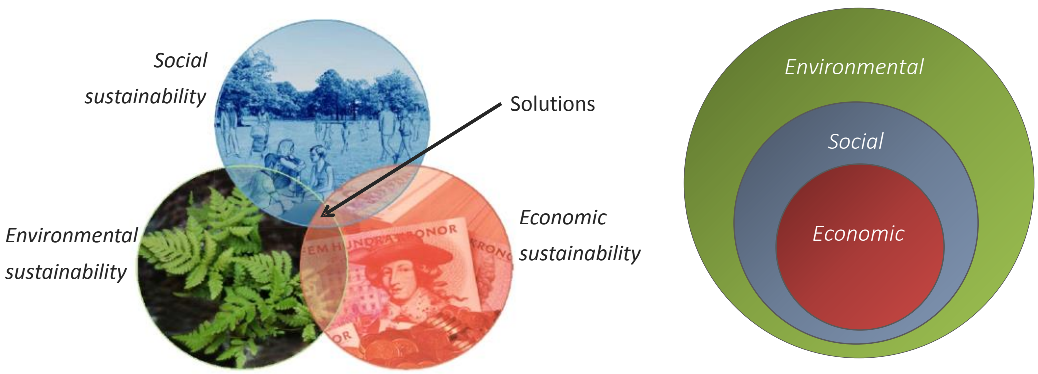

Figure 3. The two common sustainability models; Venn diagram (left) and Bull's eye (right). (Rosén et al., 2015)

The 2030 Agenda for Sustainable Development[3] outlines 17 sustainable development goals (See Figure 6), with 169 accompanying targets (United Nations, 2015). These can be found in more detail on the UN website. The goals came into force in September, 2015, when they were adopted by world leaders at a historic UN summit in New York City. The following is stated about the goals:

"While the SDGs are not legally binding, governments are expected to take ownership and establish national frameworks for the achievement of the 17 Goals. Countries have the primary responsibility for follow-up and review of the progress made in implementing the Goals, which will require quality, accessible and timely data collection. Regional follow-up and review will be based on national-level analyses and contribute to follow-up and review at the global level." (United Nations. 2017)

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[3] A/RES/70/1 – Transforming our world: the 2030 Agenda for Sustainable Development

Sustainable Development Goals (2030 Agenda)

1. End poverty in all its forms everywhere
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3. Ensure healthy lives and promote well-being for all at all ages
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5. Achieve gender equality and empower all women and girls
6. Ensure availability and sustainable management of water and sanitation for all
7. Endure access to affordable, reliable, sustainable and modern energy for all
8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
10. Reduce inequality within and among countries
11. Make cities and human settlements inclusive, safe, resilient and sustainable
12. Ensure sustainable consumption and production patterns
13. Take urgent action to combat climate change and its impacts
14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

Figure 4. The 2030 Agenda for Sustainable Development; Sustainable Development goals. (United Nations, 2015)

3.2 Sustainable Remediation Worldwide

Remediation of contaminated land, or contaminated land management (CLM), has long been considered a sustainable action (Bardos et al., 2011). According to Bardos et al. (2002), remediation of contaminated sites supports the goals of sustainable development by helping to conserve land as a resource, preventing the spread of pollution to air, soil and water, and reducing the pressure for development on greenfield sites. The main drivers for remediation, and the most often quoted positive effects, are the reduction of risks to human health and the environment. However, remediation projects are typically associated with negative effects, such as use of fossil fuels (CO_2 emissions), production of waste, and significant noise and dust on-site. (Bardos et al., 2011; Kuppusamy et al., 2016; USEPA, 2008a)

In the past decade, as a result of the increased awareness of the contradictory effects of remediation, the sustainable remediation concept has grown. Sustainable remediation can be broadly defined as:

"A remedy or combination of remedies whose net benefit on human health and the environment is maximized through the judicious use of limited resources." (USSRF, 2009)

Internationally, different frameworks, methods and tools have been proposed to assess remediation projects. The Sustainable Remediation Forum - United Kingdom (SuRF-UK) propose a framework and set of sustainability indicators as a basis to support sustainability assessment of remediation projects (SuRF-UK, 2010; SuRF-UK, 2011). In 2017, an ISO standard was published on Sustainable Remediation, which is expected to be normative, providing general procedures for these types of assessments (ISO, 2017). In parallel to the development of the sustainable remediation concept, the United States Environmental Protection Agency (USEPA) developed the Green Remediation concept for the national Superfund program (see e.g. US EPA, 2008b; Hadley & Harclerode, 2015). A number of decision support tools (DST) for assessing remediation are available and presented in section 3.3. A number of networks and forums dealing with sustainable remediation exist worldwide. Several of them are described in Table 4 below.

Table 4. Key networks and forums involved in sustainable remediation worldwide.

Network / Forum	Description
Sustainable Remediation Forum (SURF) (United States)	Initiated in 2006 to "promote the use of sustainable practices during cleanup activities" (SURF, 2017). Published white paper (USSRF, 2006) and framework (Holland et al., 2011).
Sustainable Remediation Forum – UK (SuRF-UK)	Initiative set up in 2007 to "progress the UK understanding of sustainable remediation". Published Framework, Indicator Set, and Management Practices amongst others. (CL:AIRE, 2017). Published framework and indicator set (SuRF-UK, 2010; SuRF-UK, 2011).
Common Forum (EU)	Initiated in 1994. Mission includes being a platform for knowledge exchange as well as for discussion on policy, research, technical and managerial concepts of contaminated land in Europe. (Common Forum, 2017)
Network for Industrially Co-ordinated Sustainable Land Management in Europe (NICOLE)	"The overall objective of NICOLE is to pro-actively enable European industry to identify, assess and manage industrially contaminated land efficiently, cost-effectively, and within a framework of sustainability." (NICOLE, 2017)
Interstate Technology and Regulatory Council (ITRC) (United States)	"A public-private coalition working to reduce barriers to the use of innovative air, water, waste, and remediation environmental technologies and processes." (ITRC, 2017)

3.3 Decision Support Tools

A number of decision support tools have been developed to help assess soil and groundwater remediation. A brief description of some of the most common tools are presented below in Table 5. They range in the type of evaluation used, quantitative or qualitative measurement, and in scope i.e. the number of criteria considered, ranging from footprint analyses, to holistic sustainability assessments. It should be noted that the tools mentioned here do not include assessment of total redevelopment but only of the actual remediation process.

Table 5. List of decision support tools for remediation of contaminated sites.

Name	*Description*
CO_2 Calculator (Praamstra, 2009)	• Developed by a consortium of Dutch remediation industry specialists • Environmental footprint (CO_2 emissions) calculator
SiteWise™ (US Navy, 2013)	• Developed by Battelle with the US Navy, U.S. Army Corps of Engineers, and Army • Excel-based tool calculating environmental footprint of remedial alternatives
Sustainable Remediation Tool (SRT) (USEPA, 2016)	• Developed in 2010 by the US Air Force • Calculates energy consumption, emissions, financial costs, and risk of injury to workers
Risk Reduction, Environmental Merit and Costs (REC) (Nijhof et al., 1995)	• Developed in 1995 by a Dutch consortium of remediation industry specialists • Integrates three separate quantitative tools: risk reduction, environmental merit, cost calculation
GoldSET© (Golder, 2017)	• Initially developed by Golder Associates solely for site remediation, but has

	evolved to use in other large-scale infrastructure engineering projects • Multi-Criteria Decision Analysis (MCDA) tool using both quantitative and qualitative input in the three sustainability dimensions: Environmental, Social, Economic • Includes a qualitative evaluation of potential technical performance
VHGFM	• Swedish excel-based decision support tool developed by a consortium of remediation industry specialists • Mainly calculates greenhouse gas emissions (CO_2 equivalents) (Brinkhoff, 2011)
SCORE: Sustainable Choice of Remediation (Rosén et al., 2015) CHALMERS UNIVERSITY OF TECHNOLOGY	• Developed in 2014 by Chalmers University of Technology • MCDA method and tool assessing remediation alternatives in the three dimensions of sustainability, both qualitatively and quantitatively • Includes CBA, uncertainty analysis, and sensitivity analysis • Includes consideration of soil function and project risks
Austrian National Remediation Fund model (Austrian DST) (Döberl et al., 2013)	• Excel tool based on a modified cost-effectiveness analysis • Overall objectives assessed: Environment, Local Development, Project Stability
Decision Aid for Remediation Technology Selection (DARTS) (Khelifi et al., 2004)	• Java based DST developed at UCS-Unido Trieste • Selection of most feasible remediation technology based on MCDA

Decision Support sYstem for Requalification of contaminated sites (DESYRE) (Carlon et al., 2007)	• GIS-based decision support system (DSS) • Structures into six interconnected modules: characterization, socio-economic, risk assessment, technological assessment, residual risk assessment, decision
Decision Support Tool Finland (Finnish DST) (Sorvari & Seppälä, 2010)	• Excel based MCDA DST • Four decision criteria: achievable risk reduction, costs, environmental effects, and other factors
"MCA tool" (Søndergaard et al., 2017)	• Semi-quantitative (LCA), linear additive MCA method • Five criteria: Environment, Society, Economy, Remediation Effect, Time

Due to lack of information available or availability in English, the following tools were excluded from the table above:

- BalanceE3 by Arcadis
- Sustainability Assessment Framework by CH2M Hill
- Sustainable Remediation Assessment Haley & Aldrich
- Effectiveness analysis model for environmental remediation (WILMA)
- Assessments, Benefits and Costs tool (ABC tool)
- Milieuhygienisch, Kosten en Maatschappelijke aspecten (MKM)
- Duurzaamheidsmeter Herontwikkeling Verontreinigde Sites (HVS)

Beames et al. (2014) study how the choice of sustainability appraisal tool, and its respective indicators and methods, affects the end choice of remediation alternative. Four tools were compared and analyzed, all listed and described in Table 5 above; the CO_2 Calculator, the Sustainable Remediation Tool (SRT), the Risk Reduction, Environmental Merit and Costs tool (REC), and GoldSET. The indicators included in each tool were compared with those proposed in the SuRF-UK indicator set and the four tools were used to evaluate potential remedial alternatives on a case study site in Antwerp, Belgium. It was seen that the tool structures, assessment scope, and weighting procedures differed between the tools, influencing the results generated.

Huysegoms & Cappuyns (2017) performed a critical review of thirteen tools specifically developed to assess the sustainability of site remediation alternatives. All these tools are included in the lists above. Analysis was based on six criteria; environmental, economic, and social, based on the SuRF-UK criteria framework, as well as time, uncertainty, and user friendliness. It was found that the three best performing tools in inclusion of criteria from the SuRF-UK framework were GoldSet, SCORE, and HVS. It was found that there was an imbalance in the way sustainability was considered amongst the tools, with environmental criteria generally favoured over economic and social aspects. Inconsistency in terminology used within the field, was also highlighted. The study emphasized the need for tools to be user-friendly, flexible, and transparent.

Cappuyns (2016) studied how social indicators are considered in twelve DSTs for sustainability assessment of remediation projects, based on the SuRF-UK social indicator set. Here it was found that he more recently published DSTs, SCORE and OVAM SB, paid significantly higher attention to social aspects.

A more detailed description of the SCORE method is provided in the following section. SCORE is currently being used as the assessment tool in the SAFIRE research project.

3.4 SCORE: Sustainable Choice of Remediation

The following section presents a summary of the SCORE method as described in Rosén et al. (2015). The reader is referred to the full paper for more detailed description.

SCORE is a Multi-Criteria Decision Analysis (MCDA) method for assessing the sustainability of contaminated land remediation, implemented as an Excel-based tool. The assessment of remediation alternatives is performed within three sustainability dimensions: environmental, social, economic. Alternatives must be specified prior to assessment, meeting the acceptable human health risks and other requirements specific to a site. SCORE provides information on which alternatives lead most towards sustainable development, with alternatives assessed relative to a determined reference alternative, which is typically the null alternative ("*do-nothing*"). The method has been developed to consider sustainability of the remediation strategies and does not focus on sustainability of different end land-uses.

SCORE identifies whether there is compensation between different components of the assessment or not and distinguishes between development towards *weak* and *strong* sustainability (see e.g. Pearce et al., 2006). SCORE also allows for the possibility to reflect different views on the assessment by assigning different weights to the three sustainability dimensions, though they are typically weighted equally. The SCORE framework (Figure 7) was developed in line with the view on the decision-making process of Aven (2012). It shows that the SCORE method supports an iterative working process, of which review and updating of the assessment in conjunction with stakeholders is a crucial part.

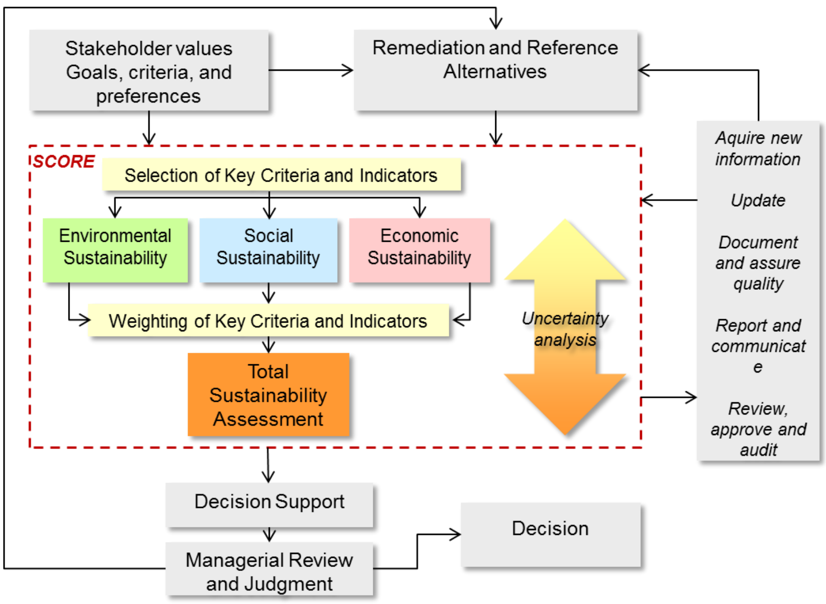


Figure 7. The SCORE decision support framework for remediation projects (adapted from Rosén et al., 2015)

Remediation effects are represented by semi-quantitative scoring in the environmental and social dimensions and quantifications of monetary costs and benefits in the economic dimension. A normalized score is calculated for each alternative using a linear additive approach, taking into account scorings and quantifications of the criteria and the relative importance (weights) of relevant criteria. An uncertainty is assigned to each scoring and quantification, facilitating uncertainty and sensitivity analyses of outcomes.

Conceptual Model

A conceptual model for SCORE is shown in Figure 8, providing a relevant structure for the MCDA, with proper consideration of the sustainability concept and possibilities for clear definitions of the boundary conditions. The conceptual model was developed according to the cause-effect chain concept commonly used in risk assessments. The *cause* of the effects is the remediation taking place at the particular site. The two **stressors** are:

- The **Source Contamination (SC) -** the change in source contamination typically results in positive effects in terms of reduced risks to humans and ecosystems and possibilities for new land utilization.
- The **Remedial Action (RA) -** In some cases (not all) results in negative effects in terms of, e.g., the use of non-renewable energy, accidental risks, air emissions, and impact on soil functions.

The effects associated with the two stressors are considered at different locations, **on-site** and **off-site**. The on-site/off-site boundary is to be defined by the assessment team but is typically the property boundary of the site. The definition is the same for all criteria, and cost/benefit items. The **receptors** of both long and short-term effects are humans, ecosystems, and natural resources.

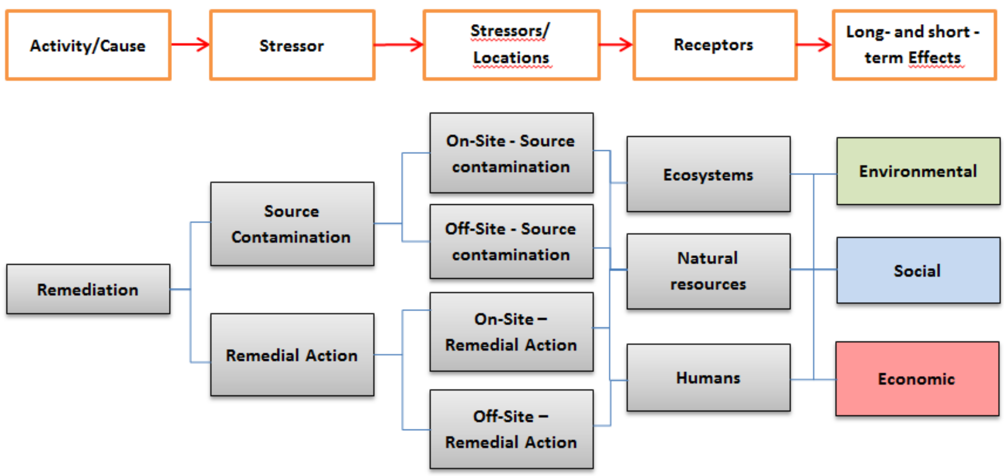


Figure 8. SCORE conceptual model. (Rosén et al., 2015)

Key Performance Criteria

The selection of key performance criteria in SCORE was based on extensive literature reviews, interviews during an expert group workshop (Brinkhoff, 2011), focus group meetings in Sweden (Norrman & Söderqvist, 2013), and an earlier prototype of the method (Rosén et al., 2009). The identified key performance criteria are listed in Table 6. The key criteria in the environmental and social dimensions have sub-criteria representing *on-site* and *off-site* effects as well as effects related to the change in *source contamination* (SC) and the *remedial action* (RA), respectively. The only key criterion in the economic dimension is social profitability, which is assessed by means of a cost-benefit analysis (CBA).

Table 6. Key performance criteria for each sustainability dimension in SCORE. (Rosén et al., 2015)

Environmental dimension	Social dimension	Economic dimension
• Soil • Flora and fauna • Groundwater • Surface water • Sediment • Air • Non-renewable natural resources • Non-recyclable waste	• Local environmental quality and amenity • Cultural heritage • Equity • Health and safety • Local participation • Local acceptance	• Social profitability

Environmental Criteria

The spatial locations of the key criteria in the environmental dimension are presented in Figure 9. Short descriptions are given in Table 7, along with the associated sub-criteria.

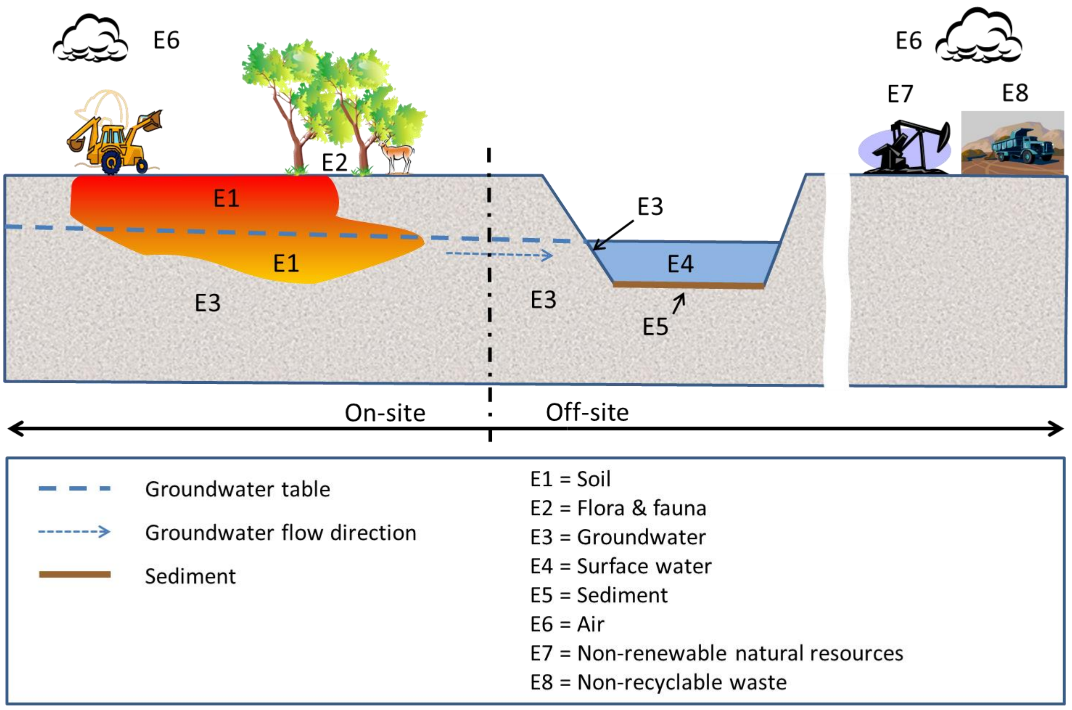


Figure 9. Schematic illustration of the environmental key criteria in SCORE and their spatial locations. (Rosén et al., 2015)

Table 7. Criteria in the Environmental dimension (RA = Remedial action; SC = Source contamination) (Rosén et al., 2015)

Key Criteria	Description	Sub-criteria
E1. Soil	The soil criterion is divided into an *ecotoxicological risk* due to the soil contamination and a *soil function* component. The ecotoxicological risk reflects the effects on the soil ecosystems due to the change in source contamination and/or to impacts of the remedial action. The soil function assessment is directed at evaluating the effects of the remedial action on soil's capability of providing good pre-conditions for organisms, taking into account factors such as soil texture, pH, organic content, availability of nitrogen and carbon, and water retention capacity. Extensive descriptions of the soil function assessment included in SCORE are given by Volchko (2013) and Volchko et al. (2013; 2014a).	Ecotox. risk RA On-site Ecotox. risk SC On-site Soil function RA On-site
E2. Flora & fauna	Physical impacts on e.g. trees, birds and mammal habitats from the remedial action.	Flora & fauna RA On-site
E3. Ground-water	Effects on groundwater quality and ecotoxicological risks in the discharge zone to e.g. wetland areas potentially affected by the source contamination and/or the remedial action.	Groundwater RA On-site Groundwater RA Off-site Groundwater SC On-site Groundwater SC Off-site
E4. Surface water	Effects on surface water quality and ecotoxicological risks in the water zone of surface water bodies and streams potentially affected by the source contamination and/or remedial action.	Surface water RA On-site Surface water RA Off-site Surface water SC On-site Surface water SC Off-site
E5. Sediment	Effects on ecotoxicological risks for organisms in sediments potentially affected by the source contamination and/or remedial action.	Sediments RA On-site Sediments RA Off-site Sediments SC On-site Sediments SC Off-site
E6. Air	Total emissions to air, including greenhouse gases, acidifying substances, and particulate matter, due to the remedial action.	Air RA
E7. Non-renewable natural resources	Total use of non-renewable energy due to the remedial action.	Non-renewable natural resources RA
E8. Non-recyclable waste	Total production of non-recyclable waste due to the remedial action.	Non-recyclable waste RA

Social Criteria

Some of the social effects that arise are related to the change in land use that is made possible by the remediation alternative, rather than due to the actual changes in the source contamination. Short descriptions of key criteria in the social dimension are given in Table 8, with associated sub-criteria.

Table 8. Criteria in the Social dimension (RA = Remedial action; SC = Source Contamination). (Rosén et al., 2015)

Criteria	Description	Sub-criteria
S1. Local environmental quality (LEQ) and amenity, including physical disturbances	Effects on e.g. recreational values, noise or/and the accessibility of the area.	LEQ RA On-site LEQ RA Off-site LEQ SC On-site LEQ SC Off-site
S2. Cultural heritage	Effects on cultural heritage items due to destruction, preservation or restoration, but *not* with regard to the increased access to those items that can be expected from a change in SC and subsequent change in land-use (this is scored in S1).	Cultural heritage RA On-site Cultural heritage RA Off-site
S3. Health and safety	Effects on human health and safety due to exposure and spreading of contaminants in soil, dust, air, water and due to accidental risks (e.g. traffic).	Health and safety RA On-site Health and safety RA Off-site Health and safety SC On-site Health and safety SC Off-site
S4. Equity	Effects on vulnerable groups in the society.	Equity RA On-site Equity RA Off-site Equity SC On-site Equity SC Off-site
S5. Local participation	Effects on how the local community is affected with regard to local job opportunities or other local activities. This criterion does *not* relate to participation of the local community in the remediation decision process.	Local participation RA On-site Local participation RA Off-site Local participation SC On-site Local participation SC Off-site
S6. Local acceptance	Effects with regard to the acceptance of the remediation alternative by the local community. It should be noted that the local acceptance for activities can be improved by open information, dialogue and/or participation processes carried out in an appropriate way.	Local acceptance RA On-site Local acceptance RA Off-site Local acceptance SC On-site Local acceptance SC Off-site

Economic Criterion

The cost and benefit items included in SCORE are shown in Table 9. The social profitability is calculated in monetary terms as a net present value (*NPV*) over the time horizon of the remediation project. See Söderqvist et al. (2015) for a detailed description of the economic assessment methodology.

Table 9. Benefits (B) and costs (C) in the Economic dimension. (Söderqvist et al., 2015)

Main items of benefits and costs	**Sub-items of benefits and costs**
B1. Increased property value on site	
B2. Improved health	B2a. Reduced acute health risks
	B2b. Reduced non-acute health risks
	B2c. Other types of improved health, e.g. reduced anxiety
B3. Increased provision of ecosystem services	B3a. Increased recreational opportunities on site
	B3b. Increased recreational opportunities in the surroundings
	B3c. Increased provision of other ecosystem services
B4. Other positive externalities than B2 and B3	
C1. Remediation costs	C1a. Design of remedial actions
	C1b. Project management
	C1c. Capital costs
	C1d. Remedial action
	C1e. Monitoring
	C1f. Project risks (See Brinkhoff et al., 2015)
C2. Impaired health due to remedial action	C2a. Increased health risks on site
	C2b. Increased health risks from transports activities
	C2c. Increased health risks at disposal sites
	C2d. Other types of impaired health, e.g. increased anxiety
C3. Decreased provision of ecosystem services due to remedial action	C3a. Decreased provision of ecosystem services on site
	C3b. Decreased provision of ecosystem services in the surroundings
	C3c. Decreased provision of ecosystem services at disposal sites
C4. Other negative externalities than C2 and C3	

Since each cost and benefit item represents the quantitative sum of all economic consequences resulting from a particular effect, there is no need for any spatial sub-division of items similar to the environmental and social dimensions. SCORE provides for a distributional analysis, in which the *NPV* for different actors is studied. The assessment team therefore needs to assign the main beneficiary or payer for each cost and benefit item. The distributional analysis is a necessary part of the CBA in order to provide a basis for fair distribution of costs and benefits among involved stakeholders.

Remediation and Reference Alternatives

Remedial alternatives evaluated by SCORE must be specified prior to performing the MCDA and all effects (impacts) are assessed relative to a *reference alternative*. It is up to the assessment team to define the reference alternative but it is typically identical to the *no action* alternative, where no action is taken to reduce the risks to humans and the environment. The identified remedial alternatives must satisfy a number of constraints, mainly time, budget, technical feasibility, legal aspects, and public acceptability, see e.g. Bardos et al. (2001). Only remedial alternatives that meet the objectives within the constraints should be considered. The constraints are project specific and they are not part of the MCDA. The reference alternative does not have to be an acceptable alternative (for example, often the no action alternative is not possible since it is required that some action is taken to improve the situation), but serves as a position against which acceptable alternatives are evaluated and compared. Note that the reference alternative cannot include remediation, since that would lead to invalid assessment of some criteria, most notably E6-E8.

Selection of Criteria

Once remediation and reference alternatives are specified, selection of the key and sub-criteria that are relevant to the analysis must be performed. In the case that a criterion is chosen to be excluded from the assessment, clear motivation should be provided by the assessor or assessment team.

Performance Scales

Scoring of effects (criteria) in the environmental and social dimensions is performed using the following performance scale: Very positive effect: +6 to +10; Positive effect: +1 to +5; No effect: 0; Negative effect: -1 to -5; Very negative effect: -6 to -10. See Figure 10.

The scorings are performed using available data, expert judgment, questionnaires, and/or individual or group interviews. The scoring procedure is supported by a guidance matrix for each criterion with examples as a basis for the assessment. For each key criterion there are also key questions to address and suggestions of key information to collect as a basis for the scoring. The assessment team should assign the score that best represents the expected effect, given the available information and knowledge. Each scoring should be shortly motivated for transparency.

Figure 10. Scoring scale from the SCORE tool.

Cost and benefit items of the CBA are monetized to the greatest extent possible, given the constraints of the assessment. All items identified as relevant but not possible to monetize are assessed as being *somewhat important - (X)* or *very important - X*, allowing for a qualitative assessment of these items and the outcomes of the CBA.

Environmental Assessment

The environmental effects are typically scored based on existing information, such as ecological risk assessments, samplings and laboratory analyses, soil function assessment (see Volchko et al., 2014a), inventories of recipient conditions, and risk analyses of the remedial action, e.g. the risk of spill to a nearby stream from a dam for collecting contaminated groundwater. Scoring of effects on air, non-renewable natural resources and production of non-recyclable waste are based on footprint analyses, e.g. quantifications of air emissions, use of non-renewable fuels, and production of non-recyclable waste.

Social Assessment

Social criteria S1 to S5 are formulated such that they can be scored by experts, whereas *Local acceptance (S6)* is a criterion that should reflect how the local community actually perceives the different remedial strategies. The social effects on S1 to S5 are scored based on existing information, e.g. the human health risk assessment, environmental impact assessment, existing documentation on cultural heritage, but also e.g. on the distributional analysis within the CBA (see below), and stakeholder analysis. However, input from experts is crucial and people with local knowledge should be involved in the scoring of the social criteria. For example, (local) experts on cultural heritage and protection should advise on the scoring relating to S2. Scoring for S6 on the other hand, should consult the local community directly.

Economic Assessment

The net present value (*NPV*) of a remediation alternative *i* is computed as follows:

$$NPV_i = \sum_{t=0}^{T} \frac{1}{(1+r_t)^t} (B_{i,t} - C_{i,t}) \qquad \text{(Eq. 1)}$$

where $B_t = B1_t+B2_t+B3_t+B4_t$ and $C_t = C1_t+C2_t+C3_t+C4_t$ (see Table 9), i.e. the sum of benefits and costs at time t (usually years), r_t is the social discount rate at t, and T is the time horizon associated with the benefits and costs. Given that all costs and benefits have been monetized and thus are included in the *NPV* computation, the remediation alternative associated with the highest *NPV* is the most profitable one to society (or, if $NPV<0$, the one that gives the least social loss).

In many cases all costs and benefits cannot be monetized and it is therefore important to also provide a qualitative discussion concerning non-monetized items. Guidance and a calculation model has been developed for how to monetize each item in the CBA, providing information and recommendations of suitable valuation approaches for the specific item.

A SCORE user may wish to only include a subset of the cost and benefit items in Table 9. For example, an alternative to perform a full CBA may be to focus on the cost side only, using a cost-effectiveness (CEA) approach. A CEA approach can be used if all studied alternatives are expected to reach the goal of the remediation (e.g. to reach acceptable risk levels), if the benefits of the alternatives are similar, and if it is not required that $NPV>0$. The output of a CEA used in a SCORE assessment is the present values of the total costs of the alternatives. As another example, a developer might be interested in delimiting the analysis to the cost and benefit items that are directly related to financial flows (primarily B1 and C1) and can thus choose to delimit the economic assessment accordingly.

Weighting of Criteria

Each key criterion and sub-criterion in the environmental and social dimensions is weighted by the assessment team with respect to their relative importance. The importance I of each key criterion k (k=1…K) in dimension D is given a numerical value according to the following scale: somewhat important = 1; important = 2; very important = 3. The weight of the key criterion is then calculated as:

$$w_{k,D} = \frac{I_{k,D}}{\sum_{k=1}^{K} I_{k,D}} \qquad \text{(Eq. 2)}$$

The importance I of each sub-criterion j (j=1…J) included in key criterion k (k=1…K) is given a numerical value according to the following scale: somewhat important = 1; important = 2; very important = 3. The weight of each sub-criterion is calculated as:

$$w_{j,k} = \frac{I_{j,k}}{\sum_{j=1}^{J} I_{j,k}} \qquad \text{(Eq. 3)}$$

The weights of sub-criteria and key criteria thus have a value [0,1] and the total weight of all criteria (sub-criteria and key criteria, respectively) sum to 1.

For each remediation alternative *i* (*i*=1...*N*) a sustainability index *H* is calculated for each dimension *D* as the weighted sum of the scorings using a linear additive approach:

$$H_{D,i} = \sum_{k=1}^{K} w_{k,D} \sum_{j=1}^{J} w_{j,k,D} Z_{j,k,D} \qquad \text{(Eq. 4)}$$

where w_j is the weight of sub-criterion *j* and *Z* is the score of the sub-criterion *j*. The weighting is performed by the assessment team, taking into consideration judgments and opinions of experts and stakeholders.

In the economic dimension, weighting of benefits and costs is carried out through the monetization in the *NPV* calculation.

Sustainability Index

A normalized sustainability score, *H*, is calculated for each alternative *i* as:

$$H_i = 100\left[W_E \frac{H_{E,i}}{Max[Max(H_{E,1..N}); |Min(H_{E,1..N})|]} + W_{SC} \frac{H_{S,i}}{Max[Max(H_{S,1..N}); |Min(H_{S,1..N})|]} + W_{NPV} \frac{NPV_i}{Max[Max(NPV_{1..N}); |Min(NPV_{1..N})|]}\right] \qquad \text{(Eq. 5)}$$

where H_E is the score in environmental dimension, H_S is score in the social dimension, *NPV* is the net present value, and *W* is the weight of each dimension. The weights of the dimensions are assigned according to the same scale as for the criteria. The normalized score has a value between -100 and +100, where a positive score indicates that the alternative leads towards sustainable development, i.e. more positive effects than negative. The normalized score can be used to rank the alternatives.

Uncertainty Analysis

The treatment of uncertainty in SCORE follows a Monte Carlo simulation approach, where statistical distributions represent the uncertainties in scores and cost-benefit items. Uncertainties are estimated based on professional judgment by the assessment team. Uncertainties in scores are represented by beta distributions and uncertainties in cost and benefit items are represented by log-normal distributions.

The assignment of the scoring uncertainty distribution (beta) is performed in three steps: (1) selection of the possible range of scorings for the specific sub-criterion; the scoring intervals are -10 to +10 if the entire scoring range is possible, -10 to 0 if no positive effects are possible, and 0 to +10 if no negative effects are possible, (2) estimation of the most likely score using the performance scale presented above in Figure 10, and (3) assigning the uncertainty category level of the estimation of the most likely effect; high, medium or low. The three-step procedure results in a scaled beta probability distribution representing the uncertainty of the scoring of the sub-criterion. Uncertainty categories for scores are represented by standard deviation values shown in Table 10. The uncertainty interval representing *high* uncertainty is twice the uncertainty interval representing *low* uncertainty. The uncertainty interval representing *medium* uncertainty is in the middle between high and low uncertainty. An example of beta distributions reflecting high, medium, and low uncertainties for the same score (+2) is shown in Figure 11 below.

Table 10. Uncertainty representations of scorings (Environmental, Social). (Rosén et al., 2015)

Uncertainty category	Range	Standard Deviation
Low	-10 to +10	0.91
	-10 to 0; 0 to +10	0.46
Medium	-10 to +10	1.37
	-10 to 0; 0 to +10	0.68
High	-10 to +10	1.82
	-10 to 0; 0 to +10	0.91

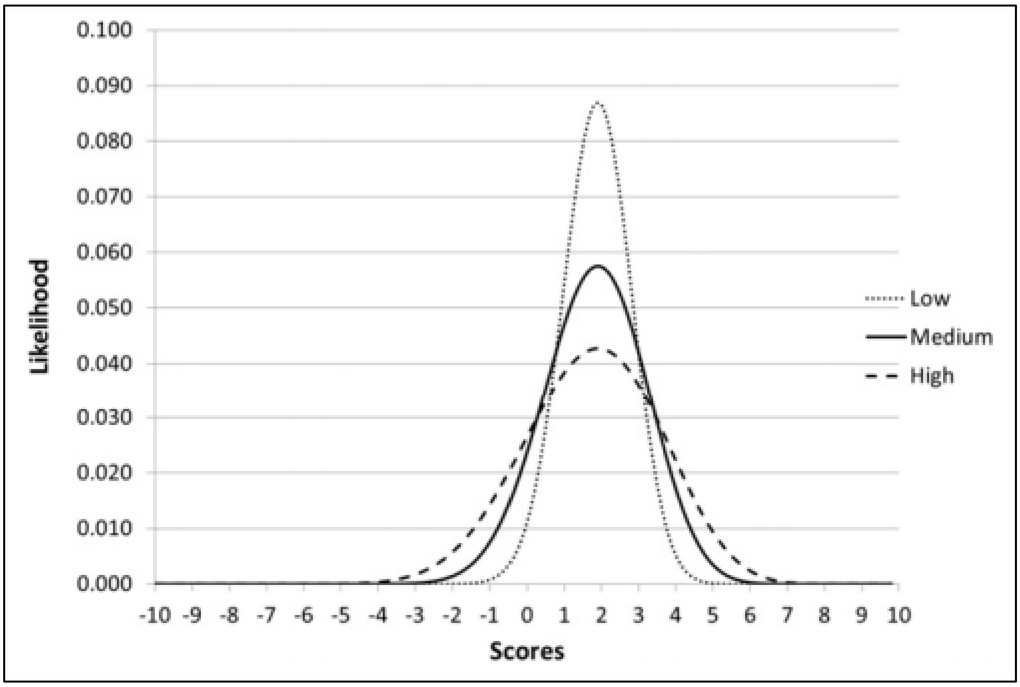


Figure 11. Uncertainty distributions (beta) for a most likely score of +2 with all scores possible (-10 to +10). Low uncertainty (std. dev. = 0.91), medium uncertainty (std. dev. = 1.37) and high uncertainty (standard deviation = 1.82). (Rosén et al., 2015)

The assignment of the uncertainty distribution for costs and benefits is performed in two steps. A user (1) provides the most likely value (*MLV*) of the present value (*PV*) of each of the cost and benefit items and (2) assigns the uncertainty level of the estimation of the *MLV* by choosing one of three different levels of uncertainty: high, medium or low. The procedure results in a log-normal distribution representing the uncertainty of the particular cost or benefit item. The credibility of the interval between the Lower Credibility Limit (*LCL*) and Upper Credibility Limit (*UCL*) is chosen to be 90%. Table 11 illustrates the relative size of this interval for the high, medium and low level of uncertainty. The 90% credibility interval is also indicated in Figure 12 for the three levels of uncertainties given a mode value of *PV* equal to 1 MSEK.

Table 11. The relative size of the 90% credibility interval for the three standard uncertainty levels of cost and benefit items. For example, the credibility interval ranges from 0.60NPV to 2.39 NPV for medium uncertainty. (Rosén et al., 2015)

Uncertainty category	LCL/NPV	UCL/NPV
High	0.52	5.16
Medium	0.60	2.39
Low	0.81	1.27

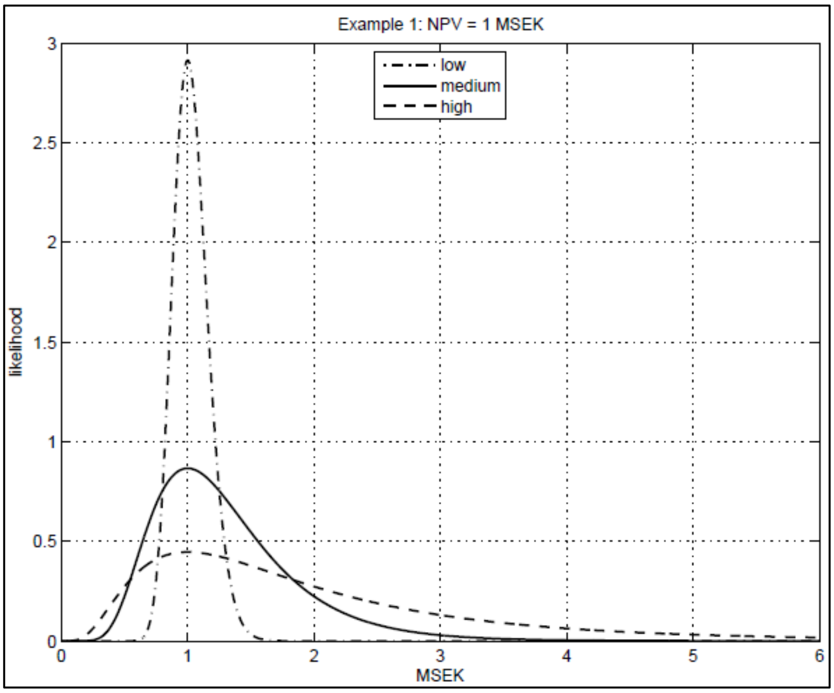


Figure 12. Log-normal uncertainty distributions for the three levels of uncertainty for a PV = 1MSEK. (Rosén et al., 2015)

SCORE Tool Results

Figure 13 shows an example of results of dimension and normalized total scores in the SCORE tool. Figure 14 shows the same normalized scores with associated uncertainty intervals. Figure 15 shows the predicted most sustainable alternative following Monte Carlo simulation.

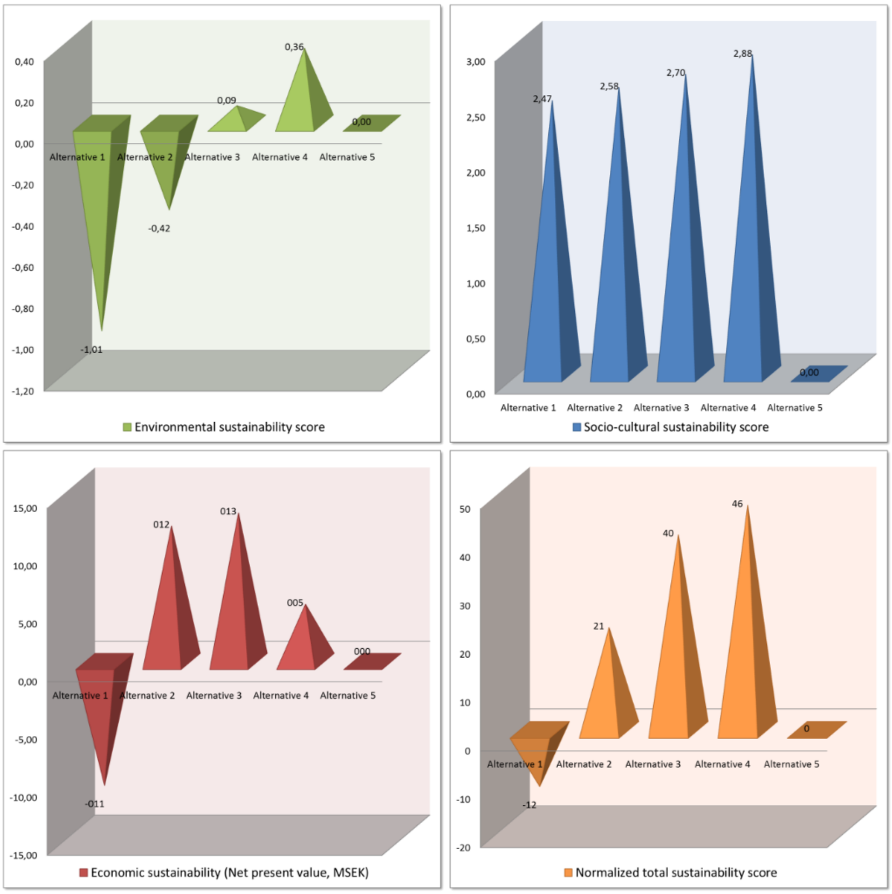


Figure 13. Results of a SCORE assessment of four remediation alternatives - Environmental sustainability scores (top left), Social sustainability scores (top right), Economic sustainability scores (bottom left), Total (normalized) sustainability scores (bottom right). (Rosén et al., 2015)

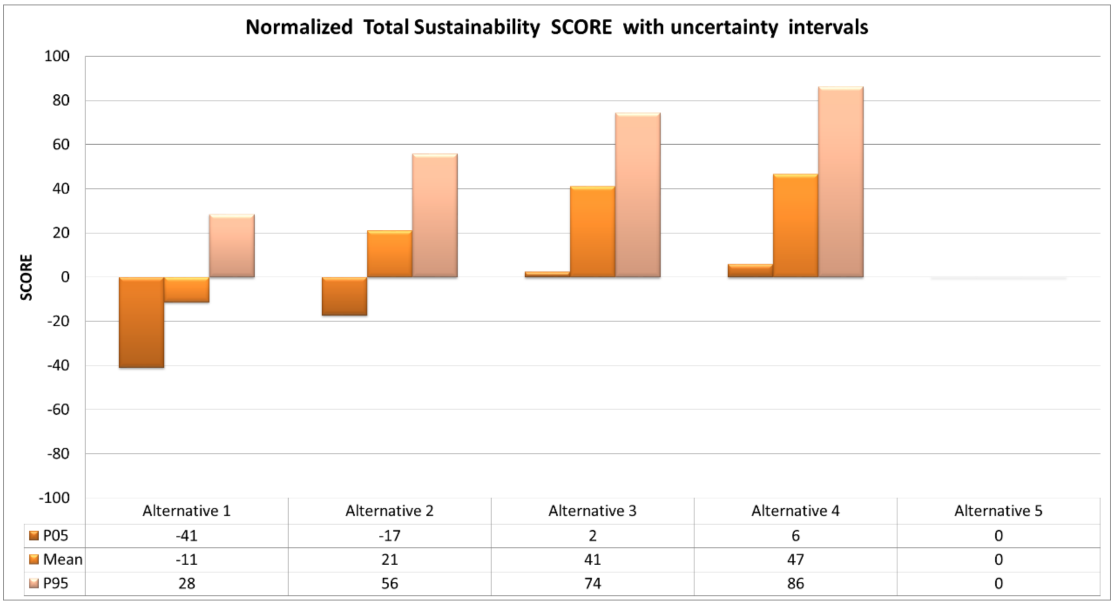


Figure 14. Normalized sustainability scores with uncertainty intervals.

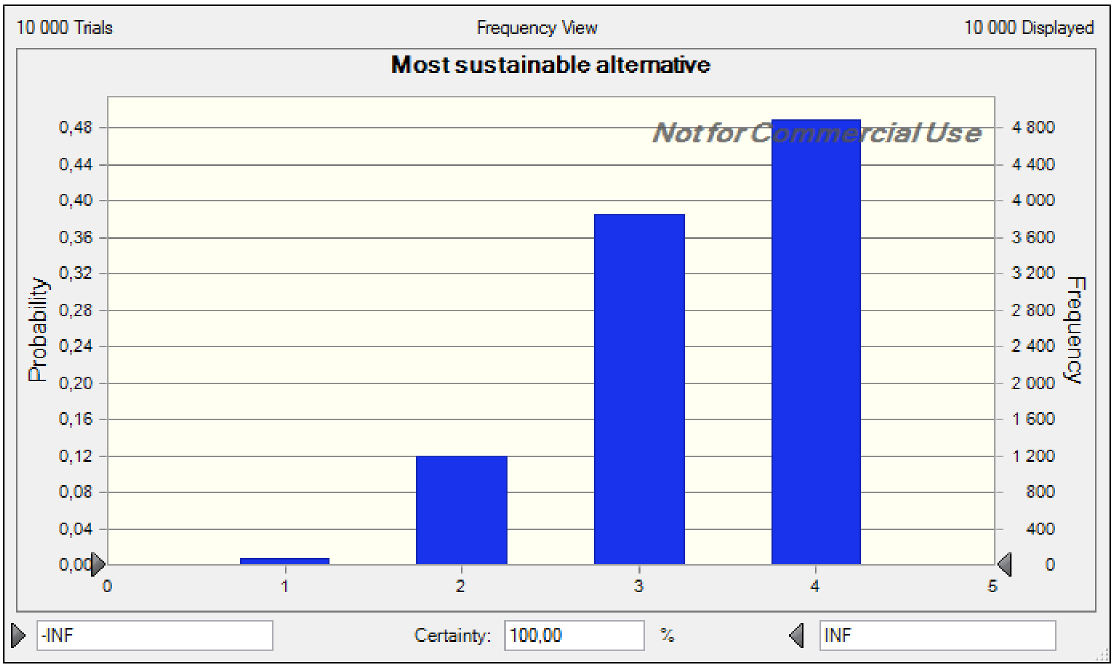


Figure 15. Most sustainable alternative predicted in the SCORE tool from Monte Carlo simulation.

4 Efficient Remediation

With increased focus in recent years on the sustainability of contaminated site remediation, the question of whether sustainability assessments lead to more efficient remediation arises. This stems from the concern over the slow progress of nationally funded projects and programs, in Sweden and worldwide. What is meant by efficient remediation, and in what ways can it can be assessed must therefore first be studied.

4.1 Terminology

A challenge in performing a literature study on efficiency in remediation comes from the definition of efficiency, and how it relates to the Swedish word "*effektivitet*", the Swedish translation of efficiency. However, it is also the translation of effectiveness, thus essentially covering both words (Svensk Akademisk Ordbok, 2017). Since the problem statement was originally written in Swedish, both efficiency and effectiveness are studied in this literature review. Definitions are provided below for clarity.

Efficient: Achieving maximum productivity with minimum wasted effort or expense. Preventing the wasteful use of a particular resource. Working in a well-organized and competent way. (Dictionary, 2015)

Efficiency: The state or quality of being efficient. (Dictionary, 2015)

Effective: Successful in producing a desired or intended result. (Dictionary, 2015)

Effectiveness: The degree to which something is successful in producing a desired result; success. (Dicitonary, 2015)

Efficiency and effectiveness can be thought of on different scales or levels with respect to remediation of contaminated soil. Traditionally, in scientific literature it is thought of as the removal efficiency of treatment technologies, but it can also be thought of on a project level and in terms of the progress of national programs. A conceptualization of the different efficiency levels is proposed in Figure 16 for the purposes of this literature study. Clarification of the levels is presented below.

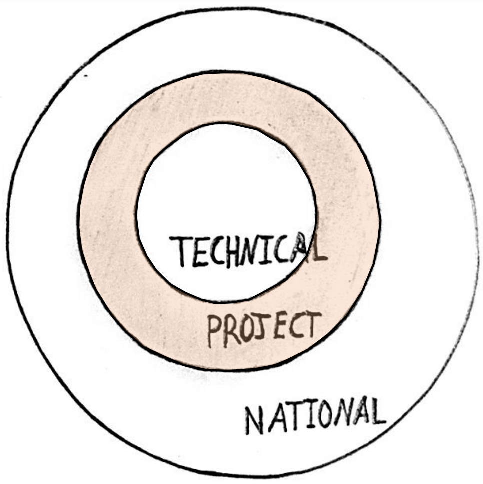


Figure 16. Conceptualization of the different efficiency/effectiveness levels in contaminated site remediation.

Technical Level – Efficiency and effectiveness of a specific soil treatment for a specific contaminant(s).

Project Level – Efficiency and effectiveness of remediation projects in terms of time, cost, risk reduction etc.

National Level– Efficiency and effectiveness of a national remediation program.

4.2 Database Search

An additional challenge in finding relevant literature is the different nomenclature used in the industry, varying from country to country. For example, from the SURF website, one can find use of many synonymous terms, including: *environmental cleanup*, *land remediation*, *contaminated land management* (SURF, 2017). Similarly, the topic of brownfield redevelopment, which typically requires remediation of contaminated land, is somewhat different in focus to the topic at hand, focusing on end land-use rather than the remediation process itself.

A summary of database searches in Scopus, including a variety of relevant nomenclature, is presented below in Table 12. The rough number of relevant articles to the project and national levels is shown in the right-most column as this is the primary focus of the SAFIRE research project. As is seen below, the number of relevant articles on efficiency and effectiveness on the project and national levels is limited.

Table 12. Database searches in Scopus (Date: October 12th, 2017). The number of relevant articles pertains to project and national levels. The number of relevant articles was not counted when more than 150 hits were found.

Key Words				*Hits*	*No. Relevant*
Remediation	AND Effectiv*	AND Soil OR Site		33, 792	-
Clean-up	AND Effectiv*	AND Soil OR Site		5, 506	-
Remediation	AND Efficien*	AND Soil OR Site		35, 471	-
Clean-up	AND Efficien*	AND Soil OR Site		6, 253	-
Remediation	AND Effectiv*	AND "Contaminated site"		4, 518	-
Clean-up	AND Effectiv*	AND "Contaminated site"		888	-
Remediation	AND Efficien*	AND "Contaminated site"		4, 218	-
Clean-up	AND Efficien*	AND "Contaminated site"		826	-
Remediation OR Clean-up	AND "Efficiency indicator"	AND "Contaminated site"		5	3
Remediation OR Clean-up	AND "Effectiveness indicator"	AND "Contaminated site"		0	0
Remediation OR Clean-up	AND Effectiv*	AND "Contaminated site"	AND Indicator	800	-
Superfund	AND Effectiveness			1, 598	-
Superfund	AND Effectiveness	AND Indicator		332	-
Superfund	AND "Efficiency indicator"			5	2
Remediation OR Clean-up	AND "Efficiency indicator"	AND US		6	0
Remediation OR Clean-up	AND "Efficiency indicator"	AND Canada		10	1
Remediation OR Clean-up	AND "Contaminated site"	AND Progress		2, 535	-
Remediation OR Clean-up	AND "Contaminated site"	AND Progress	Superfund	366	4
"Contaminated land management"	AND Efficien* OR Effectiv*			216	-
"Contaminated land management"	AND Efficien* OR Effectiv*	AND Indicator		82	3
"Contaminated land management"	AND Progress	AND Indicator		44	2
"Contaminated land management"	AND Progress	AND Superfund		34	0
"Efficient remediation"				150	-
"Efficient remediation"	AND "Contaminated site"			15	2
"Effective remediation"	AND "Contaminated site"			44	0
"Project efficiency"				283	-
"Project efficiency"	AND "Contaminated site"			0	0
"Project effectiveness"				219	3
"Project effectiveness"	AND "Contaminated site"			0	0
"Project management	AND "Contaminated site"			29	1
"Project management	AND "Contaminated land"			20	2
"Remediation project"	AND "National program"			0	0
Brownfield	AND Efficien*			228	-
Brownfield	AND Efficien*	Project		87	3
Brownfield	AND Effectiv*			328	-
Brownfield	AND Effectiv*	Project		102	2

It should be noted that *cost-effectiveness* has not been considered as a relevant term in this literature study. It is evident that cost is a relevant consideration for efficient and effective remediation, and while cost-effectiveness analysis (CEA) is established and useful in the context of remediation, the method/term has been excluded in this present study. CEA is used to analyze alternatives reaching an objective at the lowest cost. As an example, in SCORE, a CEA approach can be adopted by only focusing on costs, assuming that all alternatives reach the remediation goals and that the benefits of the alternatives are similar and with no requirement of a positive NPV (Rosén et al., 2015).

4.3 Technical Level

Remediation of contaminated soil is achieved through physical, chemical, biological, or thermal treatment. These techniques can be applied in-situ or ex-situ and often a combination of treatments types is used. The efficiency of a treatment on a technical scale is usually considered as a percentage of removal, isolation, or stabilization, depending on the method used. Technical efficiency or effectiveness could also be considered in terms of time and cost.

Countless examples in literature can be found where the efficiency or effectiveness of a remediation technique is studied for a certain contaminant and soil type, see the number of hits in Table 12 above. Often novel remediation technologies are presented and assessed with respect to efficiency, but evaluations of existing treatments on a specific contaminant is also common. Different examples of the ways efficiency is considered on a technical level are presented below, with summary in Table 13.

Jonsson et al. (2006, 2007, and 2009) compare the degradation efficiency (%) of chemical oxidation methods on polycyclic aromatic hydrocarbons (PAHs) as well as the extraction efficiency (%) of physical methods on polychlorinated dibenzo-*p*-dioxins (PCDDS) and dibenzofurans (PCDFs). The effect of soil properties on remediation efficiency was also studied.

Mallampati et al. (2015) investigate the immobilization efficiency (%) of thermal treatment/vitrification with nanometallic Ca/CaO composites on radioactively contaminated soil (^{137}Cs).

Marchiol et al. (2004) study the removal efficiency of in-situ phytoextraction using canola (Brassica napus) and radish (Raphanus sativus) on a multi-metal contaminated soil. The plants species’ efficiency in translocating metals is measured using a Translocation Factor (TF), i.e. the ability of the plant to translocate heavy metals from roots to the harvestable shoots.

Ruberto et al. (2003) evaluate the effectiveness of bioremediation on hydrocarbon contaminated Antarctic soil. Abiotic loss of hydrocarbons, biodegradation activity of indigenous microflora and biostimulation with Nitrogen and Phosphorus was studied.

Mulligan et al. (2001) evaluate the cost effectiveness of different ex-situ technologies on dredge sediments with heavy metal contamination. Pretreatment, physical separation, thermal processes, biological decontamination, stabilization/solidification and washing were assessed.

Albergaria et al. (2006) study the efficiency (%) and time of remediation (hrs) using vapour extraction on sandy soil contaminated with cyclohexane. Efficiency and time of remediation were analysed with respect to the soil water content and organic matter content.

Table 13. Examples of a select number of efficiency indicators on a technical scale.

Author	Year	Remediation technique	Efficiency measure	Contaminant(s)
Jonsson et al.	2006,2007,2008	Chemical oxidation methods Physical methods	Degradation (%) Extraction (%)	PAH, PCDDS, PCDFs
Mallampati et al.	2015	Thermal treatment/vitrification	Immobilization (%)	Radioactive (^{137}Cs)
Marchiol et al.	2004	Phytoextraction *(Brassica napus,*	Translocation factor	Heavy metals
Ruberto et al.	2003	Bioremediation; abiotic loss, biodegradation, biostimulation (nitrogen, phosphorus).	Removal (%)	Hydrocarbons (gas-oil)
Mulligan et al.	2001	Ex-situ technology (dredged sediment)	Cost effectiveness (US$/m^3, US$/t)	Heavy metals
Albergaria	2006	Vapour extraction	Remediation efficiency (%) Remediation Time (hrs)	VOCs (cyclohexane)

4.4 Project Level

Efficiency and effectiveness on a project scale can be evaluated using indicators pertaining to time, cost, risk reduction etc. A summary of reports and papers focusing on assessment of project efficiency and effectiveness is found below.

4.4.1 Swedish EPA

The Swedish Environmental Protection Agency (SEPA) (Naturvårdsverket) published a report evaluating nationally funded remediation projects with respect to their environmental benefits and socio-economic effects (Rosén et al., 2014). Ten remediation sites of differing characteristic were chosen for the evaluation, with the goal of having a set of completed projects that are representative of the nationally funded program so far. The different criteria used in choosing the sites are shown below in Figure 17.

- Geographic location
- Contamination Type
- Contamination location
- Project size
- Land-use

Figure 17. Site characteristic criteria (Rosén, 2014).

Three different evaluations were performed with respect to: 1. Effects on the environment and human health, 2. Good examples with respect to remediation technology and organization, and 3. Effects to society. Evaluation was based on quantification of environmental and health effects, environmental sustainability assessment, economic analysis (CBA), and social sustainability assessment.

A number of indicators were determined out of the above analyses, deriving from focus on two driving factors: **reduction of risk to people and the environment** and **fulfilling the Swedish national environmental objective of a *Non-toxic environment***. These are outlined below.

<u>Amounts and Costs</u>

- Total amount of contamination removed (**kg**)
- Total amount of carcinogenic substances removed (**kg**)
- Total amount of Swedish/EU prioritized substances removed (**kg**)
- Total amount of removed substances on the EU Water Framework Directive priority list (**kg**)
- Total amount of removed substance on the Helcom-OSPAR priority list (**kg**)

- Total amount of Persistent Organic Pollutants (POP) removed (Stockholm convention) (**kg**)
- Total project cost (**MSEK**)
- Cost per kg removed contamination (**SEK/kg**)

Health Effects

- Total number of human lives saved
- Number of reduced illnesses due to contamination
- Number of people no longer at risk from contamination
    - Living on the site
    - Working on the site
    - Living in the area
    - Occasional visitor
- Accident risks from the remedial activity
    - Potential number of ambulance requiring accidents from soil transport

Effects on the Environment and Land-use

- Amount of soil or sediment remediated (**tonnes**)
- Number of soil species affected positively
- Reduced contaminant load on surface water (**kg/100 years**)
- Amount of groundwater protected from contamination (**m^3/year**)
- Area remediated (**m^2**)
    - Area transformed to natural or green area (**m^2**)
    - Area that provides for a more attractive local environment (**m^2**)
    - Area transformed to residential area (**m^2**)
    - Area that provides for a good soil environment (**m^2**)

Emissions and Consumption

- CO_2 from transport vehicles (**tonnes**)
- SO_x from transport vehicles (**kg**)
- NO_x from transport vehicles(**kg**)
- Particulate matter from transport vehicles(**kg**)
- Copper (Cu) from transport vehicles (brake pads) (**kg**)
- PAH from transport vehicles (**kg**)
- Consumption of clean soil for refilling (**tonnes**)

While many of the above indicators considered by Rosén et al. (2014) pertain to efficiency or effectiveness, many can also be thought to be sustainability indicators, see Rosén et al. (2015). Relevant indicators from the report are summarised in Table 14 in section 4.6. It is noted that calculation of costs per amount removed (kg) of specific substances was avoided in the study, with only cost per total removal calculated. This is due to the fact that the contamination situation at most sites is complicated, and basing an indicator on a single contaminant can be misleading. It is also pointed out that the calculation of cost per total contaminant removal is difficult to interpret, as different contamination types can have very different remediation cost per amount.

In the evaluation of good remediation examples a number of criteria were looked at with respect to technique and organisation. This included evaluation of the projects' structures, investigations, measurements and level of innovation of chosen remediation techniques.

In looking at the effects to society of remediation projects, a number of social sustainability indicators were chosen: cultural heritage, local land-use, equity, recreation, health, and other local social effects. Difficulty in choosing socio-cultural indicators was highlighted, due to that the dimension it is multi-faceted and overlaps with criteria of the economic dimension.

The reader is referred to the report for the lengthy list of conclusions and recommendations from the study. Some findings relevant to this report are:

- Although the remediation projects clearly led to improved environmental situations with respect to soil, groundwater, surface water, and sediments, the remedial actions resulted in negative impacts (emissions, use of non-renewable natural resources, production of non-recyclable waste).
- The studied remediation projects resulted in overall positive social effects, reduced concern and nuisance to neighbouring people, and, though limited and uncertain, an improvement in human health (number of lives saved).
- In several cases, implementation of local treatment of contaminants, or pre-treatment to reduce the amount of soil transported and disposed of should have been considered in order to reduce environmental effects and costs.
- Traditional investigations in remediation projects, focusing entirely on environmental issues, human health, engineering design, and project cost should be improved, including sound assessment of socio-economic and social effects.
- Most sites were remediated by excavation and disposal, though important lessons were learned regarding the use of alternative, more innovative techniques.
- Though the evaluation of the ten projects shows positive impacts of the nationally funded program, the remediation projects could be performed in a more sustainable and cost-effective way. This can be achieved by integration of sustainability assessment in the evaluation of remedial alternatives, and remedial design processes.

4.4.2 Svenskt Näringsliv (WSP)

The Confederation of Swedish Enterprise (Svenskt Näringsliv) published a report analysing the efficiency (*effektivitet*) of Swedish publicly funded projects from 2008 to 2013 (WSP, 2014). The majority of sites analysed (26 of 30) were excavation-based remediation (dig-and-dump) along with two dredging sites. It is stated that a reason for this is that most of the analysed sites had metals as the primary or secondary contaminant, with arsenic as the primary contaminant in 12 of the sites. Three of the sites analysed here were also evaluated in Rosén et al. 2014.

The report also analyses the efficiency of 12 privately funded sites, based on the same indicators. The privately funded sites were chosen to be as similar as possible to the publicly funded sites in terms of size, contamination/remediation, and time of completion.

The analysis was based on the following indicators:

Time

- Total project time (Investigation time, Remediation time) (**years**)
- Remediation time per amount of excavated soil (**days/tonne**)

Cost

- Total cost (**SEK**) (Investigation costs + Remediation costs)
- Cost per amount of excavated soil (**SEK/tonne**)
- Cost per remediation area (**SEK/m^2**)
- Cost per amount of primary contaminant removed (**SEK/kg**)
- Cost per amount of primary and secondary contaminant removed (**SEK/kg**)
- Cost per risk-ratio for primary contaminant (**SEK/risk-ratio**)
- Cost per person in the local area (<700m) (**SEK/person**)

Arsenic Remediations

- Cancer risk reduction (**%**)

Although most of the sites were quite alike in contamination and remediation techniques used, there was significant variation in the size, conditions, and amount of contamination between the sites. It was said therefore that site comparison should not be based solely on one indicator.

In terms of time, the study found that the publicly funded sites generally took longer to complete than the private funded sites, with an average total time, from first decisions to final report, of around 9 years for the publicly funded sites. This was attributed to the large size and complexity of many of the publicly funded sites, as well as the more involved financing procedure. The fastest completed site was a private exploitation project where residential housing was to be built, which highlighted the advantage of having external motivation. It was also noted that time-efficiency cannot be considered in some cases, such as when in-situ methods are used, where long time is required to achieve other aspects of efficiency.

Remediation costs were generally high, regardless of the type of financing, and found to vary significantly between sites. Costs divided over the amount of excavated soil varied less however. Procurement, project management, site complexities, and additional environmental protection requirements are other factors that affected the total measured costs. Higher concentration of contamination, and easier accessed contamination also lead to more efficient remediation. Costs per person in the local area were found to be lower for the privately funded sites, since less people live in proximity to the public sites.

The report compared the sites on overall efficiency by identifying the top and bottom three publicly funded sites for each specific indicator. It was found that 65% of sites were found in the top three and 53% in the bottom three for at least one indicator, illustrating the difficulty in classifying any site as either completely efficient or inefficient. Some sites were found in the top or bottom three more often than others, owing partly to the similarity of some indicators. Sites found on either end more than three times were used as examples of sites being “more efficient” or “less efficient”, placed in relation to the amount of mass remediated.

From the overall comparison it could be said that site-specific conditions largely affect remediation and the results of the analysis. This was seen in the large variation between sites for a given indicator and the fact that sites were found as being most efficient on some indicators and least efficient on others. It was also observed that the smaller sites were often found to be “more effective” and that the larger sites more often were seen to be “less efficient”. Finally, it was suggested that the indicator which most realistically describes economic effectiveness is the cost per risk-ratio[4], since risk reduction is the steering factor for all publicly funded sites. Here it was found that the most expensive site in terms of total cost was much more reasonable when evaluated with respect to risk reduction, contradicting its categorisation of being “less efficient”.

---

[4] Average concentration of primary contaminant in excavated masses divided by guideline value (site-specific).

4.4.3 Zidane & Olsson (2017)

Though not pertaining directly to remediation of contaminated sites, the paper studies how the concepts of efficiency, effectiveness as well as efficacy are used in project management literature, highlighting the gap in literature concerning the practical use and interpretation of the concepts (Zidane & Olsson, 2017). Literature included *International Journal of Managing Projects in Business, International Journal of Public Management, Project Management Journal,* as well as online sources (Google Scholar and Google Books). The study aims to clarify the understanding of project efficiency, project effectiveness, and project efficacy, with the hope of supporting organisational improvement and leading to possible developed indicators.

It was found that there is a wide diversity in the interpretation of the three concepts among research scholars and practitioners. This led the authors to propose a model to describe the concepts, seen below in Figure 18. A summary of the definitions of the words was presented as the following:

1) to be efficient is to produce an output in a competent and qualified way;
2) to be efficacious involves possession of a quality that gives the produced results the potential to lead to an effective outcome; and
3) to be effective is when results accomplish their purposes, thus giving an effective outcome.

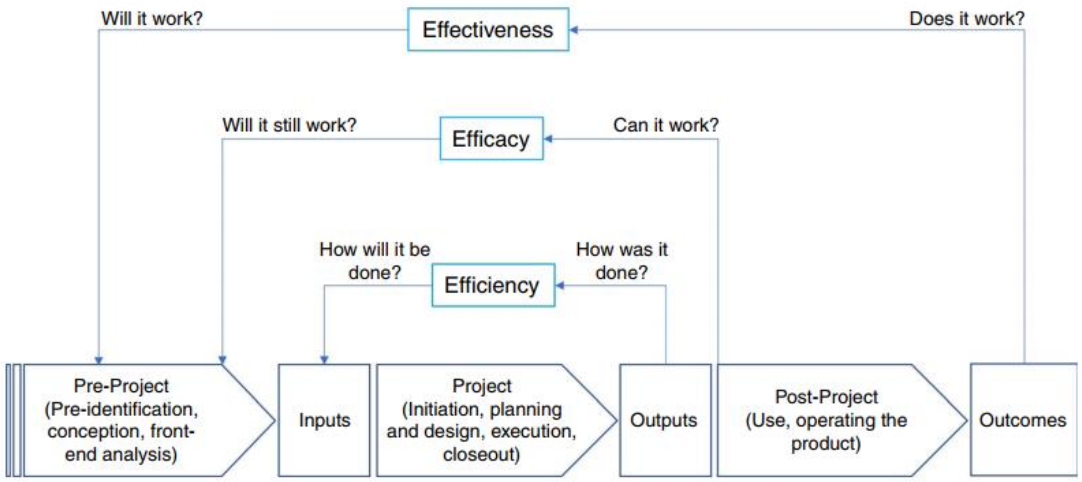


Figure 18. Model reflecting project efficiency, efficacy and effectiveness proposed by Zidane & Olsson (2017).

The authors discuss that effectiveness is the hardest to measure, that it is subjective and related to project stakeholders. They state that it is about the purpose(s) and objectives of the project, where project effectiveness occurs once the operation of the produced product generates positive impacts in the middle and long term. It is also discussed that:

"What is effective is not necessarily efficacious, and what is efficacious is not necessarily efficient". To understand the differences the authors depict between the three terms, it is helpful to look at the proposed model and the questions to ask for each concept.

4.4.4 Laniado et al. (2013)

The paper presents a methodological model to evaluate the effectiveness of environmental projects (Laniado et al., 2013). A broad set of projects with public funding in various environmental sectors were involved, with examples given as: sewage plant, car-pooling, district heating. The model considers effectiveness as: "*the capacity of the project to achieve its direct objectives and, consequently, to compare with reference values (arising from reference environmental objectives, limitations and thresholds imposed by law, benchmark values) and /or to contribute the state of targeted environmental components*". The model additionally considers efficiency as: *"economic resources (time and cost) required to implement a functional unit of the project"*, e.g. Total plant construction cost per district heating network length (€/km).

4.4.5 Sorvari et al. (2009)

The paper studies eco-efficiency of contaminated land management, performing literature review and stakeholder seminars to determine relevant factors (Sorvari et al., 2009). They define eco-efficiency in general terms as "gaining environmental benefits with fewer resources", though it is described to be synonymous with sustainability. They perform their study in a Finnish context, where, like most countries, dig-and-dump projects with minimal recycling is the dominating remediation technique. The definitions of eco-efficiency resulting from the stakeholder seminars are seen to be in line with sustainable remediation (SuRF-UK, 2011).

4.4.6 USEPA (2017)

The USEPA published the Superfund Optimization Progress Report 2011-2015 (USEPA, 2017a) which provides status updates on optimization recommendations and events conducted during Fiscal Years 2011 to 2015. This falls under the 2012 *National Strategy to Expand Superfund Optimization Practices from Site Assessment to Site Completion*. It is stated that the strategy instituted changes to promote more effective and efficient site cleanups. The use of the terms efficiency and effectiveness in the report refer primarily to the remedial action i.e. the efficiency and effectiveness on the technical level. The strategy includes an effort to unify four previously independent optimisation efforts; Remediation System Evaluations (RSEs), Long Term Monitoring Optimization (LTMO); Green Remediation; and the Triad Approach.

4.5 National Level

Efficiency on the national level considers the progress of site remediation funded by national programs. The Swedish, Canadian, and US national programs are presented here, with description of how efficiency and effectiveness are assessed in each case.

4.5.1 Sweden

Publicly funded remediation in Sweden picked up speed in the early 1990's, when the Swedish EPA became in charge of planning of measures for cleaning up contaminated sites. In 1999, the Swedish Environmental Code came into effect, along with development of the national environmental objectives as well as the method for contaminated site inventory and risk classification (MIFO) (SEPA, 1999). Today, the Swedish EPA (Naturvårdsverket) is responsible for coordination, prioritization and follow-up of remediation on a national level, working towards the national objective of a *Non-Toxic Environment*.

Swedish EPA Annual Reports (Lägebeskrivningar)

Annual status reports by Naturvårdsverket provide a glimpse on the progress of the national remediation in Sweden, with data taken from the "EBH-stödet" authority database (SEPA, 2017). In addition to detailed reporting on the government allocation (grant) spent per year on remediation measures, the reports list a number of results, including:

- Total number of risk classified sites;
- Number of ongoing and completed site investigations ;
- Number of sites ongoing;
- Number of sites with completed remediation;
- Number of ongoing sites with remediation for residential construction;
- Number of completed sites with remediation for residential construction.

Figure 19 shows the results of the 2016 report for the above indicators, which shows the slow-progress of publicly funded sites (only two sites completed in 2016).

	2014	2015	2016
Totalt antal riskklassade objekt	23 677	24 435	25 040
Antal pågående och avslutade utredningar (ackumulerat)*	777	813	845
Antal pågående åtgärder	41	53	43
Antal avslutade åtgärder, uppföljning genomförd och objektet klart (ackumulerat)*	93	100	102
Antal pågående åtgärder, efterbehandling för bostadsbyggande **	–	–	2
Antal avslutade åtgärder, efterbehandling för bostadsbyggande **	–	–	0

*De ackumulerade siffrorna gäller från när anslaget inrättades
**Nytt anslag från 2016

Figure 19. Publicly-funded site phases for 2014-2016 (from SEPA, 2017). Translation from top to bottom: Total number of risk classified sites; Number of ongoing and completed site investigations (cumulative); Number of ongoing remediation measures; Number of completed remediation measures, followed-up and the site ready (cumulative)*; Number of ongoing measures with remediation for residential construction**; Number of completed measures with remediation for residential construction**; *Accumulated numbers are from when grant was established; **New grant from 2016.*

The annual status reports are hard to interpret, making it difficult to assess the progress of remediation. For example, the 2013 report states that 191 publicly-funded sites had been completed to date (SEPA, 2014), significantly higher than the 102 sites shown to be completed as of 2016 in Figure 19. It is possible, however, that the method of consideration for completed sites has since changed, likely depending on those sites only partly funded publicly. In addition, prior to 2016, the reporting of site completion was much more limited. Earlier reports referred only to bar graphs showing annual statistics of both publicly-funded and supervision sites, without inclusion of actual numbers or indication of whether the number of sites were cumulative. Figures 20 and 21 show the progress graphs from the 2015 and 2016 reports respectively. It is seen from the 2015 graphs that a change in how information was taken from the "EBH-stödet" database changed after 2013. This is also seen in the 2016 graph where only years 2014 to 2016 were included.

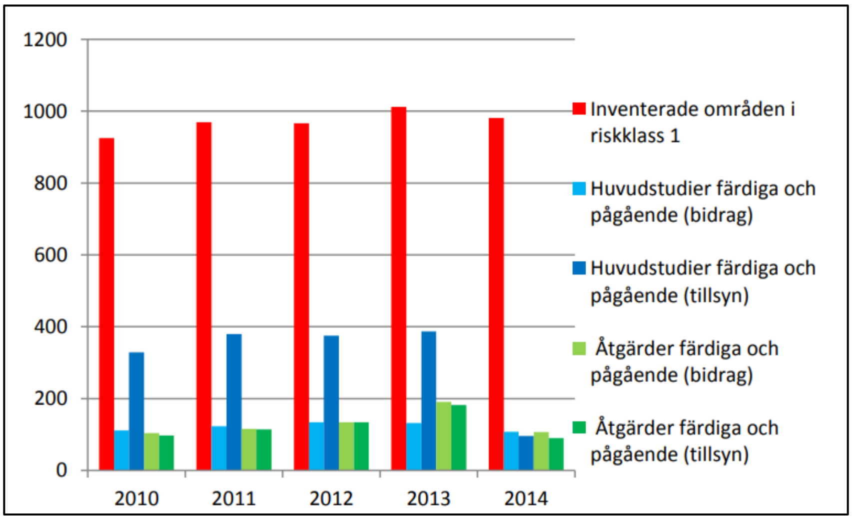


Figure 20. Progress of remediation from 2010 to 2014. A change in how data was considered from the "EBH-stödet" database is seen in 2014 (from SEPA, 2015). Translation from top to bottom: red=Inventoried sites in risk class 1; light-blue=main investigations completed and ongoing (publically-funded); blue=main investigations completed and ongoing (supervision); light-green=measures completed and ongoing (publically-funded); green=measures completed and ongoing (supervision).

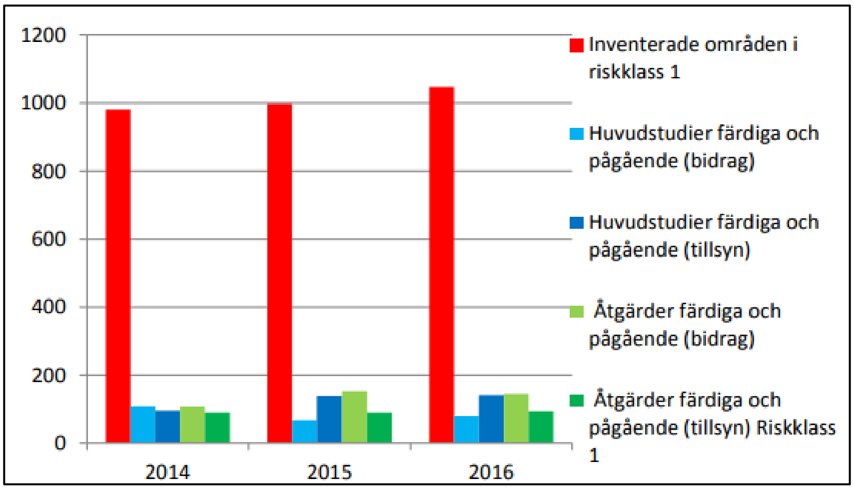


Figure 21. Progress of public remediation from 2014 to 2016 (from SEPA, 2017). Translation from top to bottom: red=Inventoried sites in risk class 1; light-blue=main investigations completed and ongoing (publically-funded); blue=main investigations completed and ongoing (supervision); light-green=measures completed and ongoing (publically-funded); green=measures completed and ongoing (supervision).

Vredin Johansson et al. (2011)

Stemming from the Swedish environmental objective of *a non-toxic environment*, which emphasizes remediation time with its stage goals, it was studied how the pace of remediation is affected by government funding in four different states of the remediation process. It was found that a particular bottleneck is the third state, from risk classification to clean-up start on a site (Vredin Johansson et al., 2011). It was concluded that the effect of increasing government funding on speeding up the process in this state is small compared to the amount of funding needed. The findings also suggested that the environmental quality objective *A non-toxic environment* is far too visionary and of little practical relevance, with other barriers to remediation speed than funding needing to be identified through research and policy-making.

Riksrevisionen (2016)

In 2016 the Swedish National Audit Office, the agency with the task of reviewing government agency spending, published an “efficiency audit” on the national remediation program. The reviews’ aim was to study the opportunity for an effective prioritization of publicly-funded remediation projects. The report focuses on identification and inventory of contaminated sites along with remediation costs, with the overall conclusion that there are significant shortcomings in the identification of contaminated sites by the analysed government agencies (County Administrations, Transport Administration, Armed Forces, and Fortifications Agency), making effective prioritization more complicated. (Riksrevisionen, 2016)

4.5.2 Canada

The Federal Contaminated Sites Action Plan (FCSAP) is the national remediation program in Canada. The 15-year, $4.2 billion (CAD) program was launched in 2005 with the objective of reducing environmental and human-health risks of federal contaminated sites. The program is now entering its third and final phase, 2016-2020. (Canada, 2015)

Included in the program are sites on land owned or leased by the federal government, or sites where the federal government has accepted responsibility for the contamination, where contamination took place prior to 1998. Site remediation within the FCSAP is conducted by federal departments, agencies and consolidated Crown corporations, who are referred to as custodians. Examples of these are: Fisheries and Oceans Canada (DFO), Department of National Defence (DND), Environment Canada, Transport Canada. Site remediation under the FCSAP program follows a common 10-step process, the *Federal Approach to Contaminated Sites*. (Canada, 2015)

In assessing the progress and performance of the FCSAP, five performance indicators are used, falling into three key areas; Assessment, Reduction of risks to human health and the environment, Liability Reduction. Further description of the indicators is provided below.

<u>Performance Indicator List</u>

1. **Assessing sites**; number of sites where FCSAP-funded assessments are being conducted. As of 2013-2014: 1395 sites. 61% of the five-year target of 2300 sites reached.
2. **Starting remediation**; number of priority FCSAP-funded sites where risk-reduction activities are being conducted. As of 2013-2014: 531 sites. 35% of the five-year target of 1500 sites reached.
3. **Completing remediation**; number of priority FCSAP-funded sites where risk-reduction activities have been completed. As of 2013-2014: 101 sites. 27% of five year target. See Figure 22.
4. **Reducing liability at key sites**; change in total liability for the 73 highest-priority FCSAP sites. Defined as the obligatory environmental liability costs of the Canadian Government for remediation of the contaminated sites. As of 2013-2014 an increase in liability of $256 million.
5. **Liability reduction effectiveness**; percentage of remediation expenditures that reduce financial liability over the five years of FCSAP Phase II. 95% of FCSAP remediation expenditures ($591million of $617million) resulted in reduced liability.

Annual FCSAP reports also consider secondary socio-economic benefits of the program. In Aboriginal or rural areas, FCSAP projects have led to opportunities for local residents and contractors resulting in active community engagement in the projects. The FCSAP led to the creation of approximately 1600 jobs from 2013-2014. (Canada, 2015)

The yearly impact on the Federal Contaminated Sites Inventory (FCSI) is also presented. The FCSI includes information on federal contaminated sites (and the respective custodians they fall under), as well as non-federal contaminated sites for which the Canadian Government has accepted financial responsibility. As of March 31st, 2014, 13 430 of 22 590 sites (59%) have been closed. 6140 sites (27%) are active and approximately 3020 sites (13%) are suspected to be contaminated but not yet assessed. (Canada, 2015)

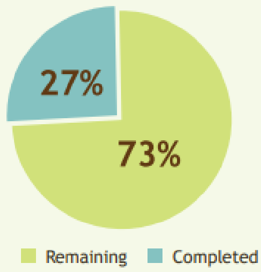
Performance indicator	Result (as of 2013-2014)	Five-year target (2011-2012 to 2015-2016)
Number of priority FCSAP-funded sites where risk-reduction activities have been completed	101 sites	368 sites 

Figure 22. FCSAP Indicator 3: Completing Remediation. (Government of Canada, 2015)

4.5.3 United States

The nationally funded program for contaminated site remediation in the US was initiated by congress in 1980 as CERCLA (Comprehensive Emergency Response, Compensation and Liability Act) and is informally named Superfund (USEPA, 2017b). The goals of Superfund are to:

- Protect human health and the environment by cleaning up polluted sites;
- Make responsible parties pay for cleanup work;
- Involve communities in the Superfund process; and
- Return Superfund sites to productive use.

Superfund Performance Measures

The USEPA keeps track of Superfund sites by means of the National Priority List (NPL) and the Superfund Alternative Agreement (SAA) program (USEPA, 2017c). The program uses six performance measures which are evaluated annually (USEPA, 2017d):

- Remedial Site Assessment Completions
- Remedial Action Project Completions
- Construction Completions
- Environmental Indicators
  - Human Exposure Under Control
  - Ground Water Migration Under Control
- Sitewide Ready for Anticipated Use

The performance measures webpage provides interactive graphs for each of the measures. As of 2017, 1,729 deleted sites were found on the NPL, indicating site completion, and ready for use. In 2016 alone, 41 sites were listed as ready for use, see Figure 23.

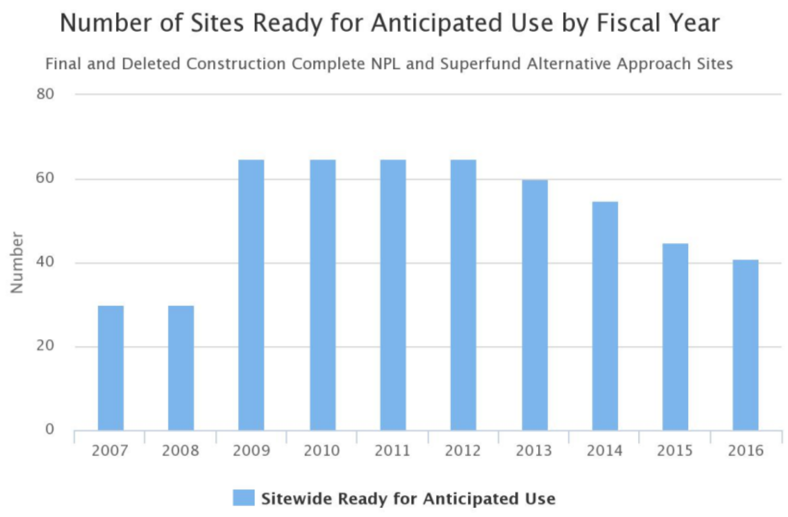


Figure 23. Number of completed Superfund sites from 2007 to 2016 (US EPA, 2017c)

In addition to the performance measures above, the USEPA publishes yearly accomplishment reports which report highlights, annual accomplishment metrics, program accomplishments, and Superfund redevelopment initiative accomplishments (USEPA, 2017d). The annual accomplishment metrics include:

- Protecting communities' health and ecosystems;
- Obligating funds for construction and post-construction activities;
- Funding new construction projects at EPA and Potentially Responsible Parties (PRP) lead projects;
- Cleaning up hazardous waste site;
- Safeguarding communities from imminent threats;
- Preparing for future cleanup efforts;
- Ensuring long-term protection; and
- Remaining committed to "polluter pays" principle.

4.6 Indicator Summary

A summary of relevant indicators found on each of the conceptualized levels is provided below. An attempt has been made to categorize the indicators as measures of either efficiency or effectiveness based on the definitions in section 4.1 and the model presented by Zidane & Olsson (2017).

Table 14. Summary of efficiency/effectiveness indicators on each level.

Level	"Efficiency"	"Effectiveness"
National		No. sites assessed[a,b,c] No. sites started[a] No. construction completed[b] Liability reduction[a] No. sites completed[a,b,c] Sites/yr[a] Environmental Indicators[b] No. sites identified[c] No. sites ongoing[c] No. sites ongoing/completed for res. construction[c]
Project	Time per amount excavated (days/tonne) [d] Cost per amt. excavated (kr/tonne) [d] Cost per remediation area (kr/m^2) [d] Cost per amount contaminant removed (kr/kg)[d,e] Cost per risk-ratio (kr/risk-ratio) [d] Cost per person in area (kr/person) [d] Total project time (yrs)[d] Total project cost (kr)[d,e]	Total project time (yrs)[d] Total project cost (kr)[d,e] Cancer risk reduction (%)[d] Total amounts contamination removed (kg)[e] No. lives saved [e] Accident risks from RA [e] Area remediated (m^2) [e] Amount soil remediated (tonnes) [e] No. soils species affected [e] Surface water protection (kg/100yrs)[e] Groundwater protection (m^3/yr) [e] Emissions (kg) [e] Consumption of clean soil for refilling (tonnes) [e]
Technical	Degradation (%)[f] Removal (%)[g] Immobilization (%)[h] Remediation Time (hrs)[i] Cost (US$/$m^3$)[j] Cost (US$/t)[j] Translocation Factor[k]	

[a] FCSAP, 2015
[b] US EPA, 2017
[c] Swedish EPA, 2014
[d] Svenskt Näringsliv, 2014
[e] Rosén et al., 2014
[f] Jonsson et al., 2006
[g] Jonsson et al., 2008
[h] Mallampati et al., 2015
[i] Albergaria et al., 2006
[j] Mulligan et al., 2001
[k] Marchiol et al., 2004

5 Discussion and Conclusions

A first challenge in performing this literature review arose from the difference in language between Swedish and English, where the Swedish word “effektiv” essentially covers both efficient and effective. It has therefore been required to study both efficiency and effectiveness as part of the SAFIRE research project. These two words, though used extensively in the context of contaminated site remediation, are often not clearly defined or are used for analyses of different things on different levels. Understanding of the use of efficiency and effectiveness with respect to site remediation in literature has been aided by organizing the use of the terms in literature to different scales or levels.

Literature on the technical level, studying efficiency and effectiveness of remediation techniques and technologies, is extensive, as seen from the thousands of hits in the database search. The objectives of the SAFIRE research project, however, focus more on the project and national levels. As such, only a summary of articles on the technical level are presented, to give an idea of the different ways efficiency and effectiveness are considered and measured here. Nonetheless, it is important to acknowledge that efficiency and effectiveness of remediation technologies potentially can lead to efficiency and effectiveness on the project and national levels.

Database search in SCOPUS was made difficult by the different nomenclature used in the field. This is apparent when looking through websites of national environmental agencies where different choices of terminology are seen. As a result, the database search required the inclusion of many combinations of search words to ensure all terminologies were considered.

Relevant literature on the project scale was dominated by two Swedish reports: the first from the Swedish EPA (Rosén et al., 2014) and the second from the Confederation of Swedish Enterprise (Svenskt Näringsliv) (WSP, 2014). The first study lists indicators with a wide focus, including many health and environmental indicators, while the second study focuses primarily on costs and removal amounts. Most of the studied sites in the second study were contaminated with heavy metals and remediated by excavation and disposal, and the choice of indicators seems to reflect this. Assessment of innovative remediation techniques, such as phytoremediation, would not have been possible given the chosen indicators. Rosén et al. (2014) stress that cost per total contaminant removal is difficult to interpret, as remediation costs can vary highly depending on the type of contamination. Ratio indicators, while providing opportunity for better comparison across sites that otherwise can be significantly different in terms of size, may be misleading when considering different contamination or remediation situations.

From the indicator lists of the two studies mentioned above, it is possible to see that indicators can be categorized as measures of either efficiency or effectiveness. Those indicators that are ratios, measuring the productivity while minimizing effort or expense (time, costs) can be considered efficiency indicators, while those measuring successes in producing a desired result can be considered effectiveness indicators. Additionally, it is helpful to consider the model presented by Zidane & Olsson (2017) when thinking about the differences between project efficiency and effectiveness. A question to ask post project for efficiency is: *How was it done?* (inputs vs. outputs); while for effectiveness, which is said to be harder to measure: *Will it work?* (outcomes).

Indicators assessed on the national level seem to be similar from country to country, though only three examples were looked at. Here the focus is on the number of publicly funded sites completed, often with indicators pertaining to different stages of completion. The naming of the different stage completion indicators is often hard to interpret, differing in each of the programs. For both the Canadian and Swedish yearly progress reports, mainly cumulative results are presented, where it is often hard to find the number of sites completed in a given year. This is likely due to the slow progress of remediation, where sites are often ongoing for a number of years, and relatively few are completed each year, making for a statistic that is not wished to be shown.

As contaminated sites can differ so greatly in terms of complexities, problem owners, and location, aspects specific to a site should be considered. A measure of project effectiveness that is therefore missing from the gross indicator list is whether a project reaches project specific goals. Examples of these could be increased recreational use on or through a site, increased access to a waterway, or contaminant removal in order to reduce the stigma surrounding a site to neighbouring people. Assessment of efficiency and effectiveness should not be limited to a generic list of indicators, but also consider important site-specific aspects brought forward by stakeholders in a project.

It can be clarified again that the terms cost-efficiency and eco-efficiency are deemed not to be relevant in the context of this literature review. Cost-efficiency analysis (CEA) focuses on minimizing the costs of alternatives in reaching an objective. This can be integrated into the economic dimension of SCORE in only focusing on costs for alternatives reaching the remediation goals with similar benefits. Eco-efficiency, as defined by Sorvari et al. (2009) as "gaining environmental benefits with fewer resources", can be said to be synonymous with sustainability, at least in the context of contaminated site remediation.

In selecting relevant efficiency and effectiveness indicators, one can think about the two driving factors of the analysis performed by Rosén et al. (2014); (1) reduction of risk to people and the environment and (2) fulfilling the Swedish national environmental objective of a *Non-toxic environment*. From the gross indicator list, it could be possible to divide the indicators based on these two categories. Assessment of efficiency and effectiveness in the context of contaminated site remediation should therefore include a balance in measuring both risk reduction as well as time and costs.

The Svenskt Näringsliv report (WSP, 2014) illustrates the difficulty in classifying sites as either completely efficient or inefficient, due to the fact that given sites were found to be most efficient on some indicators and least efficient on others. It can therefore be expected, given a more diverse set of indicators, with inclusion of more social, environmental, and site-specific aspects, that even more trade-offs between efficiency and effectiveness indicators would be seen.

The main conclusions drawn from this literature review are:

- The use of efficiency and effectiveness with respect to contaminated site remediation in literature can be conceptualized on three levels: Technical, Project, and National.
- Though focus of the SAFIRE research project is on the project and national levels, it is important to acknowledge that increased efficiency and effectiveness on the technical level can potentially lead to increased efficiency and effectiveness on the upper levels.
- The indicators found in literature can be categorized as efficiency or effectiveness indicators, depending on whether focus is on productivity in terms of outputs vs inputs (efficiency), or on reaching specified goals or outcomes (effectiveness).
- Ratio indicators, while allowing for better comparison across sites of differing size, may not be useful when considering different contamination situations or innovative treatment alternatives.
- Assessment of efficiency and effectiveness in the context of contaminated site remediation should include consideration of both risk reduction to human health and the environment as well as time and costs (reaching national objectives).
- Additional consideration should be made to whether projects are effective in reaching site-specific goals brought forward by stakeholders.
- It is likely difficult to conclude that remediation projects are completely efficient or effective, as weaknesses and strengths will always be seen for projects when looking at a diverse list of indicators.

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