Desk study on available remediation techniques for contaminated sediments

Anissa Smits, Herman Brangers, Goedele Vanacker, Nic Van den Heuvel, Goedele Kayens

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Contents

Sullied Sediments

Sediment Assessment and Clean Up Pilots in Inland Waterways in the North Sea Region

Many of the inland waterways in Europe are under threat due to the introduction of Watch List chemicals that are not currently regulated under the European Water Framework Directive. These chemicals enter our waterways as a result of our day-to-day activities and through industry, and many have been shown to be harmful to wildlife and the wider aquatic environment. Regardless of their source, these pollutants accumulate in the sediments in our rivers and canals over time.

Water regulators and managing authorities do not always know the levels, locations or impacts of these pollutants. Nor do they have the tools to assess sediments confidently and make informed environmental management decisions. To address these issues, the Sullied Sediment project partnership of scientific experts, regulators and water managers is developing and testing new tools that will enable stakeholders to better assess, treat and prevent contamination from these chemicals. This work is being carried out at selected sites in the Elbe, Humber and Scheldt river catchments.

The intention of the Sullied Sediments project is therefore to help regulators and water managers make better decisions with regard to the management, removal and disposal of sediments, thereby reducing economic costs to private and public sector organisations, and the impact of these pollutants on the environment.

The partnership is also working to reduce the extent of chemicals entering the water system by raising awareness about what we, as consumers, are releasing into the environment through the use of common drugs and household products. This includes the involvement of volunteers in a sediment sampling initiative across the North Sea Region, which will inform and empower them as water champions in their local communities.

The Sullied Sediments project has been co-funded by the European Regional Development Fund through the Interreg VB North Sea Region Programme with match funding from the 13 partners involved. The project partnership includes public, private, community and voluntary sector organisations based in the United Kingdom, Germany, Belgium and the Netherlands.

The project has been supported under the Interreg VB North Sea Region Programme's third priority, which is focused on a Sustainable North Sea Region, and is led by the University of Hull (UK).

Website: northsearegion.eu/sullied-sediments

Blog: sulliedsediments.wordpress.com

Twitter:@SulliedSediment

Abstract

The desk study aims to provide tools to European sediment remediation experts, policy makers, industrial companies, waterway managers and private individuals to support decisions regarding management, removal and disposal of contaminated sediments, thereby reducing economic costs and the impact of contaminants on the environment. It was prepared by a consortium consisting of sediment remediation experts from the engineering and consultancy company Witteveen + Bos N.V. and the environmental contractors DEME-DEC, Jan De Nul-Envisan and Ghent Dredging.

The report is published as a reference document and the results from the study have been used for the construction of an online decision support tool (BOSS-WB). The decision support tool for sediment remediation techniques (BOSS WB) is developed by VITO on behalf of OVAM.

Detailed reference documents on this subject already exist but are often aimed for use by experts. This document is meant to be of use for sediment policy makers and managers who have no expertise (yet) with sediment remediation.

The input for a decision support tool (DST) for the remediation of sediments consists of the answers you give to questions about certain preconditions. An overview of the available and applicable soil remediation techniques was chosen on the basis of:

- Their proven usefulness in previous projects;
- Their demonstrated usefulness in pilot projects;
- A promising equivalent for soil remediation. As a result, less proven techniques have also been included in this selection.

The desk study documents the basic project information such as the type(s) of contamination, type of sediment, remediation goal, etc., that should be provided in order to evaluate and eventually narrow down the several remediation possibilities. The desk study gives an overview of the feasible remediation techniques for aquatic sediments within specific boundary conditions.

Introduction

This document and the decision support tool that was developed by VITO (BOSS-WB) can be used during the entire sediment investigation and remediation process. On the basis of project information such as the type(s) of contamination, type of sediment, remediation goal, etc., can be used in order to evaluate and eventually narrow down the several remediation possibilities. The desk study gives you an overview of the feasible remediation techniques for aquatic sediments within specific boundary conditions.

Firstly, the consortium carried out extensive research on the current available remediation techniques for contaminated sediments in Flanders. This included in-situ techniques such as monitored natural attenuation (MNA) and capping and ex-situ techniques such as excavation. The feasibility and estimated cost price of the ex-situ techniques largely depends on the various possibilities for processing, transporting and de-watering of sediments, which also were investigated.

The study summarizes the review of possible preconditions that should be considered when opting for a suitable remediation technique for a specific site. In situ remediation techniques ex situ techniques are described in detail, including several case studies or (pilot) projects. Ex situ techniques; describe methods to treat the sediments but also include disposal and reuse of sediments. The main sources of information used for this desk study were (literature) studies and pilot projects carried out by:

- Interstate Technology & Regulatory Council (ITRC), a program of the Environmental Research Institute of the United States];
- SedNet, the European Sediment Network;
- United States Environmental Protection Agency (EPA);
- Vlaamse Instelling voor Technologisch Onderzoek (VITO), an independent Flemish research;
- Dredging Operations and Environmental Research Program of the U.S. Army Corps of Engineers;
- OVAM and members of the consortium (in-house knowledge and/or case studies).

Following chapters described the methodology and results. The extensive report can be consulted as appendix.

Methods

The input for a decision support tool (DST) consists of the answers given by the user on a number of questions about certain preconditions.

As a result, the decision support tool will provide a summary of the available and applicable sediment remediation techniques. The techniques included in the tool consist of a number of *in situ* and *ex situ* techniques that have been selected on the following criteria:

- They have proven their usability in former sediment remediation projects;
- Their usability has been shown in pilot sediment remediation tests;
- The technique has proven itself in soil remediation and may also be promising for sediment remediation.

In cases of *ex situ* techniques, possible methods or options for dewatering, separation, reuse and disposal need to be evaluated as well.

The output of a decision support tool will be an overview of one or several applicable remediation techniques. When multiple techniques are applicable, further evaluation might be required, based on for instance environmental, financial or social aspects. For remediation techniques that are evaluated as not being applicable, the limiting preconditions will be specified by the tool. This may inspire to engineer solutions to remedy certain preconditions.

The decision support tool must be constructed in such a way that adjustments are easy to make. Thus, it is possible to not only adapt, but also to add or remove remediation techniques, or to put them in another treatment category (phytoremediation for example, is currently regarded as a separate remediation technique, but it could also be considered as part of lagooning to enhance dewatering, or as one of the existing *ex situ* treatment techniques). Therefore, it is also possible to adapt the decision support tool to new legislations or other regulatory preconditions.

Where possible, cost estimations must be provided for each remediation option. However, the amounts stated must be used with caution, as the costs can vary greatly depending on the project.

Decision Support Tool

Applicability

Most remediation and treatment techniques discussed in this study are only feasible if certain preconditions are met. For every project, the decision support tool will evaluate which preconditions are met for which technique(s) in order to select feasible techniques.

This chapter describes all the preconditions or evaluation criteria that are considered by the decision support tool. The preconditions or evaluation criteria applied by the decision support tool can roughly be divided into the following five main groups. The detailed discussion can be consulted in the extensive report attached as appendix:

- General criteria such as the remediation objective and timing;
- Characteristics of the waterbody, such as depth, flow rate, etc.;
- Characteristics of the sediment, such as stability of the waterbed;
- Contamination characteristics, such as its potential for biological degradation;
- Other preconditions.

When contaminated sediments need to be treated ex-situ, the evaluation of feasible treatment methods requires several additional evaluation criteria or preconditions on top of the evaluation criteria already mentioned above. These additional evaluation criteria or preconditions depend largely on contamination and sediment characteristics.

Each ex-situ treatment, reuse or disposal method is subject to the legislation of the region where treatment takes place. The need for sufficient surface area varies for the different ex situ treatment methods. Most dewatering and treatment methods require a considerable amount of space (e.g., lagooning, landfarming and biological treatment). Furthermore, treatment methods may not only take up space, but also time. The need for space and time is evaluated for this criterium, to check the possibilities for on-site treatment. Furthermore, infrastructure needs to be constructed in a way that avoids emissions to air, groundwater and surface water.

In situ remediation techniques

The available remediation techniques that are currently applicable on-site - *in situ* in Flanders and for which no dredging and transportation of contaminated sediments is needed can be divided into four different main categories:

- (Enhanced) Monitored Natural Attenuation (MNA);
- *In situ* treatment (either biological, chemical or physical);
- Capping (isolation, or thin-layer);
- Phytoremediation;
- Creation of a bypass.

It should be noted however, that sediment remediation is often connected to sediment removal for navigational or hydrological purposes. Projects where the risk of contamination actually require remediation of the sediment and where only *in situ* techniques are used are still relatively scarce. The detailed discussion can be consulted in the extensive report attached as appendix:

Ex situ techniques

With *ex situ* techniques, contaminated sediments are treated at another location than where they were found. This involves removal in the form of excavation (dry) or dredging (wet) and of course transportation, which can be done with trucks over land, by ships over water, or hydraulically through pipelines.

The preferred methods for removal and transportation are usually linked and decisions are mainly based on the transportation distance, the volume of the contaminated materials and costs.

Treatment methods can be active or passive and usually take place in specialized treatment facilities. Often a dewatering step is necessary before treatment can commence (see Figure 1). A lot of dry sediment treatment methods are quite similar to their soil counterparts. After treatment, the material can be transported to its final disposal destination.

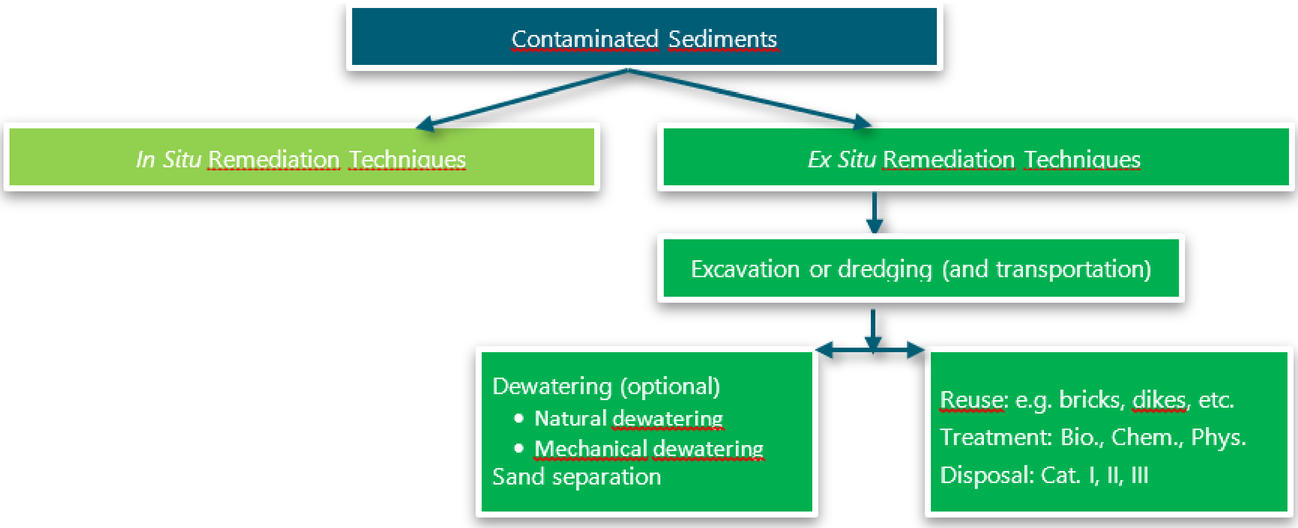

Figure 1 Flowchart for ex situ remediation techniques

Conclusion

The report is published as a reference document and the results from the study have been used for the construction of an online decision support tool (BOSS-WB).

On the basis of the answers given by the user, an online decision support tool for sediment remediation techniques will make a selection of the techniques that are suitable for this specific contamination situation. In the case of ex-situ techniques, the user may have to fill in a number of supplementary questions, on the basis of which a selection can be made between the different dewatering techniques and processing options.

In the decision support system, the user will be asked to answer a number of questions. These questions relate to, among other things, the contamination situation, the geotechnical properties of the sediment, the properties of the watercourse, the remediation objective, the duration of the remediation works and the impact on the environment.

The decision support tool (BOSS-WB) is suitable for the evaluation of remediation techniques applied within a relatively small project area with relatively similar characteristics, e.g. docks, ponds, channels, a section of a canal or river, etc. For large scale approaches (up to river basin scale) or very heterogeneous project areas, various different sets of preconditions might apply for different areas. In these cases, it might be necessary to run the decision support tool for all these various sets of preconditions in order to obtain a complete overview of useful remediation techniques for the entire area of interest.

References

The detailed list of references can be consulted in the extensive report attached as appendix

ITRC: Interstate Technology & Regulatory Council (2014) Contaminated Sediments Remediation, CS-2. Washington D.C.: http://www.itrcweb.org/contseds_remedy-selection.

SedNet (2007) Sustainable Management of Sediment Resources, Vol. 2, Sediment and Dredged Material Treatment Elsevier.

Goovaerts et al. Beste Beschikbare Technieken (BBT) voor verwerkingscentra van bagger- en ruimingsspecie (2007) Gent Academia Press.

Acknowledgements

'Sullied Sediments' has been co-funded by the European Regional Development Fund through the Interreg VB North Sea Region Programme with a grant of 2.043.413 euros with equivalent match funding from the partners involved. The project partnership includes public, private and third sector organisations based in the United Kingdom, Germany, Belgium and the Netherlands

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Interreg North Sea Region European Regional Development Fund

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Partners

The Sullied Sediments project partnership comprises 13 project beneficiaries:

Canal and River Trust (UK)

East Riding of Yorkshire Council (UK)

Ecossa (Germany)

Hamburg Port Authority (Germany)

Hamburg University of Applied Sciences (Germany)

Institut Dr Nowak (Germany)

Openbare Vlaamse Afvalstoffenmaatschappij (Belgium)

Radboud University (The Netherlands)

Socotec UK Ltd (UK)

University of Antwerp (Belgium)

University of Hull (UK)

University of Leeds (UK)

Vlaamse Milieumaatschappij (Belgium)

The partnership also receives expert advice from 12 strategic partners who form our Advisory Group:

East and North Yorkshire Waterways Partnership (UK)

Elbe Habitat Foundation (Germany)

Environment Agency (UK)

Federal Institute of Hydrology (Germany)

Foundation for Applied Water Research (Europe)

Hamburg Ministry of the Environment and Energy (Germany)

Northumbrian Water (UK)

River Hull Board (UK)

Sediment European Network Steering Group (European)

Thames Water (UK)

Vlakwa (water research consultancy) (Belgium)

Yorkshire Water (UK)

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Appendix

Desk study on available remediation techniques for contaminated sediments - Report

Sullied Sediments

Subtask 1: Desk study on available remediation techniques for contaminated sediments

OVAM

28 August 2019

Project	Sullied Sediments
Client	OVAM
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Author(s)	Anissa Smits, MSc
Checked by	ir. Herman Brangers
Approved by	Dr.ir. Samuel Van Herreweghe
Initials	
Address	Witteveen+Bos Belgium N.V. Maatschappelijke zetel: Posthoflei 5-1 2600 Antwerpen-Berchem Belgium +32 (0)3 286 75 75 www.witteveenbos.be RPR Antwerpen

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INTRODUCTION

This desk study aims to provide tools to European sediment remediation experts, policy makers, industrial companies, waterway managers and private individuals to support decisions regarding management, removal and disposal of contaminated sediments, thereby reducing economic costs and the impact of contaminants on the environment.

This study is part of the European Interreg project 'Sullied Sediments' and has been commissioned by the "Openbare Vlaamse Afvalstoffenmaatschappij" (OVAM): the Public Waste Agency of Flanders. OVAM is one of the Belgian partners in the Sullied Sediments project.
The project is carried out by a consortium consisting of sediment remediation experts from engineering and consultancy firm Witteveen+Bos Belgium N.V. and the sediment remediation companies DEME - DEC, Jan de Nul - Envisan and Ghent Dredging.

Further information concerning the Interreg or Sullied Sediment project(s) can be found on: http://northsearegion.eu/sullied-sediments/.

The project consists of two subtasks:
- Subtask 1: Desk study on available remediation techniques for contaminated sediments;
- Subtask 2: Set-up of an online decision support tool (DST) for deciding on one or more suitable remediation techniques for a contaminated sediment site.

The desk study report (subtask 1) will be published online as a reference document and the results from the study will be used for the construction of an online decision support tool (subtask 2).

By using the tool, users can acquire an overview of feasible remediation techniques for their sediment remediation problem under specific boundary conditions. A summary of the limiting conditions will be given in case certain remediation techniques are not compatible with the specified boundary conditions; for example when the required remediation goals or timing cannot be met.
The descriptions of the evaluated techniques provided in this report are included in the tool as "technical information sheets". These sheets can also be consulted separately, without actually running the tool.

Sediment remediation techniques continuously develop, thus new insights may be added in the (near) future to this study. Therefore this document and the accompanying online decision support tool may be regarded as a "growing document and tool".

1.1 Project framework

Objective

In addition to the generic objective of the desk study as presented in the introduction, the primary objective of this study is to provide a clear overview of remediation techniques that are currently available for contaminated sediments (subtask 1).
Detailed reference documents on this subject already exist, but are often aimed for use by experts. This document and the accompanying tool are meant to be of use for sediment policy makers and managers who have no expertise (yet) with sediment remediation.

Thus Flemish users of the tool could include for example members of the CIW (Coördinatiecommissie Integraal Waterbeleid) and the Port of Antwerp.

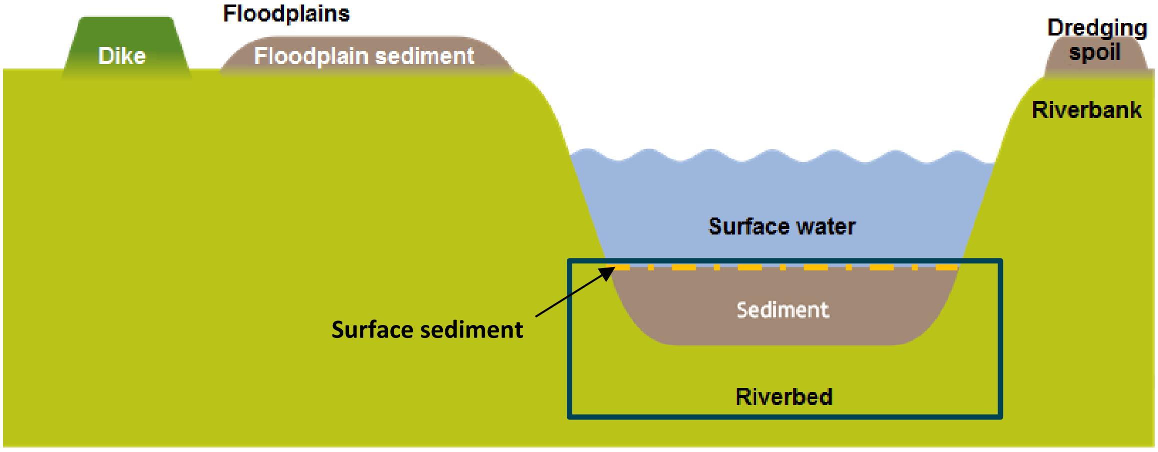
The main sources of information used for this desk study were (literature) studies and pilot projects carried out by:
- Interstate Technology & Regulatory Council (ITRC), a program of the Environmental Research Institute of the United States [Ref. 4];
- SedNet, the European Sediment Network [Ref. 5 and 27];
- United States Environmental Protection Agency (EPA) [Ref. 6 and 13];
- Vlaamse Instelling voor Technologisch Onderzoek (VITO), an independent Flemish research institute [Ref. 18 and 19];
- Dredging Operations and Environmental Research Program of the U.S. Army Corps of Engineers [Ref. 14 and 15];
- OVAM and members of the consortium (in-house knowledge and/or case studies) [Ref. 2, 22, 23, 24, 25 and 29].

The focus of this project was on Flemish cases and legislation, but results of other current and completed European (research) projects applicable in Flanders were also taken into account.

The definition of sediments

In this report, **sediment** is defined as the material at the bottom of a waterbody, including the underlying consolidated **riverbed,** that is always or nearly always covered by (surface) water [Ref. 2 (see Figure 1.1).

Figure 1.1 In this study sediment is defined as the area inside the box [Ref. 2]



OVAM distinguishes the upper part of a sediment layer, also called **surface sediment,** as a separate component of the waterway system, because it is an active layer where natural exchange processes take place with the overlying surface water (yellow surface in Figure 1.1)[Ref. 28]. Surface sediment is defined as a site-specific, biologically active layer at the sediment-surface water interface. This layer is typically 5 to 10 cm thick in fresh water systems and can thicken up to 1,0 m in estuarine and marine environments [Ref. 13]. Surface sediments are mainly composed of partly decomposed organic material, deposited soil and sediment, and weathered bedrock. They may be rich in organic matter, clay and sulfides and therefore possess a high capacity for contaminant adsorption to the sediment surface. Generally, sediment particle sizes are less than 2 mm in diameter, depending on flow conditions, morphology and upstream mineralogy.

The **bioavailability** of contaminants plays an important role within this layer, because it determines the extent to which living organisms can take up contaminants by active (biological) or passive (physical or chemical) processes [Ref. 13].
Other important elements within the waterway system include **floodplains** and **riverbanks**, where (contaminated) sediments might be deposited by either natural causes such as floods, or by human interventions such as dredging and subsequent relocation.

All these elements have a major influence on how contamination within a waterway system can spread and how the system should be remediated most efficiently. This study only focuses on the treatment and management of contaminated sediments on top or in the riverbed, i.e. the material within the box in Fig. 1.1.). For treatment/management options for contaminated riverbanks and floodplain sediments, the information provided in this study and accompanying DST may be combined with existing information on the treatment of contaminated soils (see for example https://emis.vito.be/nl/boss-bodemsaneringsselectiesysteem).

For more detailed definitions of the terms described above and other relevant terms, see also the glossary included in Appendix I.

The difference between sediments and soil

Soils and sediments are not the same and can therefore not be treated (exactly) the same way. The main differences in properties between the two are outlined in the table below. Despite these differences, some remediation techniques for contaminated sediments are directly derived from the field of soil remediation.

Table 1.1 The main differences between sediments and soil in populated areas (in the context of remediation) [Ref. 22 and 23]

Sediments	Soil
Mainly small grain sizes (clayey, loamy)	More variety in grain sizes
High water content (20-60% dry matter)	Low water content (>80% dry matter)
Relatively high organic matter content (>2%)	Limited organic matter content (<2%)
Usually contains typical cases of contamination: heavy metals, mineral oils (>C14), PAHs	Contains more varied types of contamination
Occurrence of specific contaminants such as TBT	Usually contains rocks, bricks, building- or demolition waste
Large volumes, with a relatively low pollution degree	Usually smaller volumes, with a relatively high pollution degree

Soil and sediment remediation in Europe

Sediment management is a common European issue and relates to several European directives. However, most countries or regions have (slightly) different policies and remediation approaches when it comes to contaminated sediments. Because sediments are on the borderline of soils, waste and water, this has often led to a noncoherent legislation from these different sectors [Ref. 5].
Besides that, legislation is usually complicated, especially concerning the beneficial use of dredged material.

In Belgium for example, legislation concerning soil and sediment is defined as a regional subject. Therefore, legislation and strategy considering sediment management is different in Flanders, Walloon and Brussels.

In Flanders, as of April 1st 2019, dredged or excavated materials are no longer automatically treated as a waste material (VLAREMA regulations) but as a “soil material” (VLAREBO regulations). This includes excavated soil, dredging spoil, clearance spoil, ground slurry or mixtures and bentonite sludge. The incorporation of sediments into the soil legislation might aid in removing the negative connotation of sediments with waste and thus promoting reuse.
For a more detailed insight into the specific regulations for sediments within the current soil legislation in Flanders, see Appendix II.

1.2 Decision support tool basics

The input for the decision support tool (DST) consists of the answers given by the user on a number of questions about certain preconditions (see chapter 2 for further explanation of these conditions).
As a result the DST will provide a summary of the available and applicable sediment remediation techniques. The techniques included in the tool consist of a number of *in situ* and *ex situ* techniques that have been selected on the following criteria:

- They have proven their usability in former sediment remediation projects;
- Their usability has been shown in pilot sediment remediation tests;
- The technique has proven itself in soil remediation and may also be promising for sediment remediation.

In cases of *ex situ* techniques, possible methods or options for dewatering, separation, reuse and disposal are evaluated by the tool as well (based on Flemish legislation).

The output of the DST application will be an overview of one or several applicable remediation techniques. When multiple techniques are applicable, further evaluation might be required, based on for instance environmental, financial or social aspects. For remediation techniques that are evaluated as not being applicable, the limiting preconditions will be specified by the tool. This may inspire to engineer solutions to remedy certain preconditions.

The DST is constructed in such a way that adjustments are easy to make. Thus it is possible to not only adapt, but also to add or remove remediation techniques, or to put them in another treatment category (phytoremediation for example, is currently regarded as a separate remediation technique, but it could also be considered as part of lagooning to enhance dewatering, or as one of the existing *ex situ* treatment techniques). Therefore it is also possible to adapt the DST to new legislations or other regulatory preconditions.

Where possible, cost estimations are provided for each remediation option. However, the amounts stated must be used with caution, as the costs can vary greatly depending on the project.

The DST is suitable for the evaluation of remediation techniques applied within a relatively small project area with relatively similar characteristics, e.g. docks, ponds, channels, a section of a canal or river, etc. For large scale approaches (up to river basin scale) or very heterogeneous project areas, various different sets of preconditions might apply for different areas. In these cases, it might be necessary to run the DST for all these various sets of preconditions in order to obtain a complete overview of useful remediation techniques for the entire area of interest.

1.3 Document Structure

Chapter 2 summarizes the review of possible preconditions that should be taken into account when opting for a suitable remediation technique for a specific site. In chapter 3, the available *in situ* remediation techniques are described in detail, including several case studies or (pilot) projects. Chapter 4 describes the *ex situ* techniques; methods to treat the sediments that are collected using *ex situ* techniques. These treatment methods also include disposal and reuse of sediments. Chapter 5 lists all the references used in this document.

2

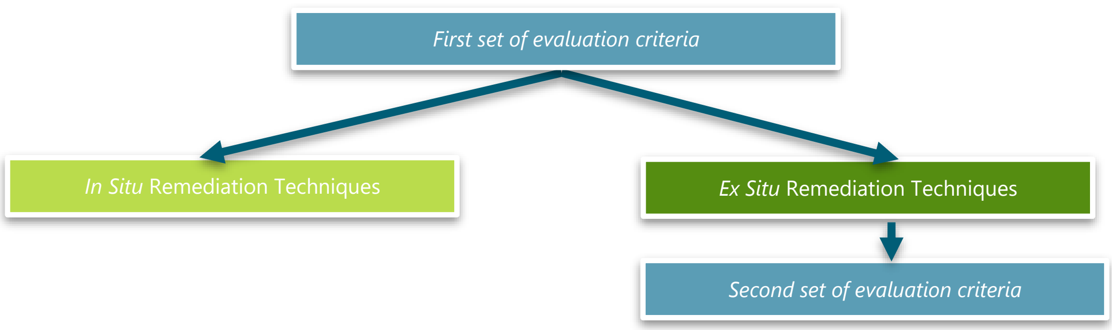
APPLICABILITY

2.1 Introduction

Most remediation and treatment techniques discussed in this study are only feasible if certain preconditions are met. For every project, the DST will evaluate which preconditions are met for which technique(s) in order to make a selection of feasible techniques.
This chapter describes all the preconditions or evaluation criteria that are taken into account by the DST. These preconditions or criteria are an adjustable feature of the DST, and can be edited, deleted or added in the future, based on new information concerning sediment remediation.

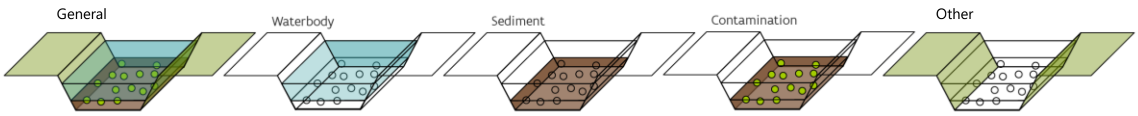
The preconditions or evaluation criteria can be grouped into two sets. With those belonging to the first set (see chapter 2.2), the DST will be able to decide whether *in situ* or *ex situ* remediation techniques will be feasible. It will also be able to select one or multiple feasible *in situ* techniques from all the *in situ* techniques that are mentioned in this document.
In order to evaluate the possible *ex situ* techniques for a certain project, the DST will need additional input from the user to asses a second set of evaluation criteria that are related to *ex situ* remediation techniques (see chapter 2.3).

Figure 2.1 Decision Support Tool flow



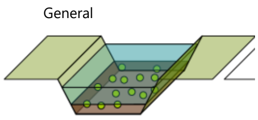
2.2 Evaluation of remediation techniques (first set)

The preconditions or evaluation criteria applied by the DST can roughly be divided into the following five main groups, which are discussed below in more detail:
- General criteria such as the remediation objective and timing;
- Characteristics of the waterbody, such as depth, flow rate, etc.;
- Characteristics of the sediment, such as stability of the waterbed;
- Contamination characteristics, such as its potential for biological degradation;
- Other preconditions.



For now, each group of criteria and each individual criterium has the same “weight” when evaluated by the DST; they are all considered to be equally important.

2.2.1 General criteria



Remediation objective(s)

The remediation goal largely determines the feasibility of the remediation techniques. For instance, when very low, close to back ground value concentrations need to be reached, *in situ* remediation techniques are seldom appropriate. Excavation/dredging may be the sole applicable technique in order to meet the remediation goal.

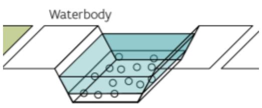
The following remediation objectives are defined in the DST for this criterium:
- To achieve a specific regulatory remediation value;
- To remove risk. This risk may either be a toxicological and/or an ecological risk or a dispersal risk;
- To obtain source control in order to prevent further spreading of the contamination;
- To set up usage restrictions: e.g. no fishing, no swimming, etc.

Timing

When rapid results are to be obtained, techniques like monitored natural attenuation will not be suitable for solving the problem in time.

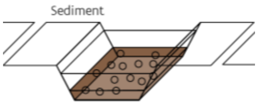
The following time frames are defined in the DST for this criterium:
- 0-1 year;
- 1-5 years;
- 5-30 years.

2.2.2 Waterbody characteristics



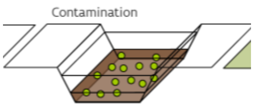
The following characteristics of the waterbody are evaluated to check the feasibility of the remediation techniques:
- Is the waterbody navigable? If so, dredging needs to be carried out periodically. In this case *in situ* techniques are likely to be inappropriate;
- The flow rate and the direction of the current needs to be known in order to predict possible spreading of the sediment;
- Is temporary resuspension of contaminated sediment acceptable? When resuspension needs to be avoided, this may render excavation/dredging unsuitable as a remediation technique;
- The depth of the water:
  - Periodically dry areas;
  - Shallow water (where excavation is possible);
  - Deep water (where dredging is possible).

2.2.3 Sediment characteristics



The following characteristics of the sediment are evaluated:
- Is the sediment susceptible to erosion? If so, a remediation technique such as (E)MNA will not be feasible because of the continuous spreading of contaminated sediments;
- Presence of rocks or debris? The presence of debris may render the application of amendments impossible if for instance a chemical *in situ* technique is anticipated;
- The stability (geotechnical quality) of the sediment. If the sediment is unstable, capping will be not feasible without additional measures.

2.2.4 Contamination characteristics



In case *in situ* remediation methods are considered, the type of contaminant will determine the feasibility of certain remediation techniques. Contaminants are divided into contaminant groups with comparable physical and chemical characteristics. In the DST, biological degradability, the possible formation of more harmful or mobile by-products and the mobility of the contaminant groups are evaluated.

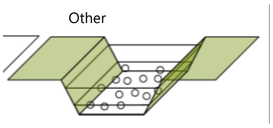
The following groups of contaminants are distinguished:
- Common contaminants in sediments of which their behavior is reasonably well known:
  - Mineral oil fractions (<C14);
  - Mineral oil fractions (>C14);
  - PAH;
  - PCB;
  - Heavy metals;
  - Cyanides;
- Common contaminants in sediments of which their behavior is not well known*:
  - Radioactive substances;
  - TBT (organotin compounds);
  - PFAS;
  - Chlorinated pesticides;
  - Asbestos;
- Common contaminants in soil, which may also have to be included in (future) sediment remediation:
  - BTEX
  - Chloro-ethenes;
  - Chloro-ethanes.

*Emerging contaminants such as pharmaceuticals, nano-/microplastics and invasive plants (e.g. Japanese knotweed) or animals are not yet included in the tool due to lack of information on behavior and possible treatment methods.

The feasibility of remediation techniques based on biological remediation depends, among other things, on the concentrations that are found in the sediment. As a general rule it can be stated that the presence of free product will inhibit or render biological treatment insufficient.

Besides the characteristics of the contaminants, it is important to indicate if there exists a risk of spreading of the contaminants towards groundwater or surface water. If so, this will render long term remediation solutions inappropriate.

2.2.5 Other preconditions



Some important other evaluation criteria are:
- What is the land use of the surrounding areas? Are there certain (re)development plans for the area that should be taken into account? Are remediation works with a big impact, like excavation or dredging, tolerable?
- Is the area located in a protected zone?
- Can the remediation site be reached by heavy equipment, such as trucks and excavators?
- Is there room (both spatially as juridically) to bypass the contaminated part of the waterway? Or to create on-site remediation infrastructure (lagooning/landfarming)?
- Is there a local need for reuse of the material (for example with Geotubes®)?

2.3 Additional criteria for *ex situ* remediation (second set)

When contaminated sediments need to be treated *ex situ*, the evaluation of feasible treatment methods requires several additional evaluation criteria or preconditions on top of the evaluation criteria already mentioned above. These additional evaluation criteria or preconditions depend largely on contamination and sediment characteristics and are discussed in more detail below.

It might be possible that the outcome of this second criteria evaluation will be that none of the existing *ex situ* remediation techniques will be feasible due to the non-treatability of the sediment.

2.3.1 Sediment characteristics

The organic content and grain size distribution of the sediment are important characteristics regarding dewatering and treatment of contaminated sediments. These characteristics determine:
- Contamination levels (contaminants absorb better on the fine fraction);
- Treatability criteria;
  - A large fine fraction content renders physicochemical treatment unsuitable;
  - Sediments with a large fine fraction are more difficult to dewater and more difficult to handle, for instance when biological treatment is anticipated;
  - Water content needs to be less than 30% for thermal treatment of sediments.

2.3.2 Contamination characteristics

In case contaminated sediments are treated by using biodegradation (biological treatment/landfarming), the same contaminant restrictions are applicable as for the remediation techniques mentioned in chapter 2.2.4.

In case thermal desorption is considered, stringent boundary values exist for heavy metals and sulphates. Asbestos is also a key contaminant to investigate in and evaluate for each treatment method. For guidelines concerning asbestos in sediments (and soil) see the OVAM website: https://www.ovam.be/asbest-in-de-bodem#reinigen) and the code of good practice for exploratory soil investigations, descriptive soil investigation and risk analysis for asbestos contamination [ref. 42].

2.3.3 Regulatory criteria

Each *ex situ* treatment, reuse or disposal method is subject to the legislation of the region where treatment takes place. In Flanders regulatory conditions are defined as follows:

- For reuse of sediments without active treatment:
  - As soil: Compliance with VLAREBO annexes II, IV and V;
  - For constructional purposes: Compliance with VLAREBO annexes VI and VII.
- For biological, physicochemical or thermal treatment:
  - Code van goede praktijk voor grondreinigingscentra (codes of good practice for soil remediation centers);
  - Acceptation criteria of the treatment plant in question.
- For disposal:
  - Compliance with VLAREM II subsection 5.2.4.1;
  - Specific acceptation criteria of the disposal site.

2.3.4 Treatment plant characteristics

The need for sufficient surface area varies for the different *ex situ* treatment methods. Most dewatering and treatment methods require a considerable amount of space (e.g. lagooning, landfarming and biological treatment). Furthermore, treatment methods may not only take up space, but also time.
The need for space and time is evaluated for this criterium, to check the possibilities for on-site treatment.

Furthermore, infrastructure needs to be constructed in a way that avoids emissions to air, groundwater and surface water.

3

IN SITU REMEDIATION TECHNIQUES

3.1 Introduction

This chapter describes the available remediation techniques that are currently applicable on-site - *in situ* in Flanders and for which no dredging and transportation of contaminated sediments is needed.
These techniques can be divided into four different main categories:
- (Enhanced) Monitored Natural Attenuation (MNA);
- *In situ* treatment (either biological, chemical or physical);
- Capping (isolation, or thin-layer);
- Phytoremediation.

It should be noted however, that sediment remediation is often connected to sediment removal for navigational or hydrological purposes. Projects where the risk of contamination actually require remediation of the sediment and where only *in situ* techniques are used are still relatively scarce.

3.2 (Enhanced) Monitored Natural Attenuation: (E)MNA

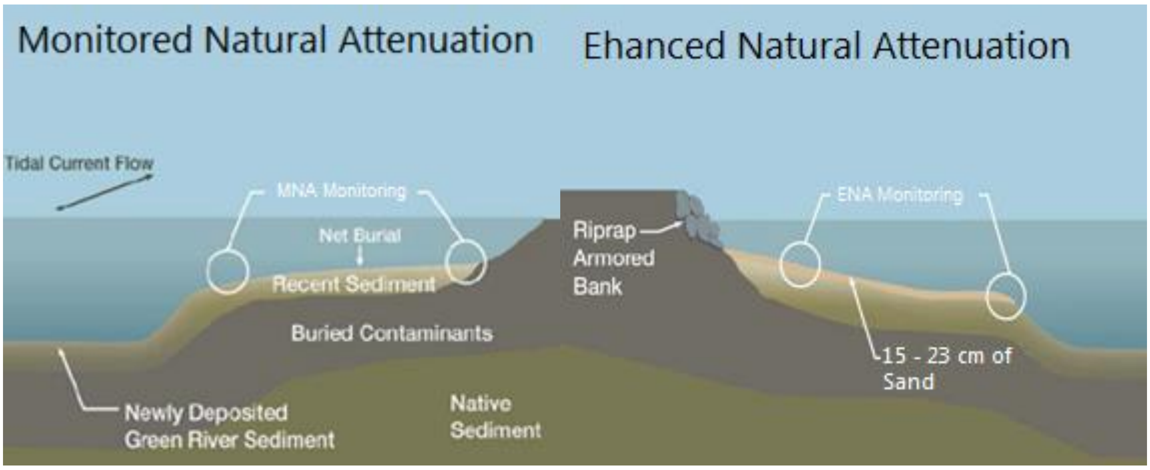
Description: MNA
Monitored Natural Attenuation (MNA) is a passive remediation technique that uses natural processes to protect the environment from exposure to contaminants [Ref. 4]. Its primary goal is to contain, degrade, or reduce the bioavailability or toxicity of contaminants in surface sediment over time [Ref. 13].

With MNA, contaminated sediments are left in place and are monitored for ongoing natural physical, chemical and biological processes that transform, immobilize, isolate, or remove contaminants until they are no longer a risk [Ref. 4]. Natural processes that contribute to MNA may include sediment burial, contaminant sequestration or degradation (by for example, precipitation, adsorption, or transformation) (Figure 3.1).
In order to successfully use this remediation technique, it is important to have a thorough understanding and control of the contamination source(s), the (bio)geochemical and physical conditions and its (predicted) interaction with the environment. Typically, MNA is considered at sites where the sediment bed stability is consistent enough, so sediment erosion and dispersion/dilution, will not pose a threat.

This technique is different from taking "No Action", since it includes source control, minimal potential for recontamination from upstream sources through sediment transportation, and requires that assessment, modelling, and long-term monitoring take place to verify the remedy [Ref. 13]. Monitoring usually consists of a periodic collection and analysis of sediment samples, to ensure that human health and ecological risks are reduced to expected levels within a specified time frame (e.g. 10 years) [Ref. 12]. Institutional controls such as fish consumption advisories, fishing bans, or waterway or land use restrictions are also common components of a MNA remedy [Ref. 12].

Description: EMNA
Enhanced Monitored Natural Attenuation (EMNA) follows the same principles as MNA and relies on the natural recovery processes that are already occurring in the soil, with the addition of a thin layer of clean or stimulating material on top of or mixed within these areas (approx. 10 to 30 cm thick, Figure 3.1). This method is usually utilized when the rate at which natural recovery processes are occurring, is insufficient to reduce risks within an acceptable time frame. EMNA should be applicable at a larger number of sites than MNA, since natural deposition of sediment is not required for EMNA [Ref. 17]. In general, EMNA is considered the same as thin-layer capping, assuming that the layer thickness placed on top is larger than the depth of the well-mixed bioturbation zone, see chapter 3.4 [Ref. 17].

Figure 3.1 The difference between Monitored Natural Attenuation (MNA) and Enhanced MNA (EMNA): Enhanced MNA increases and/or accelerates the natural recovery process by for example adding an extra layer of sand and addition of an armored shoreline. Monitoring of the recovery process remains a key element throughout the execution of both techniques [Ref. 13].



The main purpose of this extra layer is to reduce the amount of available surface contaminants by natural mixing of this clean material with underlying contaminated sediments through processes such as bioturbation. Additionally, it also accelerates the natural physical burial process. Other than the application of a thin-layer cap consisting of clean material, injections with activated carbon can be used to adsorb compounds and reduce bioavailability as well.
It is imperative to place the capping material in a careful and controlled manner, in order to minimize disturbance of the contaminated sediments and to avoid dispersion of contaminants during placement. In contrast to an engineered cap, which is intended to permanently remain stable and isolate contaminants in the underlying sediment, material placed for EMNA is not intended to resist disturbances (such as bioturbation or erosion).

MNA and EMNA are often combined with active remediation techniques such as dredging and *in situ* capping, in order to achieve the required remediation goals. They are often applied to effectively manage low levels of residual contaminants [Ref. 12].

The use of (E)MNA at a site requires an in-depth understanding of both the biogeochemical behavior of the elements of interest and the specific environmental conditions at the given site that will influence chemical and phase partitioning and biological interactions. The behavior of trace elements and metalloids in the environment is complex and depends on many interrelated chemical, biological, and environmental processes. The interaction between these natural processes that might contribute to natural attenuation usually determines the long-term risk trends at a specific site. The three processes are discussed in more detail below:

Physical processes (burial and dispersion)
Physical processes include natural burial through ongoing sedimentation and mixing of cleaner deposited surface sediments with contaminated deeper sediments. Burial occurs in depositional environments where the rate of sediment deposition exceeds the rate of erosion and transport. Meanwhile, contaminant burial results in compaction of the underlying sediments, which reduces the vertical transportation of water and dissolved components [Ref. 13].
Mixing can be caused by hydrodynamics, but bioturbation is often modelled as a physical process as well, since the net result is the physical mixing of sediments and exchange of sediment pore water with the overlying water column [Ref. 13].

Erosion, groundwater upwelling, pore water transportation and downstream dispersion/transportation of contaminated sediments are other examples of physical processes that can reduce the amount of surface contaminants at a specific site. Benthic fauna can also act as vectors for transporting contaminants into the food web, which is sometimes considered as a physical process [Ref. 13].
However, extreme erosional events caused by phenomena such as high river flow or storm waves can expose contaminated buried sediment. These eroded sediments could re-contaminate local surface sediments or be transported farther downstream, where they might create new areas of concern.

Chemical processes (sorption, precipitation, degradation and radioactive decay)
Sorption, precipitation, degradation and radioactive decay can all reduce the bioavailability and/or toxicity of a contaminant. During (ad- and ab)sorption, dissolved contaminants bind themselves onto or in the solid sediment matrix. Sorbed compounds are not bioavailable. Precipitation usually occurs when contaminants in a solution reach their saturation point and precipitate, thus reducing their bioavailability. Degradation is the transformation of a toxic component into a less toxic of non-toxic component. However, degradation can also lead to more toxic daughter products. Radioactive decay of a pollutant can cause a loss in toxicity as well, depending on the half-life of the occurring contaminant.

Sorption and precipitation are reversible processes. Changing conditions can lead to either desorption of bound compounds from the sediment or can cause precipitated particles to dissolve again. These processes are usually directly or indirectly influenced by microbiological and physical processes that govern the fluctuation of reactive chemical particles in sediments. They influence the partitioning of a chemical between solid and aqueous phases within the sediment bed and water column, thereby affecting the fate and bioavailability of the contaminant.

The fate of metals for example, depends on environmental factors such as hydrogen ion activity (pH), redox potential, alkalinity, presence of sulphides and organic carbon content. Likewise, the fate of organic contaminants might be affected by abiotic chemical processes such as photocatalysis and sorption processes when naturally occurring carbon and humic sources are present within the sediments.

Biological processes (degradation, transformation, bioturbation)
Microbes (bacteria or fungi) present in sediments have an influence on the contaminant concentration and can degrade or transform organic chemicals into less toxic forms. Whether this can occur depends on the type of organic compounds, the microorganisms present in the sediment, geochemical conditions and the substrates. All are needed to sustain biodegradation and metabolic processes [Ref. 4]. For example, low molecular weight hydrocarbons may be partially or completely degraded, while high molecular weight hydrocarbons, phthalates, dioxins and PCBs are (more) persistent and require a large amount of time for biodegradation to occur. Metals on the other hand may become chemically bound to sulphides and get immobilized, but will not be degraded. Changing redox conditions might remobilize the metals again. Furthermore, benthic mixing and bioturbation caused by burrowing or sediment-dwelling organisms also play a role in reducing the (surface) bioavailability of contaminants by further burying the contaminated sediments and by providing more oxygen and thus stimulating further biological degradation. In some cases however, bioturbation can also cause upwelling of contaminants.

Advantages and limitations of (E)MNA
All techniques described above are non-invasive and do not destroy or disrupt biologically active zones, which can be useful in sensitive habitats. (E)MNA generally also avoids contaminant resuspension, except when unanticipated extreme erosional events take place.

In general, the technique can be used for the remediation of sediments with low contamination levels of mineral oil (<C14), and chloro-ethenes. It is however not suitable for the remediation of heavy metals, PAHs and cyanides.

The main drawback of using (E)MNA is that the process of natural recovery takes a relatively long time, during which continuous monitoring is needed. Model predictions can help to decrease the amount of monitoring needed, but the models often lack data to provide truly accurate predictions and processes are often very site specific.
Moreover, the long-term effectiveness of (E)MNA is still unknown. Where natural recovery has been monitored, decreases in sediment contaminant concentrations have been observed, but the long-term monitoring of fish tissue contaminant concentrations (e.g. 5 years) is either insufficient to fully evaluate risk reduction, or has shown mixed trends [Ref. 13]. In general, natural recovery occurs over a longer timeframe than a typical active remedy (such as dredging), and longer periods of fish tissue monitoring may be needed to measure the effect of natural recovery on tissue concentrations.

Another control measure that can be used when applying (E)MNA is the installation of sediment traps at fixed intervals along a river or stream to prevent spreading if the contaminants do not degrade as expected.

Other significant relative advantages and limitations of the use of (E)MNA are listed in Table 3.1 below:

Table 3.1 Advantages and limitations of (E)MNA [Ref. 17]

Advantages	Limitations
- Least invasive and disruptive to aquatic and benthic habitats; - Least complex, quickest to implement; - Can be used to remediate a variety of dissolved-phase contaminants; - No infrastructure or space required for staging equipment and/or materials;	- Sediment contaminants remain in place, often for an extended period of time; - More time may be required to reduce exposure and risks to adequate levels (e.g. contaminants may have extended chemical and/or biological half-lives); - Disturbances (extreme erosion, sediment upwelling, bioturbation) can cause increased exposure and risks; - Monitoring costs can add up significantly over time;

Advantages	Limitations
- Typically smallest overall costs, compared to other remedial technologies.	- Incompatible with some waterway uses, e.g. navigational dredging; - Institutional controls required; - Uncertain of long-term effectiveness.

Social aspects
(E)MNA can be met with resistance from the public as contamination is "left in place" for some time, even though the process of natural attenuation is being monitored. The possibility of contaminants being reintroduced into the environment might also be cause for concern.
The acceptance of natural attenuation as a remediation strategy depends on the time needed to reach acceptable contamination concentrations, as well as whether those attenuation processes are permanent or reversible [Ref. 12]. Communication with the public and stakeholders regarding the ongoing process is crucial.

Costs
If appropriate for the site conditions, (E)MNA is a relatively easy, low-cost, low-risk option that can provide a high level of effectiveness and durability. However, exact costs are quite project specific and no reliable data is available on this matter.

State of the art/experience
(E)MNA has been used as a successful technique in full scale projects in the United States. Effectiveness and recovery time largely depend on the type and extend of the contamination and are very site-specific.
The application of (E)MNA on soils on land is widespread in Flanders and the natural processes involved are well-known. These experiences can be of great importance for any future use of (E)MNA on sediments in waterways.

Cases

Twelve-Mile Stream/Lake Hartwell, Pickens County, SC [Ref. 4]	
Environment	Freshwater lake
Scale	11,5 km long stretch of Twelve-Mile Stream and 2.95 km^2 of the Twelve-Mile Stream arm of Lake Hartwell
Contaminants of concern	PCBs
Source control achieved prior to remedy selection?	Yes
Final remedy	MNA for Twelve-Mile Stream arm of Lake Hartwell
Expected recovery time	12 years
MNA viewed as a success?	Yes

Site Description
The primary source of the contaminants is a company named Sangamo Weston which used PCBs from 1955 to 1977.
It is estimated that 3% of the yearly average amount of PCBs used, approximately 181.500.000 kilograms, ended up being discharged into Town Stream, which is a tributary to Twelve-Mile Stream and Lake Hartwell.

Contaminant Description
Sediment PCB concentrations in a 11,5 km long stretch of Twelve-Mile Stream were originally measured between 1–3 ppm at the surface and higher in deeper sediments. At some locations concentrations up to 61 ppm PCBs were found. The affected area in Lake Hartwell covers approximately 2.95 km^2 with a total estimated volume of 3.6 million m^3 of PCB-contaminated sediment.
In 1991-1992, maximum PCB concentrations measured in sediment core samples from the upper section of Lake Hartwell showed concentrations of 5–11 ppm. PCB concentrations in sediment in the lower part of the lake were typically < 1 ppm.

Remedial Objectives

Twelve-Mile Stream/Lake Hartwell, Pickens County, SC [Ref. 4]

The selected target clean-up standard for sediment was 1 ppm PCBs, based on technical feasibility. For fish, the target clean-up level was set on 2 ppm PCBs, a level which was also based on technical feasibility. This target was modelled to be reached within 12 years (by 2004).

Remedial Approaches

Sediment cores were collected in Lake Hartwell and provided data used to determine the vertical profile of PCBs in the sediment column. These data indicated that higher PCB concentrations were buried beneath sediment with lower PCB concentrations. Sediment Transport Modelling predicted net sediment accumulation in the lake to reach 5 to 15 cm/yr. A water-quality model was developed to determine the fate of PCBs in the system over time, and results of this model indicated that PCB concentrations in the water column and sediment of Lake Hartwell would generally decrease over time, even in the absence of any intrusive remediation. The primary mechanisms for PCB reduction over time were transportation and burial.

Monitoring

Annual biota and sediment monitoring occurred in the spring of each year since 1994, including surface sediment sampling at 21 locations in Twelve-Mile Stream and Lake Hartwell and (shell)fish tissue analyses in Lake Hartwell.

Sediment data from 2004 indicated that surficial sediment PCB concentrations in Twelve-Mile Stream have decreased steadily since 1990 due to ongoing physical processes such as burial, mixing/dispersion, and PCB dichlorination. However, PCB concentrations in fish did not decrease as much.

In 2006 it was decided that two of the three dams on the Twelve-Mile Stream Arm of Lake Hartwell had to be demolished in order to enhance the ongoing natural transport of clean sediment downstream to speed burial of the PCB contaminated sediment in Lake Hartwell. The removal of these two dams was completed in 2011.

3.3 In situ treatment

In situ sediment treatment involves the application or mixing of beneficial substances directly into or on top of contaminated sediments, in order to remediate these sediments or accelerate the (natural) remediation process. Mixing can be achieved passively, through natural biological processes such as bioturbation, or actively through mechanical means such as drilling or injection devices [Ref. 4].
The application of *in situ* treatment can be a combination of biological, chemical and physical forms of treatment. It can also be combined with other remedial technologies such as dredging, capping, and (E)MNA. For example, *in situ* treatment can be used below a cap or combined with (E)MNA to accelerate ecosystem recovery.

In situ treatment may be preferred in areas with higher contaminant concentrations, where (E)MNA cannot achieve remediation goals in an acceptable timeframe or where immediate risk reduction is needed. *In situ* treatment can also be used for any remaining residuals after contaminated sediments have been removed. It is an effective and sustainable remediation strategy with little impact on the surrounding environment [Ref. 4]. Remedial objectives for *in situ* treatment typically include: reducing contaminant mass, toxicity, and/or bioavailability within the sediment's biologically active zone [Ref. 17].

Many conditions, advantages and limitations mentioned in the chapters on (E)MNA (3.2) and capping (3.4) are usually applicable to *in situ* treatment as well. The applicability of *in situ* treatment greatly depends on whether the beneficial substances are mixed passively or actively into the contaminated sediments. General advantages and limitations of the treatment method are listed in Table 3.2.
Advantages and limitations of specifically biological, chemical of physical *in situ* methods are discussed in more detail in the respective chapters below.

Table 3.2 General advantages and limitations of *in situ* treatment [Ref. 17]

Advantages	Limitations
- Less costly than some other technologies; - Could eliminate need for contaminant removal; - Concept of *in situ* treatment may be attractive to regulatory authorities and other stakeholders; - Can be used to remediate a wide variety of dissolved-phase contaminant types and concentrations (although multiple treatment agents may be needed); - Could reduce or eliminate the need for long-term monitoring, maintenance, and repair.	- Some approaches are still being developed and are gaining more international acceptance; - Challenges with effective and controlled delivery of treatment agents (in deeper-water environments), especially when active mixing is applied; - Not usually appropriate for treating NAPLs; - May be incompatible with some waterway uses, e.g. regular navigational dredging; - Disruptions to the benthic ecosystem, especially when active mixing is applied.

3.3.1 Biological *in situ* treatment

Description (biodegradation, -augmentation, -stimulation and inhibition)
In situ bioremediation is based on the *in situ* stimulation of aerobic and/or anaerobic bacteria populations, by adding "enhancers" such as oxygen- and nutrient-rich minerals (containing for example calcium nitrate, phosphate and ferric chloride) and ozone [Ref. 4, 18, 19]. These enhancers are usually already present in natural sediments, but in lower concentrations. Sometimes extra bacteria populations are added as well. The addition to these stimulants (enhancers and/or extra populations) will increase the growth of endemic microorganisms, which will further accelerate the process of natural mineralization and decomposition of organic contaminants such as mineral oils and PAHs. This process usually takes 3 to 10 months [Ref. 18, 19].

Inhibition can also be a form of bioremediation, because it prevents the transformation of contaminants into more toxic forms by adding certain compounds. The release of methylmercury, for example, can be prevented by the addition of nitrate [Ref. 4].

During the actual execution of a bioremediation project, continuous monitoring and adjustment is needed as well. Monitoring usually consists of measuring the amount of contaminant degradation and volume reduction of the sediment layer (up to 50% for sediments with a very low density and a high organic content, [Ref. 18, 19]). Other treatment results can include improved transparency of the water column, reduced eutrophication caused by improved oxygen management, less odor nuisance and the rehabilitation of natural ecosystems.

Depending on the type of contaminant(s), degradation under aerobic circumstances is stimulated most often, because it is usually faster compared to anaerobic degradation and because it releases odorless nitrogen and carbon dioxide, instead of methane and H_2S.

Advantages and limitations

This technique causes minimal disturbance to the environment (especially when applied passively) and causes less resuspension of contaminated sediments, when compared to dredging. Under the right circumstances, it can also cause significant sediment-volume reductions [Ref. 7], which is favorable when managing waterways. Moreover, energy consumption is minimal and there is no consumption of water.

However, optimal conditions for bioremediation are quite specific. The technique is only applicable in fine organic-rich sediments, contaminated with biodegradable microcontaminants such as mineral oil and (simple) poly-aromatic hydrocarbons. This method does not work for non-degradable heavy metals, but these can precipitate when sulphide is formed due to reducing biological processes and stable metal sulphide precipitates are established.
In addition, the ambient temperature must be between 6 and 30 °C, with sufficient nutrients and usually also oxygen available for bacterial growth, as well as the absence of substances that are toxic for bacteria [Ref. 7].

The inability to guarantee and control continuous optimal biodegradation conditions causes *in situ* treatment to be much less efficient and more time consuming when compared to *ex situ* treatment options. Furthermore, the formation of intermediate by-products might have negative effects, as full degradation is sometimes difficult to achieve [Ref. 4].

Social aspects

Public acceptance will mainly depend on sufficient proof that there are no harmful effects.

Costs

Costs are expected to be lower than those for removal and disposal, but monitoring can be costly. Estimated prices range between € 15-30 /*in situ* m^3, which can be lower if the technique will be applied on full scale [Ref. 5; Ref. 7]. These costs cover laboratory costs needed to select and cultivate microorganisms and the subsoil injection of these microorganisms and nutrients, but not monitoring and sampling procedures.

State of the art/experience

Experiences were negative in the Netherlands (1994, 1997) due to the use of additives that proved to be inactive [Ref. 30]. More promising results in pilot tests were reported in Belgium, the United States, Canada and France. However, it is not yet an efficient technique [Ref. 4].
The method of *in situ* bioremediation remains highly controversial and no unambiguously positive results have been achieved yet [Ref. 7].

Cases

Limnofix In-situ Sediment Treatment (LIST), developed by the National Water Research Institute of Environment Canada [Ref. 31, 32]

LIST uses specially designed equipment to inject chemicals directly into contaminated sediments that will enhance bacterial activity and hence contaminant degradation. Biodegradation of simple organic contaminants including PAHs, BTEXs, and petroleum hydrocarbons has been achieved. However, the removal efficiency of full scale treatment of sediment heavily contaminated with PAHs and TPHs is unknown [Ref. 32].
LIST has been used in water depths from 2 to 23 m and has achieved treatment rates of 4000 m^2/day. Costs vary with the treatment area size and goal of the project and range from EUR 30 to 70/m^2 [Ref. 31].

3.3.2 Chemical *in situ* treatment

Description (transportation, degradation, adsorption and immobilization)

Chemical *in situ* treatment follows the same approach as biological *in situ* treatment, but instead of bacteria or fungi and nutrients, certain reactive chemicals are introduced in the contaminated environment.

Chemicals such as activated carbon (AC), organophilic clay, zeolites, bauxite, and iron oxide/hydroxide can physically or chemically bind (adsorb) hydrophobic organic contaminants and metals, which reduces their bioavailability and mobility. Adsorption and immobilization can be used for PCBs, PAHs, dimethyl dioxane, dioxins/furans, chlorinated benzenes, tributyltin (TBT) and mercury.

Other minerals, such as apatite (a calcium phosphate mineral) might be used as well, as they can react with metals to form phosphate minerals that can sequester divalent metals (Cd, Co, Hg, Ni, Pb, Zn, and U) and reduce toxicity to aquatic organisms by reducing their bioavailability [Ref. 4].
Another option is the addition of zero-valence iron (ZVI), combined with a bimetal catalyst, which can chemically reduce and subsequently immobilize a variety of compounds, such as mixtures of PCBs and other chlorinated solvents, nitroaromatic compounds, arsenic, chromium (VI) and lead (II) in aqueous solutions and dichlorodiphenyltrichloroethane (DDT) and related compounds, through reductive dehalogenation [Ref. 4; Ref. 5].

Advantages and limitations

The application of AC is the most widely used and tested version of the techniques described above [Ref. 4]. AC amendments need time to become effective, as sorption does not reach equilibrium immediately and complete mixing of amendments with the contaminated sediment takes time as well. Theoretical studies have shown that AC is not easily broken down in the environment and binding remains strong, resulting in a high confidence in the short-term and long-term fate of the bound chemicals [Ref. 4].
In general, passive chemical *in situ* treatment with these kind of materials is considered the same as thin-layer capping with active sorptive materials like AC.

Both apatites and ZVI's have only been successful in laboratory studies on sediments, but they have been successful in full scale projects for soils on land [Ref. 23]. Apatite has a relatively short reaction time (in the order of weeks) which could be a great advantage compared to other methods. Incomplete reactions with ZVI's on the other hand, could potentially produce compounds that are more toxic than parent compounds. Long-term studies on the effectiveness of *in situ* chemical treatment are not yet available.

Social aspects

In situ treatment implies that any disturbance will be limited to the project area, which is seen as one of its main advantages.

Costs

Unknown in Flanders.

State of the art/experience
Recent large scale references are scarce.

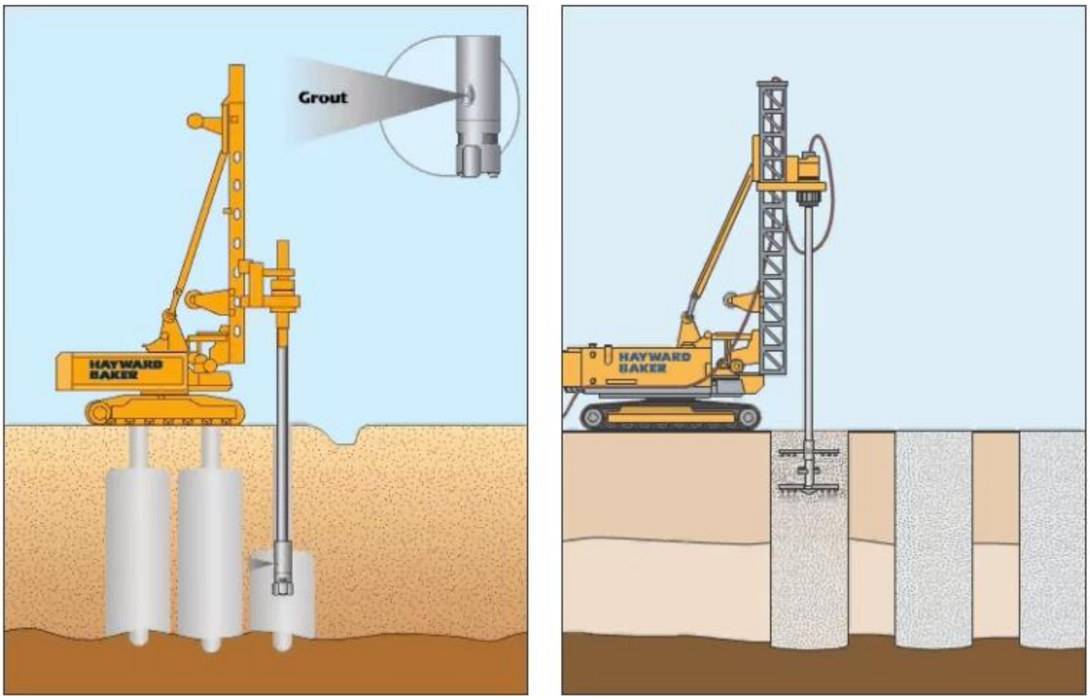
Cases
See SedNet [Ref. 5] for some older reference projects.

3.3.3 Physical *in situ* treatment

Description (stabilization or solidification)
Physical *in situ* treatment is the addition of chemicals or cements, such as Portland cement, quicklime, and fly ash, which then encapsulate contaminated sediments into a solidified mass that reduces contaminant mobility and bioavailability [Ref. 4].

An example of this technique is Soft Soil Improvement® (SSI). SSI is a physicochemical *in situ* stabilization technique which uses both high pressure hydraulic grout injection and mechanical mixing of soft soil and cement grout, see Figure 3.2.
Originally, both techniques were developed separately to strengthen and stiffen soft soil. By adding specific binding agents to the injected cement grout however, these techniques can also be used to immobilize and/or stabilize contaminants in sediments. Moreover, the injection of certain bacteria can also enhance the biodegradation of organic contaminants [Ref. 5].
The technique is suitable for soft soils and sediments in river beds, lakes, etc. Particularly heavy metals, PCBs and TBT can be immobilized into a solidified mass, which leads to a reduction of leaching, erosion and/or dispersion of these contaminants, because they are no longer “floating around”. As a bonus, the addition of iron to the sediments will also reduce the mobility of phosphorus, thus improving the water quality above the sediment bed [Ref. 5].
In another technique; the introduction of large amounts of organic matter, iron and sulphates will cause the formation of very low soluble iron sulphides, which will precipitate with heavy metal sulphides [Ref. 5].

Figure 3.2 Soft Soil Improvement® is a combination of jet grouting (left) and soil mixing (right) [Ref. 9]



Advantages and limitations

This technique does not cause disturbance of areas other than the contaminated area. It is an *in situ* technique that does not require any transportation of contaminated sediments, nor any treatment- or disposal facilities [Ref. 5].

Soft soil improvement can be applied in sediments with higher concentrations of contaminants than other *in situ* techniques, but is considered to be a more active and invasive form of in situ treatment.

Social aspects

Energy consumption for this technique is relatively low and there is no emission or production of waste materials. The amount of water and additives consumed depends on the type and degree of contamination. Because contaminants are left in place, this type of treatment might be a cause of concern for the public. Clear communication is considered necessary.

Costs

Costs typically range between € 60-100 / *in situ* m^3 [Ref. 5].

State of the art/experience

Soft soil improvement has been applied successfully in Belgium [DEC, see below] and in Germany and France.

Cases

Obourg, Belgium - DEC - 2011

Environment	Former manufactured gas plant (sediment storage lagoons)
Scale	110,000 m^3
Contaminants of concern	Coal Tar (PAHs, DNAPLs, LNAPLs)
Final remedy	Solidification of soft sediments

Site Description

The Walloon authority SPW (Service Publique de Wallonie) wanted to install a new sediment treatment center along the Canal du Centre, which is known for its four large ship elevators (UNESCO world heritage). Two sediment storage lagoons that were present on the site located near Obourg were filled with soft poorly consolidated sediment. The proposal was to solidify the soft sediments (110,000 m^3 in total) and use the product in the construction of base layers and in new dykes.

Objectives

The objective of the work was to solidify the soft sediments and turn them into a construction material that could achieve a compressibility modulus of 11 MPa (or 17 MPa at surface layer). The execution method chosen by DEC, the contractor, imposed an extra boundary condition: after treatment with binder, the material had to be stockpiled for several weeks before being compacted in its final place, ruling out the use of cement as an additive.

Formulation

The clayey-silty sediment present at the site varied between 40% dry matter content (very soft) to 65% dry matter content (plastic). The sediment was not solidified with a traditional cementitious binder, as this would result in a short term curing. Therefore a specific additive which absorbs the sediment's pore water, improves the structure, and flocculates the clay particles, was applied. These properties result from using paper sludge ash, a meta-kaolin based fly ash, produced from incineration of paper mill waste. This product can be found in sufficient large quantities in most countries. On this site an average dosing of 20 % w/w was used, resulting in the use of about 35,000 tons of paper ash.

Method

Although the initial plan was to use a batch-wise pug-mill mixing plant, a less complex and cheaper method was applied. Standard soil liming equipment (dosing and rotary mixing) was used on layers (or lifts) of 0.5 m, and then scraped and stockpiled by a bulldozer.

Testing

Validation of the solidification treatment was carried out on both laboratory- and field scale. Freshly treated sediment was sampled and compacted in a proctor mold, tested immediately, at 14 days and after 28 days by means of CBR (Californian Bearing Ratio). The results can be correlated to field plate tests, which were also carried out to confirm the target values were achieved.

Obourg, Belgium - DEC - 2011

3.4 Capping

Description

Capping is the process of placing a clean layer of sand, clay or another material on top of contaminated sediments in order to prevent or minimize resuspension, transport and emission of contaminants to other sites. The cap can consist of different layers and might include geotextiles, which aid in layer separation and/or geotechnical stability and integrity, or composite geotextiles that contain reactive/adsorptive materials, such as activated carbon (AC) or apatite, to enhance their protective function (see also chapter 3.3, on *in situ* treatment) [Ref. 4]. Non-reactive caps are usually referred to as conventional caps and often consist of sand or a similar granular material. Reactive caps are also called active or amended caps.

Usually, a distinction is made between **isolation capping** and **thin-layer capping**. These two major sediment capping "strategies" differ mainly in terms of respective objectives for cap performance [Ref. 17]. Performance objectives for isolation capping typically include: physical and chemical isolation of the cap's biological zone from contaminants underneath and stabilizing the sediment against erosion by natural and human-related forces. The main performance objective for thin-layer capping is to reduce, but not necessarily eliminate, biological exposure to contaminated sediments. As mentioned in chapter 3.2, thin-layer capping with conventional materials is generally considered identical to EMNA, although remedial objectives may be somewhat different.
In reality, site-specific sediment caps are often a combination of isolation and thin-layer capping, both in terms of cap design and performance objectives.

Advantages and limitations

Capping is a low-tech, cost efficient alternative to dredging and *ex situ* treatment. They are preferably applied on sandy sea-bottoms with a high bearing capacity, but can be placed on very soft sediments as well [Ref. 5]. However, on soft sediments caps need to be placed as several thin layers in order to prevent failure and mixing of clean and contaminated material. The addition of sorptive materials might also be necessary, to adsorb contaminants migrating with the porewater due to the consolidation process.

Other than that, caps are generally used in areas where sediment contamination occurs in smaller, discrete and manageable areas. Any cap-disrupting natural and/or man-made erosive situations, such as currents, flooding and boat anchoring, should be low or controllable. Additional concerns can be the minimum required water depth, water body use, ebullition, the (partial) destruction of certain habitats and groundwater interaction close to the capping site [Ref. 4]. Monitoring and maintenance of the function of the cap might be required as well.

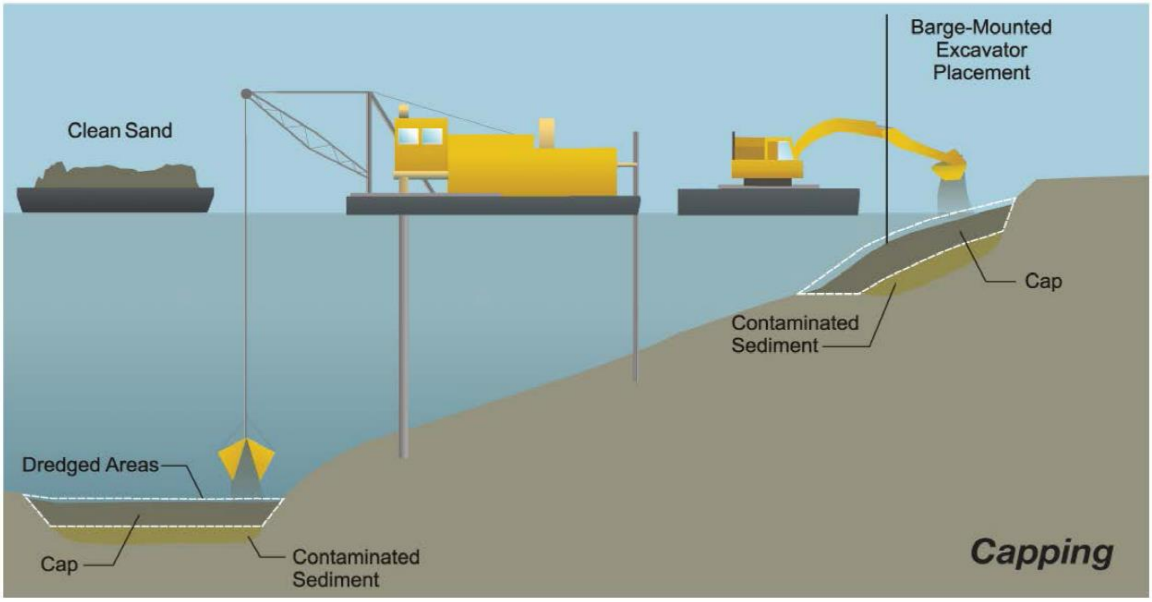
The main advantages and limitations of capping are listed in Table 3.3 below.

Table 3.3 Advantages and limitations of capping [Ref. 17]

Advantages	Limitations
- Less complex, quicker to implement than removal-based remedies; - Quickly reduces exposure and related risks. - Little to no residual contaminants involved; - Typically easy to construct; - Suitable types and quantities of cap material are often readily available, and at reasonable costs; - Can be used to remediate multiple contaminants and NAPLs; - Can be applicable to a variety of aquatic environments, e.g. lakes, rivers, harbors, wetlands, etc.; - Anticipated infrastructure needs (e.g., piers, pilings, buried cables) might be integrated with capping; - Provides clean and possibly also unique habitat for floral and faunal benthic communities;	- Most contaminants remain in-place long-term (they do not degrade significantly); - Not appropriate if the contamination risks spreading to the groundwater; - Potential for post-cap disruption and sediment exposure (if not designed and/or constructed properly); - Area needs to be accessible for placement of the capping material; - The capped sediment needs to have sufficient physical strength (bearing capacity) to support a cap's weight; - Some approaches are inappropriate when significant erosive forces might occur;

Advantages	Limitations
- After capping, less disturbance to habitat than removal (with time); - Typically less costly than removal-based remedial technologies.	- Some approaches are inappropriate when significant groundwater upwelling might occur; - Could adversely affect hydrology and/or ecology of a site; - May be incompatible with some waterway uses, e.g. when regular navigational dredging occurs; - May be inappropriate where water depths are already shallow, and a thick cap would further decrease water depths; - Long-term monitoring and perhaps also maintenance and repair required.

Figure 3.3 The process of capping, both near shore as on the bottom of a waterbody [Ref. 13]



Social aspects
Even though capping is a low-tech and highly efficient technique, it is not always the most favored approach by the public since it leaves the contamination in place. Additional research is required to prove both short and long term effectiveness, which will contribute to the acceptance of this technique [Ref. 5].

Costs
Energy consumption, space and time requirements and by-product production for capping are negligible or non-existent.
Costs depend on the type of capping material used. For the use of reasonable quality sand, costs around € 30-40 /m^2 have been reported [Ref. 23]. Thin-capping for example, with layers of 0,1m thick, costs 20% less than regular (isolation) capping. Furthermore, if excess sand or clay from construction works can be (re)used, capping can be done almost for free.

State of the art/experience
Capping has been studied and applied worldwide on all scales, from theoretical to pilot and full scale projects. It is often used in combination with dredging works, where contaminated sediment has been removed from one location and redeposited in another location or where residual contaminants have been left in place.

Cases

Eternit: Promatbeek, Tisselt (Willebroek), Belgium

Project team	Witteveen+Bos Belgium: Sigrid Willems, Roel Vleeracker
Duration of project	2012-2016
Client	Eternit NV, Kris Asselman
Environment	Stream and its embankments
Scale	100 m length
Contaminants of concern	Asbestos
Final remedy	Excavation and capping (isolation with *in situ* hydrobeton)
Costs	EUR 200.000,-

Site Description
Non-navigable waterway or stream (category 2) and its embankments.

Contaminant Description
Historical contamination with asbestos, attributed to the supplementation of soil to an adjacent site in the period 1929 to 1992 and to the historical production of asbestos-containing products until 1998. Asbestos was found in the sediment in the bedding of the stream and on its right embankment.

Remedial Objectives
Control of the asbestos contamination on the riverbanks, obtained by partial removal of contaminated sediments and capping. There was no remediation required for asbestos contamination in the stream itself, but the sludge from the stream was dredged as well.
The natural course of the waterway and its discharge flow was not to be disturbed, nor the infiltrating capacity of the bedding and the quality of the water in the waterway.

Remedial Approaches
Completion of the soil investigation and remediation (BBO, BSP and BSW), including sediment removal in the stream, bank reinforcements with hardwood planks and poles, removal of contaminated soil on the right bank and covering of the right bank with a 50 cm thick cap, of which the upper 20 cm consisted of soil.

Any excavated contaminated soil was transported to an authorized treatment facility.

Monitoring
After the initial dredging of the stream, it became apparent that asbestos contamination concentrations were much higher at deeper levels than expected. Additional dredging of the deeper part of the sediments in the stream was necessary as well, but still not all asbestos could be removed from the bedding.
In order to avoid exposure and possible further spreading of the asbestos contamination still present, the sediments were covered with foil (non-woven geotextile), rubble stone and colloidal concrete with a thickness of 30 cm over a distance of about 100 m.

In order to provide extra protection on the left bank and the cap in the stream bed, gabions filled with limestone, were installed on the left bank.

Eternit: Sasbeek, Kapelle-op-de-Bos, Belgium

Project team	Witteveen+Bos Belgium: Sigrid Willems, Roel Vleeracker
Duration of project	2014-2016

Eternit: Sasbeek, Kapelle-op-de-Bos, Belgium

Client	Eternit NV, Kris Asselman
Environment	Stream and its embankments
Scale	45 m + 180 m (Non-navigable waterway or stream (category 2))
Contaminants of concern	Asbestos
Final remedy	Excavation and capping (immobilization)
Costs	EUR 660.000,-

Site Description
Non-navigable waterway or stream (category 2) and its embankments, near the Eternit factory compound.

Contaminant Description
Detection of high asbestos contamination in the sediments of the Sasbeek near a discharge point.

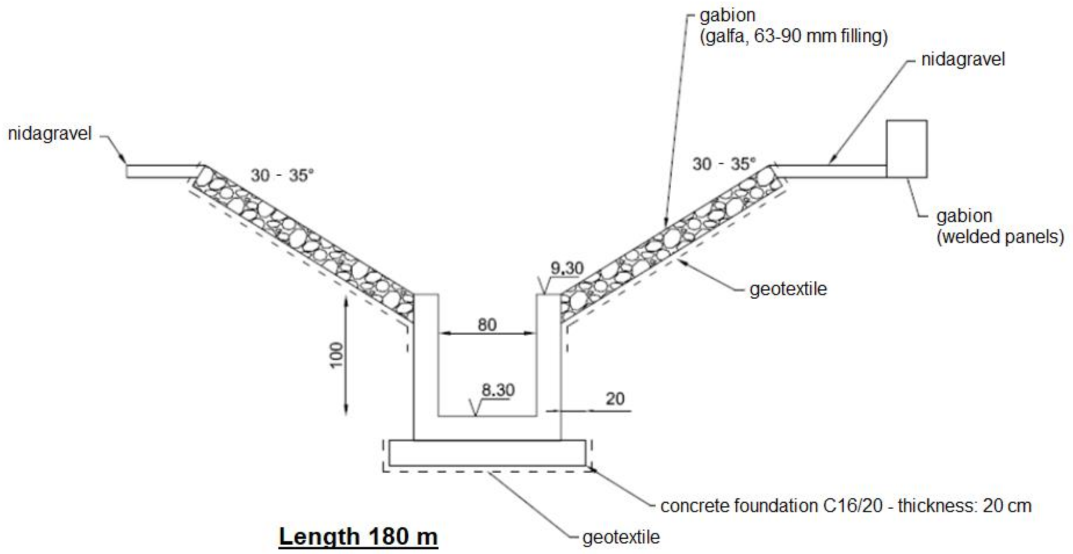
Remedial Objectives
Mapping of the extent of the contamination in the stream and its surroundings. Laboratory tests were carried out to see whether the asbestos could be immobilized. Complete removal of contaminated sediments if possible, capping if this is not possible.

The public sewage system of a residential area is also connected to this stream, so the remediation works were not allowed to impact the discharge capacity of the stream. Correct dimensioning of the drainage system had to be taken into account in order to prevent discharge problems during and after the remediation works.

Remedial Approaches
At locations where asbestos contaminated sediments could be completely removed, the remaining clean soil was covered with hardwood, geotextiles and soil. Coconut mats where applied on the slopes.
At the discharge channel itself, complete removal of contaminated sediments was not possible and geotextile and welded panels of 20 cm thick were used against the slopes and gravel on the top. At the bottom of the channel, concrete U-shaped panels on top of a concrete foundation were applied, see the figure below.

The soil investigation and remediation (BBO, BSP and BSW) was completed after sediment removal in the stream, bank reinforcements with hardwood planks and poles, removal of contaminated soil on the right bank and covering of the right bank with a 50 cm thick cap, of which the upper 20 cm consisted of soil.

All excavated contaminated soil was transported to an authorized treatment facility.



3.5 Phytoremediation

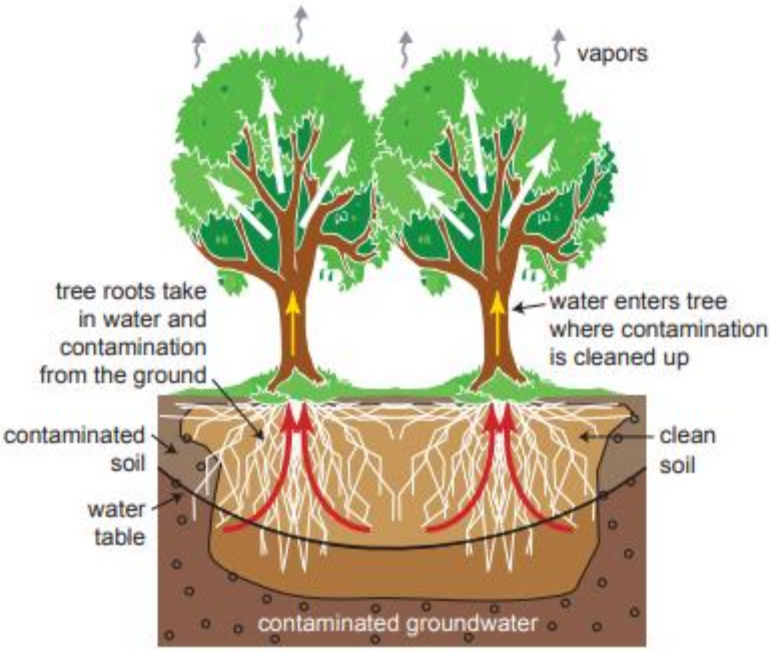
Description

Phytoremediation is a nature based remediation technique that could also be regarded as a type of Natural Attenuation or biological remediation. It includes a range of techniques that use plants and their associated micro-organisms to capture, remove, convert and degrade contaminants in soil, (ground)water and sediment.

Phytoremediation differs from other biological remediation techniques because it uses living microorganisms in combination with living plants to remove or stabilize pollutants from the environment [Ref. 33]. In recent years, instead of the traditional term "phytoremediation", the term "phytotechnologies" has often been used to emphasize that it also includes plant-based technologies that immobilize contaminants. This is due to the fact that the term phyto"remediation" is often misinterpreted as plant-based remediation techniques with the sole aim of "removing" contaminants.

Some phytoremediation applications can be used as a main remediation method (whether or not in combination with other remediation techniques) for remediation of contaminated soils, groundwater and sediment, while others can be used as aftercare after applying conventional remediation methods (e.g. after excavation).

Figure 3.4 The process of phytoremediation [Ref. 34]



Phytostabilization

Contaminated sediment can mobilize both vertically and laterally when exposed to uncontrolled water flows or wind, causing erosion or leaching. Stabilizing vegetation covers that are rooted in the sediment offer a natural barrier and resistance to these processes.

Phytoremediation

Trees can pump up 200 liters of groundwater every day, attracting high amounts of dissolved contaminants. Some trees such as poplar and willow are phreatophytic, which means that their roots can always reach down to groundwater level, even when this level lies at a depth of 10 meters [Ref. 21].

Plant and tree root systems can perform phytoremediation through phytosequestration, rhizodegradation, phytodegradation, phyto-extraction and/or phytovolatilization (Figure 3.4).

Through **phytosequestration,** certain contaminants can become chemically immobilized within the root system of a plant (30 to 60 cm below the ground surface) or a tree (down to groundwater level). Plants can also decompose contaminants through **rhizodegradation** (in the rhizosphere) and **phytodegradation** with the help of microbial populations in the rooting zone. Through **phytovolatilization**, plants can release volatile components into the atmosphere, while **phyto-extraction** is used for plants that accumulate contaminants in their parts above the ground that can be harvested, thereby removing the contamination from the site (*ex situ*).

The extent of remediation properties of plants and trees depends on the species, soil/sediment properties (texture, water and nutrient content, pH and permeability) and contaminant type, depth and volume. For many plant species this accumulation process is passive. For some plants however, accumulation of metals appears to be an active process, possibly related to a tolerance mechanism for their survival on contaminated sites [Ref. 5]. Planting of a tree also strongly contributes to an improved aeration of the soil, stimulating aerobic degradation processes [Ref. 33].

Advantages and limitations

The main advantage is that the process is completely solar powered. The main drawback is that phytoremediation takes a long time (up to several years).

Phytoremediation has been applied on a large scale for the remediation of groundwater contaminated with both metals (inorganic) as with BTEX, mineral oil and chlorinated hydrocarbons (organic, especially the lighter fractions of these components which are generally mobile, soluble and biologically available) [Ref. 33]. Phytoremediation is also used on soil contaminated with PAHs, PCBs and other persistent organic pollutants that are generally less mobile, soluble, biodegradable and available [Ref. 33].

In order to ensure an efficient degradation, bacteria with the appropriate characteristics can be enriched inside the plant by means of inoculation [Ref. 21].
When chelates are used to enhance bio-availability, care should be taken to avoid leaching losses.

Social aspects

Phytoremediation is a relatively unknown technique and not proven yet on sediments. The general public should be informed about this. They also might object against the long treatment times that are needed.

Costs

There is no information available on costs.

State of the art/experience

No successful application have been published yet.

Cases

Bio2clean, Belgium
See: http://www.bio2clean.be/

3.6 Creation of a bypass

Description

Contaminants present in sediments might no longer pose a threat if they can no longer spread into the overlying waterbody. This can be obtained by isolating the contaminated area and creating a new bypass nearby for the waterbody. If spreading towards the groundwater does not occur, the contaminated sediments can be left in place.

Advantages and limitations

The main advantages and limitations of creating a bypass are listed in Table 3.34 below.

Table 3.4 Advantages and limitations of bypassing

Advantages	Limitations
- It may be an effective and efficient way to eliminate the risk emanating from a contaminated sediment. - Cost efficient. - No transport or treatment of sediment necessary.	- No removal of contaminants. - Property issues may arise if the surface water is the border between different properties. - Hydrology of the site needs to be respected.

Social and economic aspects

Special care needs to be taken to respect the hydrology of the site. A good understanding between all the stakeholders (owners, managers and users of the waterbody) is necessary.

Costs

The remediation effort can be minimal, based on the distance of displacement of the waterbody.

State of the art/experience

Not many known cases, except for Carcoke Zeebrugge (see below).

Cases

Carcoke Zeebrugge - OVAM
As a part of the remediation works at an old cokes factory, a heavily polluted channel (Zijdelingse Vaart) needed to be relocated. Costs for this relocation are unknown.

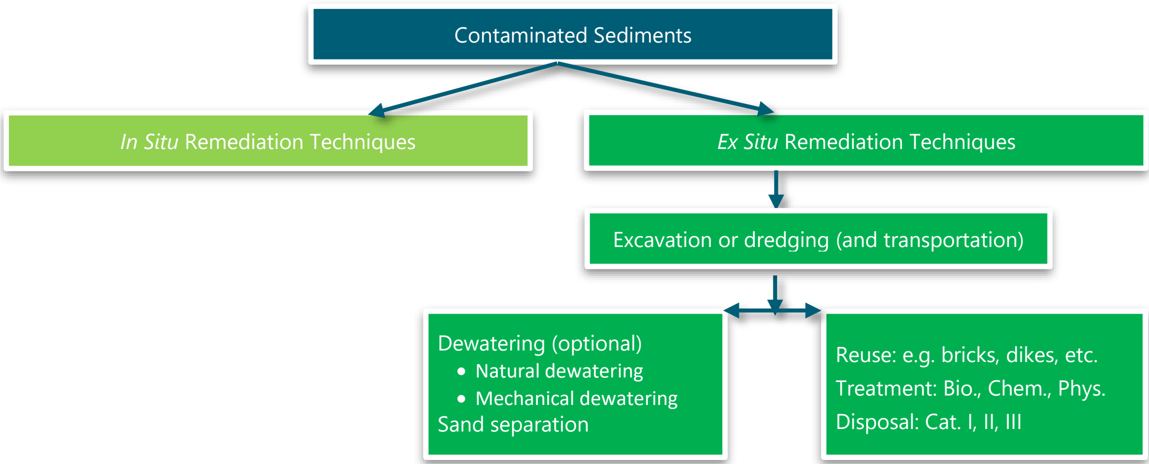
4

EX SITU TECHNIQUES

4.1 Introduction

With *ex situ* techniques, contaminated sediments are treated at another location than where they were found. This involves removal in the form of excavation (dry) or dredging (wet) and of course transportation, which can be done with trucks over land, by ships over water, or hydraulically through pipelines.
The preferred methods for removal and transportation are usually linked and decisions are mainly based on the transportation distance, the volume of the contaminated materials and costs.
Treatment methods can be active or passive and usually take place in specialized treatment facilities. Often a dewatering step is necessary before treatment can commence (see Figure 4.1). A lot of dry sediment treatment methods are quite similar to their soil counterparts. After treatment, the material can be transported to its final disposal destination.

Figure 4.1 Flowchart for *ex situ* remediation techniques



4.2 Excavation and Dredging

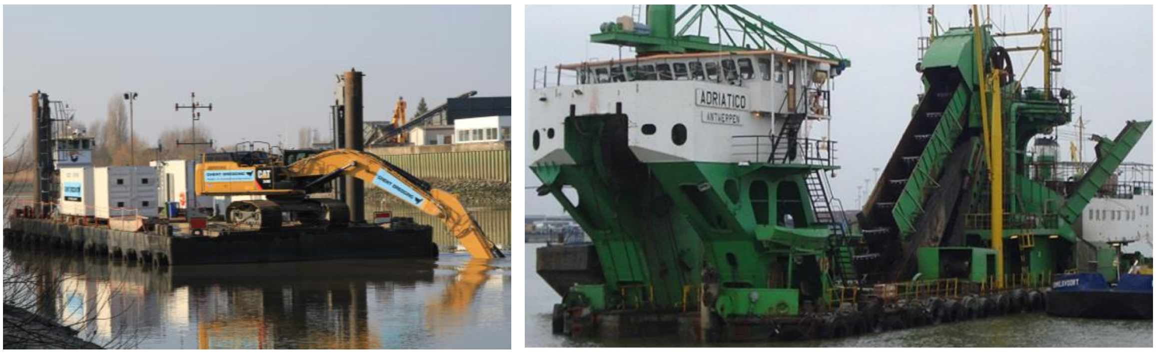
Of all the sediment remediation techniques available, removal-based techniques have been in existence the longest, and are thus the most well-known. The first removal-based projects completed for environmental (rather than navigational) purposes took place decades ago in the U.S.A. [Ref. 17].
Excavation of dry soil can be applied on riverbanks and on riverbeds which are seasonally dry. The latter can also be achieved by creating a man-made bypass for the waterway, for example. Dredging is the removal of soil and/or rocks from the bottom of a usually relatively shallow body of water or an aqueous environment. After excavation or dredging, the material needs to be transported and treated or deposited at another location.

Mechanical dredging

Backhoes and bucket ladder dredgers
Excavations along shores are generally carried out by backhoes (BHDs) or other types of excavating equipment on wheels or caterpillar tracks. Backhoes can also be used for dredging by fixing them on the back of a stationary pontoon in shallow water (Figure 4.).
More powerful and modern excavators are no longer (solely) mechanical and combine engine power with three (or more) hydraulic pumps.

Bucket Ladder Dredgers (BLDs) are old-fashioned dredgers that scoop up material with multiple buckets which are fixed onto a rotating chain (Figure 4.). They are still used for extremely accurate dredging jobs or when little soil disturbance is allowed due to environmental restrictions.

Figure 4.2 Backhoe on pontoon (BHD) on the left and BLD on the right [Images from Ghent Dredging and DEME]



Hydraulic dredging

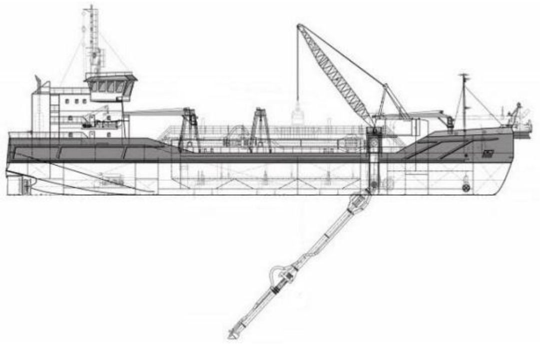
Both trailing suction hopper dredgers (TSHDs) and cutter suction dredgers (CSDs) use hydraulic pumps to loosen and remove the material in order to be dredged. Both types of dredgers are usually used for infrastructural dredging works and seldomly for environmental dredging works.

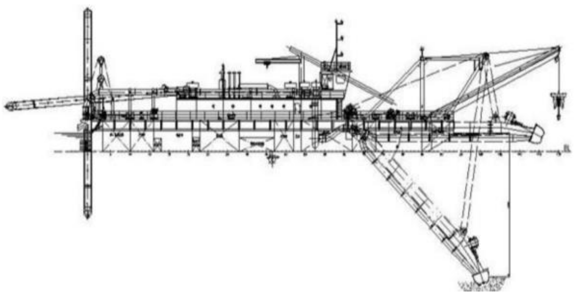
Trailing suction hopper dredger
A TSHD has a large suction pipe that is trailing along the bedding of a waterbody to collect material through its draghead during sailing (Figure 4., left). Some dragheads are equipped with water jets and teeth that cut the soil before it is being sucked in. The collected material is a mixture of solids and water, called slurry, which is collected inside the hopper. Here, the material can settle and the surplus of water is removed by an overflow-system. TSHDs can dredge unconsolidated material, such as soft clays, silt, sand and gravel. When the hopper is full, the vessel will sail to a location where the material can be deposited. Unloading of the vessel can be done in three different ways: directly through the bottom doors, through submerged or floating pipelines, or by spraying the slurry into the air. This last process, called rainbowing, is usually not used for remediation projects.

Cutter suction dredger

Strong CSDs can dredge almost all kinds of soil and even (weathered) bedrock; they are used when the material to be dredged is too strong or cohesive for a TSHD. The teeth of a cutter are mounted on a rotating cutterhead that cuts the hard soil or rock into smaller pieces. These pieces get sucked up through a suction pipe that is mounted on a mobile arm (Figure 4.3, right). The material is then transported onshore or into a hopper barge through pipelines. Hard material causes a significant amount of wear and tear on the teeth and pipes of the cutter, and the teeth will often need replacement during dredging. A CSD is a stationary dredger, which can be self-propelled. It uses its anchors to swing its arm and its spuds to move forward while dredging.

Figure 4.3 Schematic drawing of a TSHD with draghead, on the left [DEME] and a CSD with spuds and an extended arm with suction pipe and cutterhead on the right [Hi-Sea dredge]





Advantages and limitations

Excavation or dredging is often a quick method to remediate relatively large but distinct areas containing (highly) contaminated sediments. It is a good option to consider when there is a suitable disposal site available nearby and when there is enough space available for handling of dredged material. Ideally, contaminant concentrations are highly correlated with sediment grain size, which facilitates grain-size separation and minimize disposal costs [Ref. 17].
Sometimes environmental dredging works can be combined with navigational dredging works, lowering the overall costs.

However, dredging causes a significant amount of disturbance of the water column, which can be harmful for sensitive ecosystems such as coral reefs and spawning areas. It can also cause resuspension of sediments, the release of bound contaminants and the exposure of residual concentrations associated with the newly created surface area. Post-dredging monitoring data collected at a number of sites have demonstrated temporary spikes of contaminants in the water column and fish tissue following dredging activity [Ref. 4]. Dredging can re-mobilize buried contaminants back into the ecosystem, re-exposing the biological community to it.
In order to minimize these negative effects, the dredging sector is strictly regulated, both internationally and nationally. Environmental monitoring during dredging works is mandatory and activities can be suspended when certain thresholds are reached. Countermeasures such as silt curtains are often applied as well. However, if contamination levels are too high, dredging might not be feasible.

The main advantages and limitations are discussed in Table 4.1 below.

Table 4.1 Advantages and limitations of removal-based techniques (excavation or dredging) [Ref. 17]

Advantages	Limitations
- Contaminants are removed from the aquatic environment; - Can be used to remediate a wide variety of contaminant types and concentrations, multiple contaminants, and non-aqueous phase liquids (NAPLs); - Can sometimes quickly reduce contaminant exposure and related risks; - Greater certainty of long-term effectiveness; - Typically few to no restrictions on-site use after removal; - Offers potential for beneficial reuse of removed sediment material.	- Adequate nearby disposal options may be limited; - At least some residual sediment contamination always remains after removal; - Removal (during and after) is relatively disruptive to benthic and/or aquatic habitats, compared to *in situ* techniques; - Typically more costly than other remedial techniques;. - Water diversion, or flow velocities should be low or need to be minimized to reduce re-suspension and downstream transport of contaminated sediments during dredging operations; - Sediment will have to contain relatively low amounts of debris (e.g., logs, boulders, scrap material) or debris removal prior to dredging or excavation should be possible; - Varying water levels due to tides should be taken into account, which might cause delays; - Seasonal restrictions due to fauna and flora (e.g. breeding months of birds) should be taken into account.

Social aspects
The main concerns of the public and other stakeholders are often related to disturbances of sensitive ecosystems and the resuspension of contaminants during and (shortly) after dredging works. These risks can be minimized by continuous monitoring.

Costs
Costs largely depend on the volume of the material that needs to be dredged. The costs for dredging or excavation are usually separated from the remediation costs. For price ranges, see cases below.

State of the art/experience
Excavation and dredging is being used worldwide on full scale. Not only for remediation works, but also for maintenance of waterways and reclamation works.

Cases

Lobroekdok, Belgium	
Project team	Witteveen+Bos
Duration of project	2017 - Ongoing
Client	Beheersmaatschappij Antwerpen Mobiel
Environment	Dock
Scale	94.100 m^2 and approx. 200.000 m^3 of contaminated sediments
Contaminants of concern	Heavy metals, PAHs, mineral oils and organic material
Final remedy	Excavation (mechanical dredging) and *ex situ* treatment at AMORAS
Costs	EUR 3.300.000 (excavation) and +/- EUR 4.000.000 (treatment at AMORAS)

Site Description
Navigable dock (Lobroekdok) in the port of Antwerp which is connected to the Albertkanaal.

Lobroekdok, Belgium

Contaminant Description
Heavily contaminated sediments have accumulated in the Lobroekdok. The sediments contain heavy metals, PAHs, mineral oils and organic material. Debris and several car- and shipwrecks are also present at the bottom of the dock.

Remedial Objectives
The entire dock needs to be dredged up to the existing clay layer at the bottom of the dock, in order to prevent further spreading of the contaminants. All alien material needs to be removed as well. Transportation of the dredged material has to be done by ship in order to avoid adding more traffic to the already really busy roads surrounding this area in Antwerp. The material will be transported to the treatment facility of AMORAS in the port of Antwerp.

Remedial Approaches
In May 2017, remediation works started at Lobroekdok. Witteveen + Bos conducts the management on behalf of BAM. The remediation is supposed to be carried out in about 7 dredging campaigns of 2 weeks. Between each dredging campaign, it takes approx. 10 weeks to process the dredged material at AMORAS. A unique aspect of this project is that it is the first time that the treatment site AMORAS has processed highly contaminated sediments. Hence, special adjustments to the installation were necessary.

Winterbeek, Belgium

Project team	DEC
Duration of project	2017 – 2018
Client	OVAM and VMM
Environment	Stream (non-navigable)
Scale	1^{st} of 4 sections (17 km long in total)
Contaminants of concern	Heavy metals, chlorides and radium
Final remedy	Hydraulic dredging and *ex situ* treatment (lagooning)
Costs	EUR 2.239.742

Site Description
The Winterbeek is a non-navigable stream and is mainly located in a nature reserve or in agricultural area.

Contaminant Description
The project area is historically contaminated with heavy metals and chloride in the subsurface, heavy metals in the sediment and chlorides (salts) in the groundwater at the level of the waterway, banks and valley area of the Winterbeek. Additionally, increased concentrations of radium are also found in the soil and in the sediment (causing ionizing radiation).
The contaminants that have been found are residues from the process water of a chemical plant.

Remedial Objectives
The entire stream and valley area needs to be remediated over a distance of 17 km. The remediation works are divided into 4 different phases or working areas over 4 years, following the direction of the flow of the stream, in order to prevent recontamination of already cleaned areas.

Winterbeek, Belgium

Remedial Approaches

The first contaminated section of the Winterbeek has been cleaned by DEC with the use of a hydraulic excavator with a submersible DOP pump. Both the sediments in the stream as the bottom and banks of the stream were removed.
The pumped up material was then pumped through pipelines over a distance of more than 1 km, to one of the four constructed lagooning fields, where the material could consolidate. This way, the impact of the works on the fragile ecosystem of the streams valley is as limited as possible.

Sediment traps, or locally broadened sections, were also created at several places along the stream, where excess and possibly contaminated material can be collected and removed from the system.

Sanitation of the Hollandsche IJssel, the Netherlands

Project team	Witteveen+Bos
Duration of project	2009 - 2011
Client	Department of Transport and Public Works Zuid-Holland
Environment	Tidal river
Contaminants of concern	Heavy metals
Final remedy	Mechanical dredging and excavation

Site Description

The Hollandsche IJssel is a tidal river in the greater Rotterdam area.

Contaminant Description

The banks, the shores and the sediments were heavily contaminated with heavy metals.

Sanitation of the Hollandsche IJssel, the Netherlands

Remedial Objectives and Approaches

Witteveen+Bos made a design for the redevelopment of this river. This design included the construction of natural banks which should restore the ecological environmental status of the river and also secure the navigation on the river. Part of the design was the removal by dredging of about 500.000 m^3 of contaminated sediments. The design had to be approved by the authorities and all involved stakeholders. After the approval of the design, Witteveen+Bos was commissioned to write the contract for the entire project and afterwards to supervise the contract.

4.3 Transportation

Transportation of excavated or dredged material is usually carried out by trucks over land, by ships or barges over water, or hydraulically through pipelines. The choice for a specific transportation method depends on a number of different factors, mainly taking into account: costs, the used excavation/dredging method, the transport distance and volume, and the density of the contaminated material.

For example, for small scale excavation works such as those in ditches or streams, an excavator working from the shore will generally be used. Relatively, a lot of material is being excavated and only little water is present in the area, so loading the material into trucks and transportation by road seems to be the most suitable option. If a decent road is not present nearby, it might be possible to construct one, for example by installing a temporary one with road plates. This is not an option if the number of truck movements should be kept as low as possible due to environmentally vulnerable areas or because heavy traffic is already an issue. In those cases, hydraulic transportation would probably be favorable.

When a slightly broader waterway with bigger volumes needs to be dredged, it usually becomes necessary to use an excavator from a pontoon. If the waterway is navigable, dredged material can be transported by ship or in barges, which can contain relatively large volumes.

Hydraulic transportation through pipelines is preferred when dredging is done with a cutter or when the impact on the surrounding area must be minimal. The construction of the pipelines must be proportionate to their use. Booster stations might have to be added to the trajectory when the pipeline needs to cover longer distances. All the different parts of the pipeline will also have be delivered by either truck or by ship.

Cases
Hydraulic transportation of dredged sediments has been used by DEC for the remediation of the Winterbeek (see case (incl. costs), chapter 4.2) and by Envisan for the construction of a dyke in Vlassenbroek (see case (incl. costs), chapter 4.6.2).

4.4 Dewatering

Dredged sediments often contain relatively large amounts of (pore)water and need to be dewatered before the sand/silt fractions can either be treated at a treatment facility, disposed, or reused. After or even during this dewatering step, the sand and silt fractions need to be separated as well, because they will be processed differently due to their specific properties. E.g. the smaller sized particles attract more contaminants and often need further treatment, while sand-sized material is cleaner and might be directly suitable for construction purposes due to its geotechnical properties. See also chapters 4.5 and 4.6.

4.4.1 Natural dewatering (lagooning)

Description

Accelerated dewatering, lagooning or ripening is the optimization of natural dewatering, consolidation and oxidation processes by mechanical means (for example turning), in order to increase the evaporation and drainage of water. It is generally used for dredged material containing smaller particles, which take relatively long to settle by themselves. In a lagooning facility, dredged material is put into dewatering fields or treatment lagoons, where dewatering and consolidation can take place. The main purpose of lagooning is to improve the mechanical properties of the product and not to improve its environmental quality. Sometimes the latter can also be achieved up to some level however. When the sediment is left to dry and consolidate long enough, this gives organic matter and organic contaminants the chance to biodegrade, as long as enough oxygen is present. Nowadays this process is no longer called lagooning (dewatering) but landfarming (see chapter 4.6.3).

During the first couple of weeks, the sediments will mostly lose consolidation water, causing an increase in the amount of dry matter in the sediments from 30 to 40% to about 55%. The excess process water that is released during the lagooning process is partially rainwater, partially transport water and partially consolidation water that is pressed out of the sediments while it dries and consolidates. All the excess water can escape the basins through several outlets at the top and drains at the bottom of the sediment. This water often needs to be treated afterwards, because it still contains small sediment particles to which contaminants are bound [Ref. 7].

After this first phase, evaporation will be the main process. It lasts on average 3 to 5 months and causes the sediments to dry further from approx. 55% dry matter to approx. 75% dry matter, causing a significant volume reduction. This second half of water disappears for the most part by evaporation.

After lagooning, the dried sediments will have to be excavated mechanically, since hydraulic transportation requires the use of water. It also still contains contaminants, so in general additional treatment is still necessary.

This technique is the most common one and is used at full scale in Europe and the rest of the world. It is suitable for large volumes, has a relatively high production rate and shows the best results with sandy materials.

Advantages and limitations

Table 4.2 Advantages and limitations of natural dewatering [Ref. 5]

Advantages	Limitations
- Energy, water and additives consumption is low; - Air emissions are negligible; - Additional effect: dredged material will become more and more oxidized.	- Discharged drainage water has to meet environmental criteria and needs treatment afterwards; - Due to the maximum height of the fields (approx. 1-2 meter), relatively large surfaces are needed + one or several retention basins;

Advantages	Limitations
	- Retention basins are often required as well due to the inconsistent supply of sediments; - Processing times can take up a few months to a whole year, depending on: • The climate (rain, sunshine, humidity); • The required level of dewatering; • Drainage- and dewatering material used; • The composition of the sediments (fine particles and organic matter take longer to dewater); • Other additional (mechanical) measures taken to accelerate the dewatering process.

Social aspects

There is still a lack of public knowledge on lagooning and the products are often seen as 'waste'. Because of this, communication with the public and other stakeholders is very important.
Furthermore, when the sediments just arrive at the treatment site, they might cause a putrid odor, due to their mostly anaerobic character.

Costs

Costs at different production scales and under different conditions are estimated to be around € 10 - 25 /m^3 [Ref. 5]. Theoretically, products made of the dried sediments can be applied as construction material. Compared to other dewatering techniques it is still the most cost effective dewatering technique for silty sediments as well. However, costs are partly determined by the price of the surface area that is needed for the dewatering plant. In areas where land is very expensive, mechanical dewatering (on limited areas) can be advantageous.

State of the art/experience

Applied on industrial scale.

Cases

Fasivier, Belgium	
Project team	DEC
Duration of project	1999 - Ongoing
Client	Fasiver cvba + PPS VMH, provincie Oost-Vlaanderen, stad Gent, DOMO Service Gent and DEC
Scale	175.000 m^3 of sediments treated initially
Contaminants of concern	Viscose and heavy metals, oil, PAHs, organic material
Final remedy	*In situ* stabilization/immobilization, isolation and natural dewatering
Costs	EUR 8.000.000 (remediation) + EUR 57.800.000 (sediment treatment)

Fasivier, Belgium

Project Description
Remediation and redevelopment of the site "'t Eilandje" between the old and new Scheldt in Zwijnaarde near Ghent. It was an abandoned industrial site (42 ha), strategically located at the intersection of two European motorways (E40 and E17).
The project comprises three phases:

- Remediation;
- Use of the site as a sediment processing center;
- And eventual redevelopment.

Technical Specifications
The remediation consisted of *in situ* stabilization/immobilization of 175,000 m³ viscose contaminated sediments in 5 separate evaporation ponds, by mixing in cement and steel slag. This was followed by isolation of the site with on one hand a cement-bentonite wall up to approx. 30 m-mv and on the other hand a HDPE foil of 2.5 mm thick. A gas drainage had to be installed under the foil. A final additional cover was applied, as well as a green zone. The groundwater was remediated by means of pump and treat in the hot spots around the contaminated site.

The installation of a temporary sediment processing center on-site ensured financial resources for the remediation of the highly polluted sediments, while the processing and storage of external dredging spoil could be used to raise the terrain in order to create a new construction site for high-tech companies.

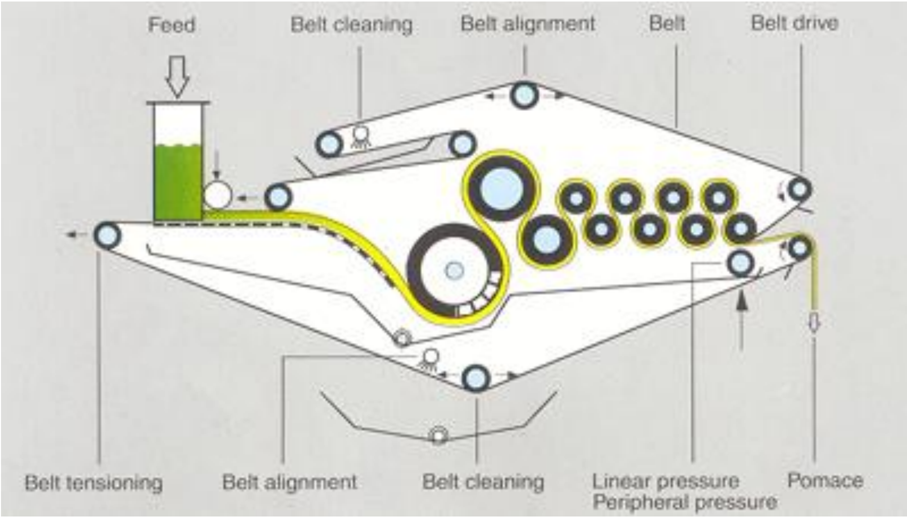
4.4.2 Mechanical dewatering

Large scale mechanical dewatering facilities exist in the Netherlands, Belgium and Germany. Average volume reductions of 50% are obtained.

Description: Pressure belt presses and chamber/membrane filter presses

A *pressure belt press* is an installation where the sediment is being pressed between two revolving porous filter belts. The sediments are transported along the lower filter belt. As the available space between the two belts becomes smaller and smaller further along the process, more and more pressure is applied, releasing the sediment pore water (see Figure 4.4).

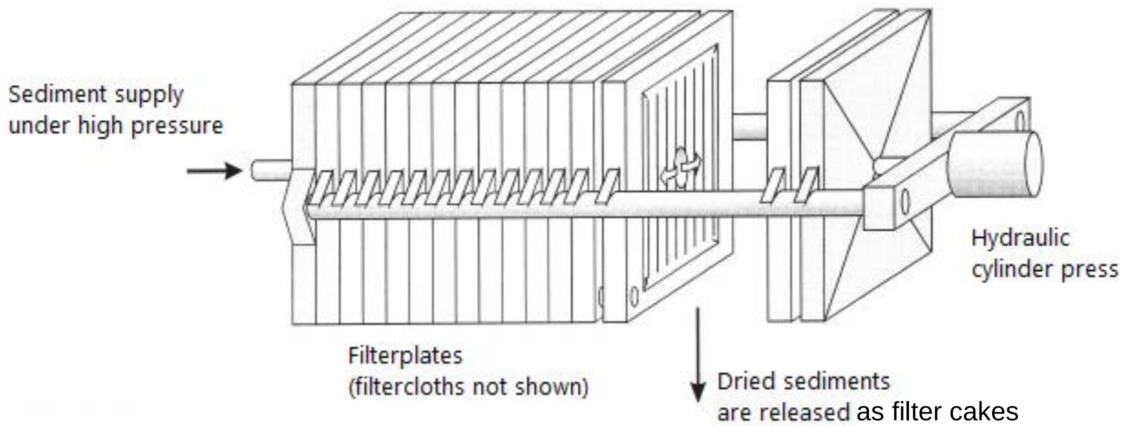
Figure 4.4 Pressure belt press [Ref. 23]



After treatment, the dehydrated sediments can be collected from the conveyor belts as “filterkoeken” or filter cakes, which can reach maximum dry matter contents of up to 50% [Ref. DEC] [Ref. 7]. The volume can be reduced by a factor of 1,3. In contrast to lagooning, a flocculant is always used for mechanical dewatering, accelerating the dehydration process.
One pressure belt press with a 3 m width can produce 12 ton dry solids/hour. Sand can be extracted from the mixture for recycling purposes by letting it pass through a cyclone beforehand (see chapter 4.5).

A *chamber filter press* consists of a large number of filter plates with raised edges that are slowly pressed together to form “chambers”, at a pressure of 300 bar. Sediments are pumped into these chambers at a pressure of 13-15 bar, pressing the porewater out of the sediment. The porewater is able to leave these chambers through filter cloths that cover the filter plates, while the dehydrated sediments are left behind inside the chambers, where they form filter cakes (see Figure 4.5).
After opening of the chambers, the cakes will automatically fall out and can be collected on a conveyor belt or in a truck below the installation.
Depending on the height of the plate edges, filter chamber depths vary between 2 to 8 cm. Installations generally contain 50 to 150 chamber-plates, depending on the required capacity of the installation [Ref. 7]. When the applied sediments have a relatively high dry matter content, a dry matter content of 50 to 70% can be achieved within reasonable pressing time. The collected porewater often receives some form of post-treatment. The filter cloths need to be cleaned as well.

Figure 4.5 Chamber/membrane filter press [Ref. 7]



A variation on the chamber filter press is a membrane filter press, where an elastic membrane is applied in between the filter plates and the filter cloths. Again, sediments are pumped into the chambers (at a pressure

of max. 8 bar) and a pressure of 15 bar or higher is applied to the elastic membranes as well, causing them to stretch out. This stretching decreases the volume of the chambers and consequently applies extra pressure on the sediments inside.
This technique reduces pressing time with 50% of more and creates filter cakes with a higher dry matter content compared to regular chamber filter pressing [Ref. 7].

If the sediment to be treated contains a high sand content, it needs to be sieved in two steps before pressure belt presses or chamber/membrane filter presses can be used. The coarse fraction (stones, plastic, wood, etc.) are removed by sieving through a 2 mm vibrating screen, after which the fraction larger than 60 µm is separated as well, by means of hydrocyclones. This is done in order to prevent excessive wear of the installation and/or to recover the sand fraction if sufficient sand is present.
Furthermore, the sediment must be supplied in liquid form, so water needs to be added in order to properly fill the devices. Flocculants need to be added as well to accelerate the process.

One (membrane) filter press with a volume of 20 m^3 can produce 12 ton dry solids/hour. Sand can be extracted from the mixture for recycling purposes as well by letting it pass through a cyclone beforehand (see chapter 4.5). Additionally, chalk might be added in order to obtain the desired geotechnical quality of C_U = 25 - 50 kPa.

Description: Decanter centrifuge

Sediment enters the decanter centrifuge through a feed pipe in the center, after which the centrifuge will start to rotate and centrifugal forces will push the solid sediment particles to the walls of the centrifuge chamber. These walls taper towards a conical shape, through which the sediment exits the centrifuge. Meanwhile the separated water fraction will exit through the opposing cylindrical side of the centrifuge chamber.
The operation of a decanter centrifuge is quite similar to that of the hydrocyclone that is used for sand separation (see chapter 4.5).

Advantages and limitations

Table 4.3 Advantages and limitations of pressure belt presses and chamber filter presses [Ref. 7]

Advantages	Limitations
- Great operational security; - Continuous process; - Not labor-intensive; - Relatively high dry matter content, compared to non-mechanical techniques, keeping in mind that chamber filter presses are more effective than pressure belt presses; - Can be used with different and changing types of sediments; - The process is weather independent; - It is semi-mobile, so sediment transportation can be limited; - Surface needed is also limited.	- Storage is often necessary, because the dewatering process does not line up with the dredging process; - The knowledge-level of the operators must be relatively high; - Constant need for water and energy; - Maximum dry matter content of 50% to 70% can be achieved for chamber filters. - Dehydrated sediments still contain residues of the added conditioning agents (flocculants, etc.), but some flocculants (iron and calcium compounds) are favorable for construction in terms of stability and resistance to erosion.
In general, chamber (or membrane) filter presses are more effective compared to pressure belt presses: Energy, additive consumption and personnel and maintenance costs are lower and feasible dry dust levels, capacity, reliability and effluent quality are higher.	

Social aspects

Mechanical dewatering is a relatively well known technique that has proven to be effective. To counter possible NIMBY effects, stakeholders and the general public should be informed.

Costs

At large scale facilities such as AMORAS and METHA, prices for mechanical dewatering are much lower than at smaller facilities or mobile installations [Ref. 7]. At large scale sites different dewatering techniques can often be combined as well, making the process more efficient.
Based on the annual operating costs for mechanical dewatering with chamber filter presses, including sand separation, water treatment and transportation to a disposal site, prices are estimated at € 15 to 28 / tds at AMORAS. At METHA costs limited to only dewatering with chamber filter are estimated at € 8 to 10 / tds (excluding wages and maintenance) [Ref.7].

From a comparative study at AMORAS, mechanical dewatering turned out to be cheaper than (intensive) lagooning of hydraulically sprayed sediments.
Based on the results of the chamber filter press test of the Antwerp Port Authority and according to METHA-energy consumption is estimated at 15 to 45 MJ / tds. METHA processes around 500.000 tds every year [Ref. 23].

State of the art/experience

Applied on industrial scale.

Cases

AMORAS, Belgium

Project team	JV Partner JV SeReAnt (DEME - JDN) Jan De Nul NV and Envisan NV
Duration of project	2009 - Ongoing
Client	Flemish government
Scale	Over 2.500.000 m^3 of sediments treated every year
Contaminants of concern	Heavy metals, oil, PAHs, organic material
Final remedy	Mechanical dewatering, sand separation (hydrocyclonage)
Costs	EUR 97.503.226 (design and construction) + EUR 271.850.354 (exploitation and management) + EUR 20.000.000 (further improvements)

Project Description

- Phase 1: contract for the construction of a mechanical dewatering and separation facility for sediments, including storage space for sediments from the Port of Antwerp;
- Phase 2: management and exploitation of the system for 15 years;
- Phase 3: construction of an upgraded sand separator (during phase 2).

Technical Specifications

Material is stored in 4 ponds, each with a capacity of 120,000 m^3, and dewatered via mechanical dewatering by means of 12 chamber filter presses of 21.5 m^3 each.

4.4.3 Geotubes®

Description

A geotube® is an long bag of well-drained geotextile, see Figure 4.6. The sediments are pumped directly into the geotube® through a number of openings. Excess water can escape through the permeable geotextile, decreasing the volume of the contaminated material. Dewatering is accelerated by adding a flocculant (polyelectrolyte). Volume reductions of 1,2 can be obtained.
Essentially, geotubes® function both as a filter cloth that separates water and sediment and as a "bag" that collects the dehydrated sediments. When the sediments have become stiff enough, the bags can be opened and the contents can be removed with an excavator and processed further.
Often, the sediments need to meet certain environmental standards before they are dewatered in a geotube®, because geotubes do not remove contaminants. The released pore water is collected separately and often requires some form of post-treatment before it can be disposed.

The dimensioning of a geotube® (length, diameter, strength and permeability) is variable and depends on the project size, the flow and the composition of the dredged sediment. 'Standard' geotubes® are available in diameters from 1,5 to 5,0 m and lengths up to 100 m and come with a special closing system which makes reuse possible.

Geotubes® can drain any type of sediment, but fine grained sediments dewater more slowly.

Figure 4.6 Geotubes® [Ref. 23]

Advantages and limitations

The following parameters greatly influence the success of the mechanical dewatering techniques discussed above:

- Organic matter content:
  High organic matter content means that the sediment will be hard to dehydrate. The shape of the organic matter is also of importance, seeing as fiber shapes are easier to separate through filters than very small particles. Organic contaminants such as mineral oils are also harder to remove than inorganic components such as heavy metals;
- Particle size distribution:
  If the vast majority of the particles is smaller than 16 µm, the dewatering ability of the sediments is lower and additives (flocculants such as chalk and PE (polyelectrolytes and possibly ferric chloride)) are needed during the process;
- Salt content:
  Sediments from a salty environment (sea or brackish water) have poorer dewatering properties than those from fresh water surroundings, due to the poor operation of polyelectrolytes in a salty environment;
- The temperature:
  Temperature influences the viscosity of the supplied sediments and therefore also its dewatering properties. High temperatures are also favorable for the functioning of polyelectrolytes (PE).

The main advantages and limitations of geotubes® are summarized in the table below.

Table 4.4 Advantages and limitations of geotubes® [Ref. 7, 36]

Advantages	Limitations
- Cheaper than conventional dewatering techniques; - Energy- and environmentally friendly; - Relatively large capacity; - Low-tech and easy to install; - Robust and resistant to mechanical damage (long life expectancy) and reusable; - Originally designed as construction material; if sediments are clean enough, Geotubes® can be used in construction; - Use of geotubes® can retain and isolate some forms of contaminants; - No pre-treatment needed to remove coarser particles; - Dredging and dewatering can be synchronized.	- Some space is required in a relatively close proximity to the dredging works (hydraulic transportation); - Large volumes might be difficult to process due to space issues; - Geotextiles come in a variety of materials which have different (dis)advantages, so pilot projects or lab tests might be necessary for specific projects; - Generally available in specific sizes which may not necessarily suit a particular application. Custom sizing may be expensive; - Risk of tearing / distortion of geotubes®.

Social aspects
Geotubes® and geotextiles are relatively well known. To counter possible NIMBY effects, stakeholders and the general public should be informed. Reuse of geotubes® in construction is seen as a great advantage.

Costs
Based on experiences in the Netherlands, dewatering costs using geotubes® are estimated at 28 to 35 € / tds, including costs for site planning, handling and material costs and excluding water treatment [Ref. 23]. Presumably, the energy consumption for the application of geotubes® is similar to the energy consumption of (extensive) lagooning (approx. 2-4 MJ / tds) [Ref.7].

Geotubes® are only cost efficient if the material can remain or be reused in close proximity to the dredging area [Ref. 23].

State of the art/experience
Applied on industrial scale.

Cases

Pilot study for the remediation and redevelopment of Lobroekdok, Belgium	
Project team	Witteveen+Bos: Peter Van den bossche, Lize Tegenbos, Roeland Van Muylder
Duration of project	2011
Client	AG Stadsplanning Antwerpen and BAM (Beheersmaatschappij Antwerpen Mobiel)
Scale	Dock
Contaminants of concern	Heavy metals, oil, PAHs, organic material
Final remedy	Mechanical dewatering with Geotubes® (pilot study)
Costs	EUR 90.000,--

Site Description
The Lobroekdok is located north of downtown Antwerp, between the Ring and the Singel Noord. This dock has a heavily contaminated mud layer. A feasibility study has been carried out to remediate the contaminated sediments in the dock, in combination with the intended redevelopment (construction of the new Oosterweel connection).

Remedial Objectives and Approaches

Pilot study for the remediation and redevelopment of Lobroekdok, Belgium

One of the remediation alternatives for the Lobroekdok consisted of dredging the sediment with a piston and pumping the sediments into Geotubes®. One of the advantages of a Geotube® is that they can also be used under water, for example on the bottom of the Lobroekdok.
The results from this study are being used to set up a soil remediation project (BSP).

Svartsjö project, Hultsfred, Sweden

Project team	JV DI-DEC
Duration of project	2004-2007
Client	Hultsfred kommun
Scale	Two lakes
Contaminants of concern	Mainly mercury
Final remedy	Dredging and mechanical dewatering with Geotubes®
Costs	EUR 8.848.887,--

Site Description
The sediments are located in two lakes near the town of Hultsfred in Sweden. The timber industry (paper industry in particular) has contaminated the environment in this area. In these two lakes, unacceptable amounts of mercury were found.

Remedial Objectives and Approaches
The joint venture DEC and DI built a new vessel called "Pixie" that is able to dredge sediments mechanically and transport them hydraulically. In total, 280,000 m³ of contaminated mercury sediments were dredged. Afterwards they were pumped to a protected landfill where a system of geotubes® was used for dewatering. The geotubes® had a diameter of a few meters and were 50 to 100 meters long. The excess water from the dewatering process was purified before it was discharged.


Ieperlee, Belgium

Project team	Ghent Dredging
Duration of project	2008-2009
Client	NV. Waterwegen en Zeekanaal
Scale	Channel (Ieper-IJzer)
Contaminants of concern	Heavy metals, oil, PAHs
Final remedy	Dredging and mechanical dewatering with Geotubes®
Costs	EUR 4.924.821,62

Ieperlee, Belgium

Remedial Objectives and Approaches

The project consisted of dredging of the channel Ieper-IJzer, including UXO-detection. The sediment was dewatered using lagooning fields and geotubes® (also called geocontainers). Ghent Dredging has a terrain of 8.000 m^2 along the channel Ieper-IJzer at its disposal, where 50.000 m^3 of sediments can be dewatered every year using geotubes®.

4.5 Separation

Sediment characteristics such as particle size distribution (PSD) and organic content are important parameters for reuse of dredged material. These parameters influence the geotechnical properties of the sediment and are also linked to the level of contamination present within the sediments.
Generally, most of the contamination is bound to the smaller sediment particles and to organic matter, while larger particles (sand) are less contaminated and geotechnically more suitable for reuse in construction purposes. Sand separation is therefore often a necessary step in the *ex situ* treatment chain, in order to make reuse of this fraction possible.

Separation of differently sized sediment particles can be obtained by:
- Longitudinal separation in sloped flushing fields and sedimentation basins;
- Mechanical separation using sieves, hydrocyclones, upstream-current-classifiers, spirals, jigs and floatation-cells.

Separation is normally used in combination with other dewatering techniques and is not used as a standalone technique.

4.5.1 Longitudinal separation

Description Sedimentation basins
A sedimentation or separation basin usually consists of a rectangular basin installed under a slight slope [Ref. 7]. Dredged material is introduced as a liquid mixture at the top, along one of the short sides, and will spread out on its way down. Larger, heavier particles will settle faster and closer to the point where they were introduced, while smaller and lighter particles settle slower and are transported farther away (see Figure 4.7). This way, in theory, the smallest and lightest material, which is sludgy sediment or organic material, can be separated from sand with the use of an overflow (e.g. a vertical panel). Usually, these small particles contain the highest amount of contaminants. After sedimentation of the smallest particles in the "sludge" basin behind the overflow, the excess transportation water can be drained and possibly reused. In some cases, purification of the excess water will be necessary in order to remove contaminants.

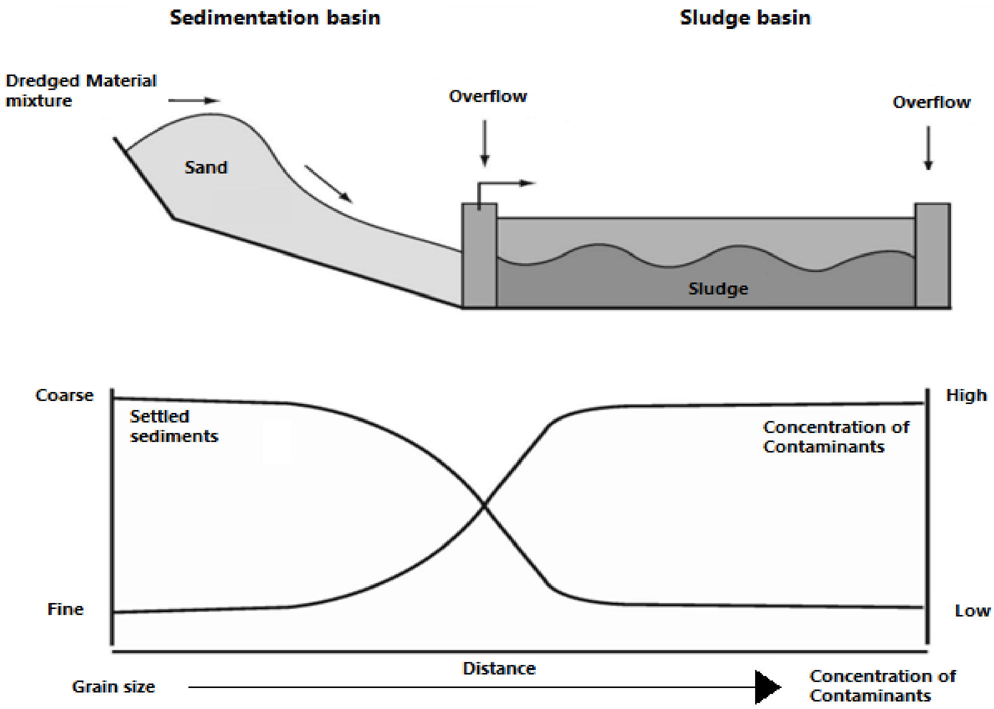
Ideally, this technique should only be used on sandy to moderately sandy material. The dredged sediment must consist of at least 40 to 50% of particles with a grain size of 63 µm or more, in order to make the use of sedimentation basins efficient enough [Ref. 7]. Furthermore, a sufficiently low flow rate in the sedimentation basin needs to be maintained, in order to prevent resuspension of the settled material. Moreover, the amount of dry matter in the dredged material must be less than 15% in order to prevent the formation of viscous currents in the sediment flow.
The material must also be properly mixed beforehand, in order to prevent the formation of clumps and aggregates of organic material [Ref. 7]. Large particles of waste materials also need to be separated in advance, by sieving or other means.
Sedimentation basins are being used on an industrial scale in Germany, the Netherlands and Belgium. At these locations, large amounts of sand can be recovered from the dredged material [Ref. 7].

Advantages and limitations
This technique is technically and environmentally feasible [Ref. 5].

Sedimentation basins actually decrease the volume of contaminated materials. The volume of the residual contaminated material will be around 10 to 50% of the original input volume, depending on the grain size distribution of the sediment and the separation efficiency of the installation [Ref. 7].
However, the disadvantage of this technique is that there is a relatively large transition zone involved, where the sand and sludgy sediments are insufficiently separated.
In sedimentation basins, the separation efficiency is about 60% [Ref. 19]. This means that only 60% of the sand fraction is recovered and that a considerable amount of sludgy particles remains in the sand as well. Furthermore, the sand in a sedimentation basin is not very homogeneous and might still contain

contaminants (especially farther away from where the material is introduced), so the sand also needs to be post-treated before it can be reused. Even then, there are only limited options for reuse of the separated sand fractions.

Figure 4.7 Schematic representation of a sedimentation basin [Ref.10]



Social aspects

The location of the treatment facility should be well chosen and communicated with neighbors, although noxious odors will rarely occur. Usually, dredged material has already come into contact with oxygen during dredging or transportation, so the chance of noxious odors at the site of the separation basins is therefore very small.
Soil protection can be applied underneath the sedimentation- and sludge basins in order to prevent spreading or leaking of contaminants into the groundwater and its surroundings, hence minimizing possible environmental effects.

Costs

Costs are estimated between € 3,- to 11,- /m^3 *in situ*, depending on the technique, scale and local conditions. No costs for transportation, extra treatment or disposal of residues were included in these costs [Ref. 4].

State of the art/experience

Applied on industrial scale.

Cases

Sand separator, Sint Joris-Beernem, Belgium [Ref. 19]	
Project team	Flemish Waterway NV
Duration of project	2001 – 2008
Client	-
Scale	Full scale
Contaminants of concern	Mineral oil, PAHs and the vast majority of heavy metals

Sand separator, Sint Joris-Beernem, Belgium [Ref. 19]

Final remedy	Sedimentation basins
Costs	EUR 3 /m^3 (costs for construction)

Remedial Objectives, Approaches and Results

At this location, sand separation is followed by lagooning of the fine sludge fraction. The sludge fraction (approximately 50%) is disposed after dewatering. Up until 2007 no suitable reuse options for the clean sands were found.

The sand is not homogeneous and still contains a relatively large fraction <63 µm which is likely to require additional treatment before it will be appropriate for construction. Most of the sand has a grain size between 63 µm and 0,25 mm and more than 50% of the sand has a grain size <0,125 mm. It is therefore a very fine sand that, without further treatment, could only be used as filling sand.

The costs for the construction of a full scale sand separator amounted to 3 €/m^3 for six separation basins and two sludge basins. Temporary storage of the material in the basins costs 1,2 €/m^3 in situ and final disposal costs (including transportation) are 2,2 €/m^3.
The maximum capacity of this facility was 150.000 m^3 (~127.000 tds) / year in 2007.

4.5.2 Mechanical separation

Description: Hydrocyclone

A hydrocyclone is a conical, downwards tapering cylinder, with an inlet for dredging material at an angle of 90 degrees near the top and two outlets: one for fine materials at the top and one for denser materials at the bottom, see Figure 4.8.
The force of the ”input-stream” combined with the shape of the hydrocyclone creates centrifugal forces, which causes denser particles to be flung against the sides of the cylinder, where they are “caught” by a downward spiralling current that has also formed against the sides of the cylinder. Eventually, this current transports the denser particles out of the hydrocylone through the bottom outlet.
Meanwhile, the lighter particles keep floating and end up in the central part of the cylinder where they keep moving up and leave the hydrocyclone through the upper outlet.
Hydrocyclones are being used on an industrial scale in Germany, the Netherlands and Belgium, but also in many other countries.

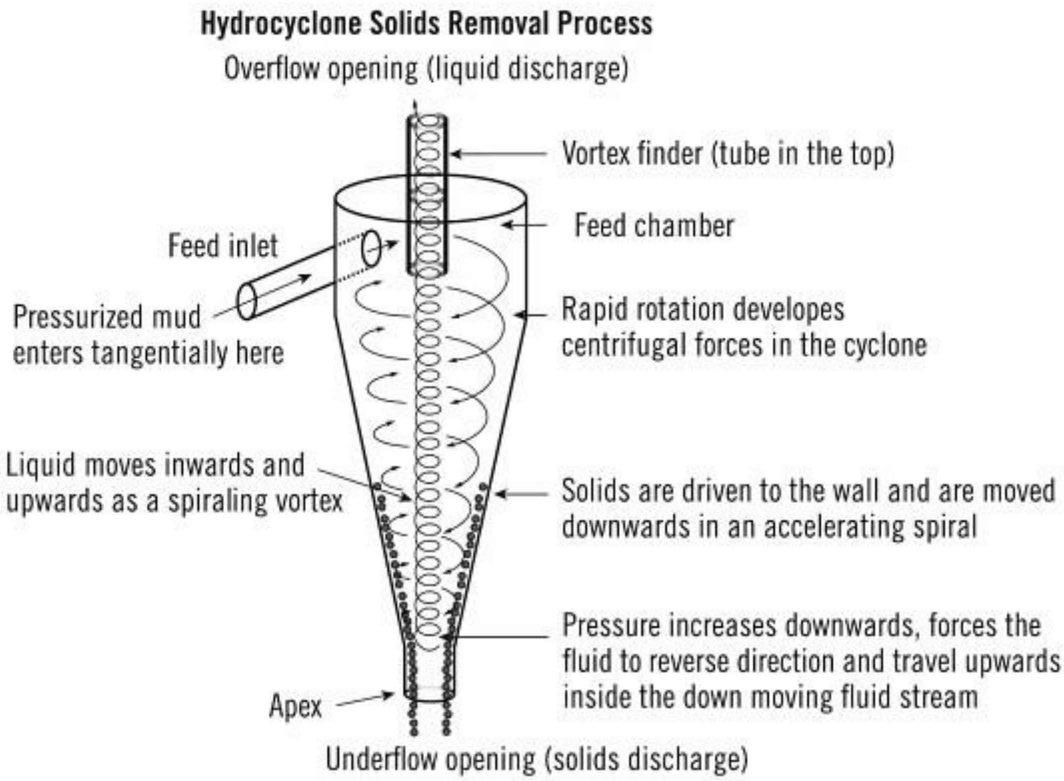
Advantages and limitations

The main limitation of using a hydrocylone, is that part of the sediments end up in the wrong outlet. This amount is defined by the separation efficiency. For very sandy sediments, the efficiency is about 90-95%. For moderately sandy sediments, extra adjustments on the hydrocyclone apparatus are needed to achieve the same efficiency, which usually leads to higher costs.
A dry matter content of 15 to 25% is necessary for a good operation of the hydrocyclone, even as a constant and homogenous flow through the inlet. The latter can be achieved by sieving and pumping of the material before bringing it into the cyclone.

Other than that, the required space of mechanical separation is smaller than for longitudinal separation. They even come in different sizes, varying from a couple of centimetres up to one meter high, depending on the separation diameter (D50) of the hydrocyclone.
Because it is a mechanical system that needs a constant energy and water supply, consumption levels are higher, even though treatment water can usually be (partially) reused.

In general, environmental effects are minimal and there can be beneficial use of the products. Flocculants might need to be used to improve dewatering of the very fine fraction and the installation might have to be built on liquid-proof floors, in order to prevent spreading of contaminants into the groundwater and its surroundings.

Figure 4.8 Schematic representation of a hydrocyclone [Ref. 35]



Social aspects
The location of the treatment facility should be carefully chosen and communicated with neighbors.

Costs
Costs depend on the technique, scale and local conditions [Ref. 5].
In the Netherlands, processing costs for a hydrocyclone vary between € 5,- and 30,- /tds (excluding costs for transportation, extra treatment or disposal of residues).
In Belgium, costs between € 30,- to 100,- / tds have been reported, at sites such as De Bree Cleaning in Maldegem and Watco Ecotechniek in Grimbergen. This includes dewatering, transportation and disposal [Ref. 7].

State of the art/experience
Applied on industrial scale.

Cases

METHA III hydrocyclone in Hamburg, Germany [Ref. 3], [Ref. 7], [Ref. 20]	
Project team	Port Authority of Hamburg
Duration of project	1993 - present
Scale	Full scale
Contaminants of concern	Mineral oil, PAHs and the vast majority of heavy metals

METHA III hydrocyclone in Hamburg, Germany [Ref. 3], [Ref. 7], [Ref. 20]

Final remedy	Hydrocyclonage and dewatering
Costs	EUR 70.000.000,- (costs for construction)

Remedial Objectives, Approaches and Results

The METHA (MEchanical Treatment and Dewatering of HArbor-sediments) plant in Hamburg separates dredged material into silt, fine sand and sand, and dewaters the silt.

The plant has a throughput rate of about 1,000,000 m^3 *in situ* volume per year, with a content of silt and clay of 50 % by weight.

The first separation step is realized at a grain size of 63 µm. Hydrocyclones and upstream separators produce a clean sand fraction with grain size >63 µm and which is free of any organic material. Sand is dewatered by a vibration screen.

Part of the silt fraction from the first separation step is treated in a second separation at 20 µm. With hydrocyclone separators and spirals, a clean fine sand fraction with a grain size distribution of 20-150 µm and which is free of any organic material is produced. Fine sand is dewatered by a vacuum belt filter. Final separation efficiencies of up to 90% have been reported.

The dewatering of the silt fraction is realized in two ways. One dewatering line comprises a sieve-belt press and a high-pressure post dewatering press. The second dewatering system comprises membrane-chamber presses. The objectives of the dewatering is to obtain a silt product with a water content to approximately 45 % by weight and a sufficient shear strength (cu > 25 kN/m^2) for mechanical aspects. The total amount of flocculant used in the dewatering process varies between approximately 500 and 1300 ppm, depending on solid matter content and type of dewatering technology.

The excess water from the transport of dredged material, pre-treatment and disposal is treated in a two-stage treatment plant with a capacity of 600 m^3 per hour. Suspended solids (which are usually bound to the contaminants) are removed to concentrations below 25 mg/kg.
Aside from this dewatering step, dewatering of the silty dredged material is also done in dewatering fields. These fields exhibit sizes ranging from 2 to 4 ha and encompass a total area of about 100 ha.

The capital investment for the plant including all technical equipment, engineering as well as surface and subsurface construction and deep foundation amounts to € 70 million.
Annual operating costs are approximately € 6.5 million.

Costs for m^3 sediments *in situ* have been calculated to be around € 15,- to 20,-.

4.6 Treatment

4.6.1 Introduction

After dredging/excavation and/or dewatering and separation of the sediments, a treatment step is often still needed in order to minimize the environmental impact and to maximize reuse of the contaminated sediment fraction. The extent at which sediments can be usefully recycled depends largely on the removal of contaminants. The optimal treatment depends on the type of contaminants and the concentrations at which they occur.
If no treatment option is available, which is often still the case these days, disposal of the material in question might be the only option left. Besides technical issues, reuse of contaminated sediments is also complicated because of legal boundaries in the region where remediation has been carried out. The legal framework in this chapter focusses on the situation in Flanders.

If contamination levels were already low to begin with, sediments can be reused directly.

For an up to date overview of reuse options for dredged material see: Interreg project Using Sediments As a Resource (USAR) [Ref. 37]. One of the project partners, the French Institute of Mines and Telecommunications (IMT), Lille Douai is developing two online information tools to stimulate sediment reuse:
- WikiSed: Inventory catalogue of uses of sediment as a resource and limitations for use;
- Operational Sediment Management System: ICT tool for water managers to make business cases and management decisions for the recycling of sediment.

4.6.2 Direct reuse of (untreated) sediment

Description
Sediments can be reused without an active treatment step if they can be applied in such a way that the contaminants present in the sediment pose no risk. The technical criteria for reuse of sediments are determined by the type of reuse that is envisioned. Normally dewatering is a necessary step, see chapter 3.4.

Besides the technical qualities of the sediments in question, reuse without active efforts to remove contaminants in Flanders is regulated in VLAREBO (2008) and VLAREMA (2012). The preconditions for reuse of soil for constructional purposes are included in annexes VI and VII of VLAREBO. If no use is possible within the VLAREBO framework, the preconditions described in annex 2.3.2 of VLAREMA can be considered.

Reuse of sediment may never lead to:
- Additional groundwater contamination;
- A larger risk than is emanating from the soil in place.

SedNet describes legal frameworks for beneficial reuse of sediments in Germany, Italy, the Netherlands, Norway and Flanders (Belgium) in its 2007 publication [Ref. 5].

Advantages and limitations
Because no active treatment is involved, this remediation method has a low impact both financially and ecologically. However, no removal of contaminants will take place.

Social aspects
This treatment method will be accepted if the absence of risks originating from the reused materials can be proved.

Costs
Immediate reuse of sediments is a cheap way of sediment treatment. Costs will largely depend on the degree of contamination.

State of the art/experience

Applied in pilot projects.

Cases

Lower-Durme, Belgium	
Project team	Witteveen+Bos Belgium NV
Duration of project	2016 - ongoing
Client	NV Waterwegen en Zeekanaal (Flemish Waterways)
Environment	Stream (non-navigable)
Scale	7 km
Contaminants of concern	Heavy metals, TPH, PAH, PCB and PFAS
Final remedy	Dredging and reuse of dredged sediments
Costs	-

Site Description

Within the framework of the Flemish flood protection program "SIGMAPLAN" for the river Scheldt estuary, the Flemish Waterways plans to renovate the Controlled Flood Area (CFA) "Potpolder IV".
Dredged material from the Durme river will be used as building material for the construction of new embankments. The project is a pilot within the Interreg 2 Seas program, „Using Sediments as A Resource" (USAR).
The trajectory of approx. 7 km is situated between the bridge of Waasmunster (N446) and the dam in Lokeren.

Contaminant Description

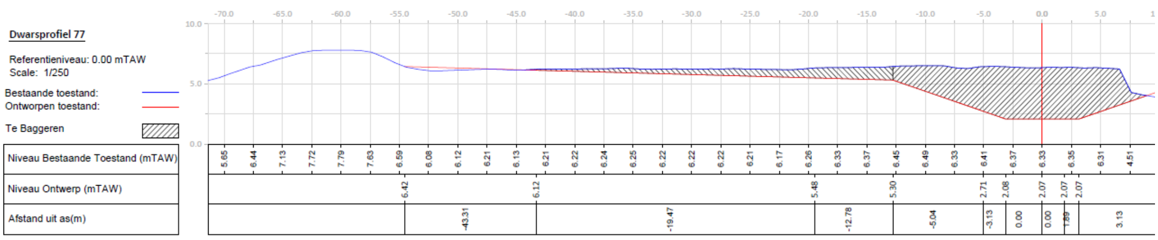
Increased levels of heavy metals, TPH, PAH, PCB and PFAS were measured in the sediments. From the 260,000 *in situ* m³ of sediments to be dredged, in total approximately 26,000 *in situ* m³ is unsuitable for direct reuse, based on the levels of TPH and heavy metals. Cleaning of these sediments is required.

Remedial Objectives and Approaches

Part of the project is to evaluate different processing options.
Sediment thicknesses range from 0,5 m to a maximum thickness of approx. 4 m. The sediment from the Durme is both silty and sandy. Based on the geotechnical properties, an evaluation was conducted on whether sand separation is necessary and what quantities of aggregates are needed for the application of the sediments in the embankments.
The remediation technique must also take into account that the Durme is a tidal river with a daily height difference of approx. 3 m between low and high tides. Besides that, the optimal depths for the water-carrying and ecological function of the stream should also be taken into account.

Because of the swampy environment, excavation works at the Durme could not be carried out in winter.
The reuse of the sediments directly next to the dredging area also avoids transportation to an external processor, which reduces the impact on the environment.

Lower-Durme, Belgium



Vlassenbroek, Belgium

Project team	JV Jan De Nul NV-Envisan NV
Duration of project	2012 – 2013
Client	NV Waterwegen en Zeekanaal (Flemish Waterways)
Environment	Navigable channel
Scale	Approx. 6 km
Final remedy	Dredging and reuse of dredged sediments
Costs	EUR 4.061.999

Site Description
The project concerns the construction of a dyke in Vlassenbroek, as part of the creation of a Controlled Flood Area (CFA). The dyke will be constructed using engineered sediments from the river Scheldt between Melle and Gentbrugge (95.000 m^3).
This technique was geotechnically analyzed and modeled in detail. Meanwhile 20 different kinds of additives were tested in a laboratory in different concentrations. Pilot studies were also carried out with a selection of additives.
Based on the results of these studies, a final design was drawn up and then verified by an independent consultant.

Remedial Objectives and Approaches
The sediments were transported towards Vlassenbroek by barges and dumped on land by means of an ingenious system based on concrete pumps. The additives were added on-site, just before the sediments were poured into the dyke profile (800 m long).

4.6.3 Extensive landfarming

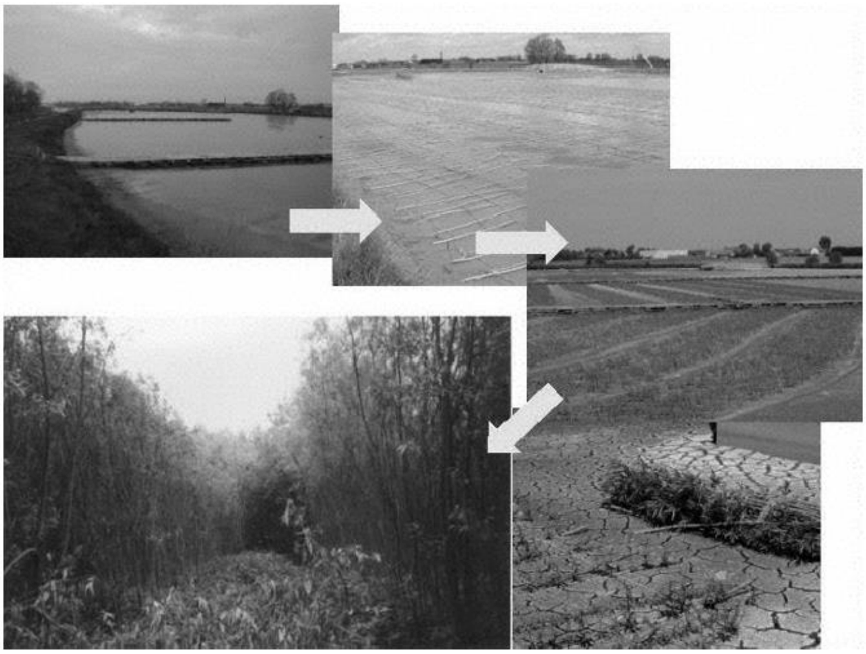
Description
Contaminated sediments are transported to a landfarming site, where they are incorporated into the soil surface and periodically turned over (tilled) to aerate the mixture. By creating aerobic soil conditions through aeration and addition of nutrients, biological degradation of (easily) degradable contaminants is stimulated. Aeration works best on sediments with low clay contents and high permeability, but can also be used for

treatment of low permeable soils. Aeration is a key factor to successfully perform landfarming. Therefore the water content needs to be limited to develop a proper soil structure. Dewatering and development of a proper soil structure (ripening) can be combined with treatment of the sediment.

Since passive landfarming requires very long treatment times and a lot of space, beneficial uses have to be found. The surface taken up by the treatment facility can also be used for energy production, for instance when producing biomass.

The typical layout and operation of landfarming is illustrated in Figure 4.9. In the first pictures, newly dredged sediments are being spread out on the landfarming location, after which they are aerated. The sediment will be used as a substrate for growing willows, which were planted by using rolls of connected willow rods (SALIMAT). This is an economical and effective planting technique for large areas of wet substrate. In the last pictures, the willows are growing while the soil ripens as well.

Figure 4.9 Landfarming: Salimat technique (Jan de Nul/Envisan) [Ref. 5]



Advantages and limitations

Since the maximum thickness of the treated material is about 1 m, treatment plants require a large amount of space. Energy consumption of passive landfarming is comparable to normal agricultural practices. Passive landfarming can result in almost clean soils given a sufficiently large treatment period (years) and aerobic conditions. Treatment periods strongly depend on the type of contaminants and the required degree of remediation.

During landfarming, high degradation percentages of biological contaminants can be obtained. Heavy metals can be remediated either by adding immobilising agents or by phytoremediation.

Landfarms have been in use for a long period of time. The growing of biomass for energy production is applied in The Netherlands and Belgium. Though cultivated willows yield only a low profit, a positive effect of these plants are shown on the dewatering process. Furthermore willows are characterized by a high metal tolerance and accumulation.

Social aspects

Because of the demand for large surfaces, social support is needed.

Costs

Costs for landfarming are 20 euro/m^3 [Ref. 5]. Since the costs of land are dominant, the search for beneficial land use is important (biomass, nature development).

State of the art/experience

Pilot scale only.

Cases

The SALIMAT technique mentioned above resulted in high-density fast growing stand development and biomass production for over 4 years. The development of willow stands was unsuccessful on parts of the depot with a sand fraction of 60% [Ref. 38]. For other case studies, see SedNet [Ref. 5].

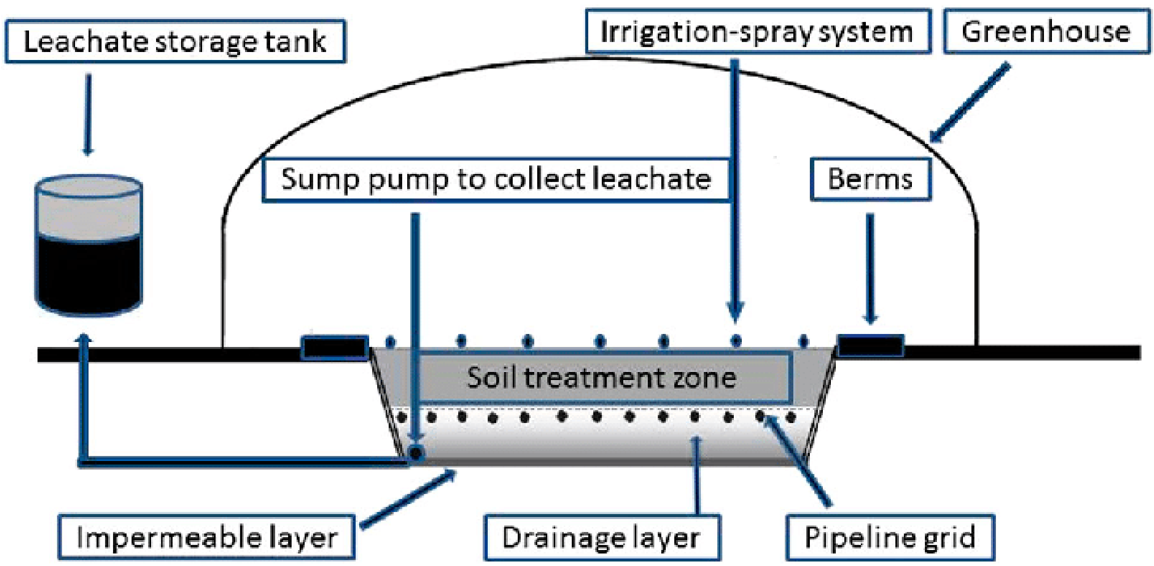
4.6.4 Biological treatment - Intensive landfarming

Description

This technique is also used for cleaning soils that are contaminated with biologically degradable contaminants. Aerobic soil and other favorable conditions are enforced to stimulate biological treatment of degradable contaminants. By aeration and addition of nutrients, biological degradation is stimulated. Aeration works best on sediments with a low clay content, but can also be used for treatment of soils with a low permeability. Aeration is a key factor to successfully perform biological treatment. Therefore the water content needs to be limited prior to treatment in order to develop a proper soil structure.

All processes are optimized to obtain the residual concentration as quickly as possible. Nutrients and more importantly oxygen are added through means of drains or mixing. A possible infrastructure layout for intensive landfarming is shown in Figure 4.10. In order to treat the sediments as shown in the figure, in the form of a biopile / forced aeration, prior dewatering is necessary (see chapter 4.4).

Figure 4.10 Intensive landfarming layout [Ref. 39]



Biological treatment is well established. In Flanders a framework for (biological) cleaning of soils is described in “Code van goede praktijk voor grondreinigingscentra” [Ref. 40].

Advantages and limitations

Biological treatment is a well-known and affordable technique for cleaning soils. It is however limited to easily degradable organics. Oil fractions with long chain lengths, PCBs and PAHs are not treatable. Furthermore, the concentration of heavy metals will be unaltered after treatment.

Biological treatment can last about 1 to 2 years. Since the maximum thickness of the treated material is limited, treatment plants need a lot of space. When treatment involves maintaining sufficiently high temperatures, in winter this will result in high energy consumption. The necessary aeration will also result in a high energy input.

Social aspects
Because of the demand for large surfaces, social support is needed.

Costs
Costs for biological treatment are 20 euro / m^3 [Ref. 5].

Recently, bioreactors are being developed that can treat sediments without dewatering beforehand. Pilot tests have been successful as to the result of the treatment, but because of the cost of this treatment, full scale applications have not been developed yet.

State of the art/experience
Plenty of experience on treating soils, but treatment of contaminated sediments occurs at pilot scale only.

Cases
See SedNet [Ref. 5] and "Code van goede praktijk voor grondreinigingscentra" [Ref. 40].

4.6.5 Washing Extraction: example BioGenesis

Description
Physical/chemical treatment of soil is a well-established technique for treatment of contaminated soils. Soils are "washed" with surfactants and chelating agents. Both organic and inorganic contaminants are thus removed. Since the contamination is concentrated in the fine fraction of the soil and in the organic material, the remainders will need to be further treated or removed to a dumping site. This is the reason why this technique is not applicable to soils with organic material and fine fraction concentrations of more than 40 %.

The framework for (physico-chemical) cleaning of soils is described in "Code van goede praktijk voor grondreinigingscentra" [Ref. 40].

Though physicochemical treatment of soil is a widely spread treatment method, it may not be applicable to sediments due to the need for storage facilities. Specific acceptance facilities for sediments may have to be available in order to store sediments with a high water content. Presently, a dewatering step is necessary before treatment can commence.
An example of physicochemical treatment that has focused on the treatment of sediments is the "BioGenesis Sediment Washing Process", which uses the same principles as the soil treatment plants [Ref. 41]. The contaminant reduction depends on the sediment matrix and organic carbon content (fine fraction) and the contaminant concentration and type. In the Biogenesis project, removal rates of 60-80% for fine materials have been established. Removal rates for coarser materials are higher [Ref. 5].

Advantages and limitations
Physicochemical treatment is a well-known and affordable technique for cleaning soils. Adaptations may have to be made to apply this treatment technique on sediments. The use of the method is limited by the fine fraction and organic material content, which are usually much higher in sediments than in soils.

Social aspects
The processing system is closed, thus there are no emissions. Water usage is about 2-3 times the amount of washed sediment. The process results in beneficial products.

Costs

Costs depend on the scales of the installation: for 300,000 meters^3 per year, costs are around EUR 55-80/m^3, while 50,000 m^3 per year costs EUR 90-130/m^3.

In the Biogenesis project the energy cost amounts to 600-800 kW for cleaning 20 m^3/h of sediment.

State of the art/experience

Pilot scale.

Cases

BioGenesis [Ref. 41] and Code van goede praktijk voor grondreinigingscentra [Ref. 40].

4.6.6 Thermal Treatment

Description

Classical thermal treatment consists of thermal desorption. The material to treat is heated up to temperatures of 600°C. Since the material will be difficult to treat with a high water content, it must first be dewatered. The water content of the material must be less than 30 %. Even with low water contents the treatment process is very energy intensive. Depending on the temperature, thermal processes can destroy or dis-associate organic contaminants. Inorganic contaminants can only be decreased in concentration through volatilization from the sediment (especially volatile metals).

Besides thermal desorption, the SedNet publication [Ref. 5] also mentions a number of thermal treatment methods that use contaminated sediments in production processes to render sediments beneficial. The treatment results in a thermal immobilization of the contamination in the sediments. Examples of this are the production of bricks, light weight aggregates, artificial basalt and the production of cement (see Figure 4.11). Some of these projects have proved to be successful. This approach is desirable due to the useful reuse of dredged material which decreases the need for disposal solutions. Furthermore the reuse of secondary materials saves natural resources. Generally speaking however, these treatment methods have not been viable on a larger scale, mainly due to the costs (natural resources are often cheaper).

Advantages and limitations

This method can treat soils (and thus dewatered sediments) with a wide range of organic contaminants with high concentrations. Typical limiting factors are the presence of asbestos, mercury (and other heavy metals) and sulphates in the soil, which cannot be treated.
The treatment method is more expensive than biological and physico-chemical treatment.

Social aspects

This treatment method is characterized by a high energy consumption and missions need to be controlled for environmental standards.
Furthermore, there is currently no demand for material created from thermally treated contaminated sediments.

Costs

For the production of bricks or light weight aggregates in Northern Germany, costs between 15 – 30 €/ m^3 *in situ* were calculated (excluding pre-treatment and under the following assumptions: treatment of approx. 200.000 m^3 de-watered sediment, an investment of € 35.000.000, 20 years of devaluation and a retail price of the bricks that is 10% below the usual market price) [Ref. 5].

These prices are similar to the price of upland disposal in the same area, which does not stimulate reuse.

State of the art/experience

This treatment method is in operation at full scale in The Netherlands, Belgium and Germany. The framework for (thermal) cleaning of soils is described in "Code van goede praktijk voor grondreinigingscentra" [Ref. 40].

The production of bricks, light weight aggregates, etc. from thermally treated contaminated sediments has not yet proved to be viable on a larger scale, mainly due to the costs.

Cases

See SedNet [Ref. 5].

Figure 4.11. Thermal immobilization combined with the production of bricks or light weight aggregates [Ref. 23]

4.7 Disposal

As a last step in the treatment chain, sediments or fractions of sediments can be disposed at confined disposal facilities (CDFs).

4.7.1 Upland Confined Disposal Facilities

Description
Upland disposal is performed above groundwater level and is confined by a dyke. These landfills are considered as a last resort solution when no reuse or other treatment of the sediment is possible.

In order to achieve a stable landfill, the sediment has to be dewatered first. The landfill has to be constructed to avoid emissions via air or groundwater through leaching. This means that these landfills have to be confined at the base and at the top. Layers with disposal materials alternate with sandy layers provided with a drainage system to intercept and treat any leachate or runoff water. All emissions need to be monitored.

In Flanders acceptation criteria of disposal sites are regulated in VLAREM II. Besides these general regulations, each disposal site may be restricted in accepting certain materials. Acceptance on a certain disposal site will be subject of the approval of the disposal site management which will check the compliance of the sediments with their specific acceptation criteria.

Advantages and limitations
At first view disposal presents an easy and sometimes cheap way to remove sediments. However disposal is viewed as a last resort solution, because the material remains contaminated and the “problem” is only being relocated.

Social aspects
Disposal sites are rarely supported by the public and subject to the NIMBY (Not In My back Yard) effect which makes it necessary to choose the location of these sites with care and to communicate clearly about any changes in permissions and use.

Costs
Usually disposal is a last step in a longer process, which can be an expensive chain. The costs for disposal amounts to 10 - 75 euro / m^3 *in situ*, including long term monitoring.

State of the art/experience
As not all sediment can be treated or reused, disposal sites are widely spread and applied on an industrial scale.

Cases
Several disposal facilities exist in Flanders and abroad. Applicability mainly depends on acceptance criteria.

4.7.2 Sub-aquatic Confined Disposal Facilities

Theoretically, sub-aquatic CDFs can accept all types of contaminated material, even if they are not dewatered. They require a lot of space in for example large waterways nearshore or in large delta areas further inland. Sub-aquatic CDFs are largely applied worldwide and capacities up to 100 000 000 m^3 have been reported [Ref. 5].
In Flanders, however, licenses are no longer issued for new sub-aquatic CDFs. But existing storage cells in the port of Antwerp for example are still being used as temporary facilities in anticipation of more permanent treatment options on the mainland.

5

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Appendices

APPENDIX: GLOSSARY AND LIST OF ABBREVIATIONS

Glossary of terms related to sediment remediation and list of abbreviations	
Active sediment	Upper part of a sediment layer, usually up to a few centimeters thick, where natural exchange processes take place with the overlying surface water.
BBO	In Flanders: Beschrijvend BodemOnderzoek. Translation: Descriptive soil investigation.
Bentonite sludge	A mixture of excavated soil and betonite used in construction-, drilling- and earthworks.
BHD	Backhoe Dredger.
BLD	Bucket Ladder Dredger.
BSP	In Flanders: BodemSaneringsProject. Translation: Soil remediation project.
BSW	In Flanders: BodemSaneringsWerken. Translation: Soil remediation works.
Canal	A ditch or small waterway (non-navigable).
CDF	Confined Disposal Facility.
Channel	A navigable waterway.
CIW	In Flanders: Coördinatencommissie Integraal Waterbeleid. Translation: Integral Water Policy Coordination Committee.
Clearance spoil	Material originating from the deepening, widening or maintenance of non-navigable waterways belonging to the public hydrographic network, or other non-navigable waterways and water bodies.
Crown of a slope	The upper edge of the slope, being the tipping point where the sloping slope ends and the horizontal part of the plains further inland starts.
CSD	Cutter Suction Dredger.
Dredging spoil	Material originating from the deepening, widening or maintenance of navigable waterways belonging to the public hydrographic network, or the construction of new water infrastructure, including canals, ports and docks.
Dm	Dry matter.
DST	Decision Support Tool.
ECOS	Environmental Council of the States
ERIS	Environmental Research Institute of the States
Floodplain	Area near the shore, limited by straits, inner dikes, valley edges or other boundary structures. Overflows regularly, either naturally or in a controlled manner at regular intervals. Functions as a water storage element.
Floodplain sediment	Deposited sediment that remains after a river floods outside its banks.
Ground slurry/mixture	The leftover soil(slurry) after washing recently harvested crops.
IPPC companies	Companies with Integrated Contamination Prevention and Control.
ITRC	Interstate Technology & Regulatory Council

Glossary of terms related to sediment remediation and list of abbreviations	
Linear waterways	Surface waters whose length is considerably greater than their width (canals, streams, rivers, channels, ...).
OBO	In Flanders: Oriënterend BodemOnderzoek. Translation: Exploratory soil investigation.
OVAM	Openbare Vlaamse Afvalmaatschappij: Public Waste Agency of Flanders.
PAHs	Polycyclic Aromatic Hydrocarbons.
PCBs	Polychlorinated Biphenyls.
PFAS	Per- and polyfluoroalkyl substances.
Navigable waterways	The waterways included in the Royal Decree of 5 October 1992, in order to establish a list of waterways and their appurtenances transferred from the State to the Flemish Region.
NAPLs	Non-aqueous phase liquids (hydrophobic liquid solution contaminants).
NIMBY	Not in my backyard.
Non-linear water surfaces	Surface waters whose length is not significantly greater than their width (ponds, lakes, reservoirs, reservoirs, harbors, docks, ...).
Non-navigable waterways	The waterways not included by the government in the Royal Decree of 5 October 1992. Non-navigable waterways can belong to the 1st, 2nd, 3rd category or can be unclassified.
ppm	Parts per million.
River bank	Land strip from the top of the roadside and further inland over an arbitrarily fixed width.
River bed	The naturally present, consolidated part of the bottom of a surface waterbody, specific to the region in which the surface waterbody is located and that is always or nearly always submerged.
Sediment	Suspended or deposited solid, of mineral as well as organic nature, acting as a main component of a matrix, which has been, or is susceptible to being transported by water.
SedNet	European Sediment Network.
Surface water	Inland waters, with the exception of groundwater.
Surface waterbody	A distinct surface water, such as a lake, a reservoir, a (part of a) stream, a river, a canal or a transitional water.
TBT	Tributyltin.
Tds	Ton dried solids.
TPHs	Total petroleum hydrocarbons.
TSHD	Trailing Suction Hopper Dredger
VITO	Vlaamse Instelling voor Technologisch Onderzoek, an independent Flemish research institute.
VLAREMA	Flemish Regulations for sustainable management of material cycles and waste.
VLAREBO	Flemish Regulations on soil remediation and soil protection.
w/w	Weight for weight; the proportion of a particular substance within a mixture, as measured by weight.

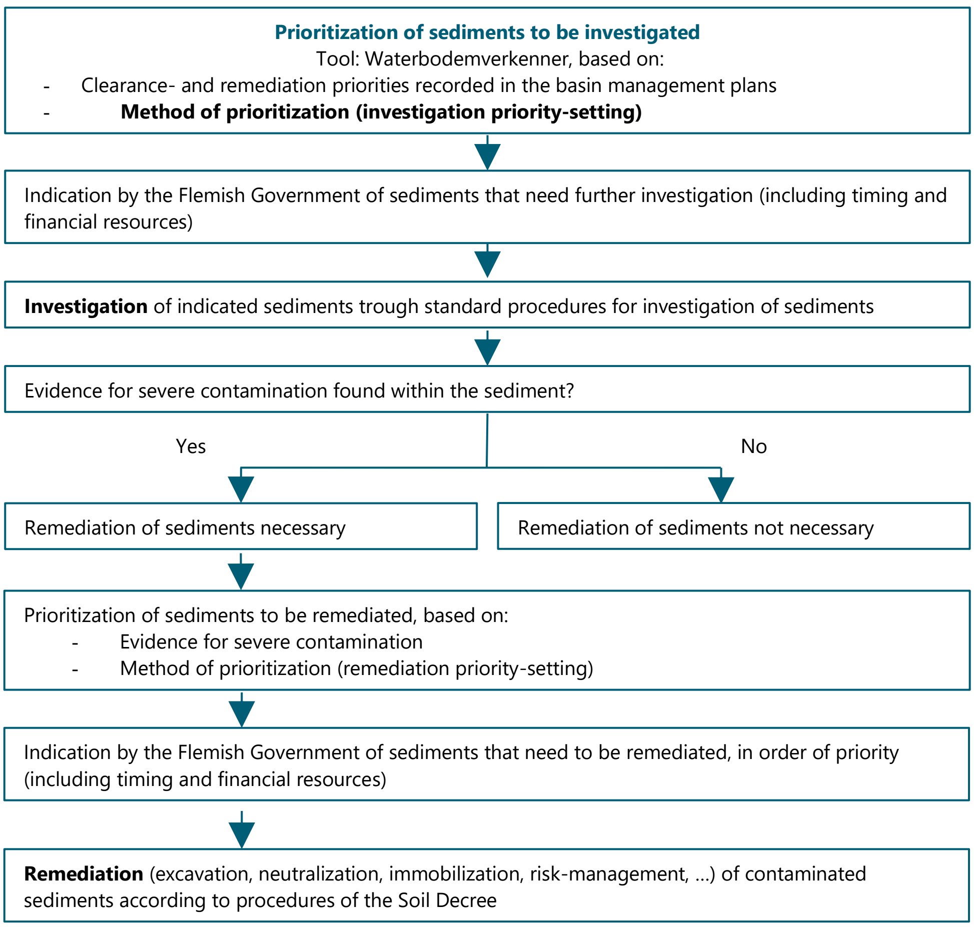
II

APPENDIX: SEDIMENT REGULATION IN FLANDERS (IN CONTEXT OF THE CURRENT SOIL LEGISLATION)

Currently, the following specific regulations for sediments are being used within the current soil legislation in Flanders, Belgium: *"According to the Soil Remediation and Protection Decree, the obligation to carry out a sediment investigation lies with the waterway manager. Advised by the Integral Water Policy Coordination Committee (Coördinatiecommissie Integraal Waterbeleid; CIW) and OVAM (Public Waste Agency Flanders), the Flemish Government will designate those waterways where the manager must carry out a sediment investigation within a certain period. Prioritization will be based on the methods used within the Work Group for Dredging- and Clearance Spoils. If a serious sediment contamination is discovered during the investigation, it will be necessary to proceed with remediation"* [Ref. 29].

The flowchart shown in Figure II.1 below describes this process in further detail.

Figure II.1 Flowchart prioritization sediment investigations in Flanders [Ref. 29]



This document and the accompanying DST can be used during the entire sediment investigation and remediation process described in Figure II.1, but basic project information such as the type(s) of contamination, type of sediment, remediation goal, etc., should be provided by the user in order to evaluate and eventually narrow down the several remediation possibilities. Further information on the necessary basic input information is provided in Chapter 2 "Preconditions".

A specific approach for the investigation of contaminated sediments is currently still under construction. For comparison, the existing method used in soil investigations in Flanders is outlined below [Ref. 3]:
- Oriënterend BodemOnderzoek (OBO) or exploratory soil investigation: An OBO serves as a first estimate in assessing whether or not soil has been contaminated by current or past activities that took place in the area. This investigation is carried out near high-risk locations (e.g. storage tanks, production areas) and is mandatory in cases of soil transfers or periodic investigation obligations;
- Beschrijvend BodemOnderzoek (BBO) or descriptive soil investigation: carried out if (substantial) contamination has been discovered during an OBO. A BBO is used when there is a possibility of contamination spread, for instance, or when the contamination could endanger people, plants, animals and ground- and surface water. For new cases of contamination (originated after October 28, 1995), a BBO needs to be carried out if the soil remediation standards have been exceeded.
  During a BBO, the extent of the contamination will be defined in three dimensions. In addition, all risks, such as the risk of contamination spreading, are assessed.
  An OBO and BBO are sometimes combined in one study called: OBBO;
- BodemSaneringsProject (BSP) or soil remediation project: in a BSP, a soil remediation expert will examine which remediation technique(s) are suitable to eliminate the contamination and will select one or multiple techniques, depending on the situation (including costs);
- BodemSaneringsWerken (BSW) or soil remediation works: execution of the soil remediation works, supervised by a soil remediation expert (including a final technical evaluation report).

Naturally, other causes or factors than the ones mentioned above might also give rise to the need for sediment remediation.

III

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