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Developing an Evidence Base for In Situ Contaminated Sediment in England

Work Package 1B Report

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Developing an Evidence Base for In Situ Contaminated Sediment in England Work Package 1B Report

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REPORT

Developing an Evidence Base for In Situ Contaminated Sediment in England

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Acronyms

AC	Alternating Current
BLD	Bucket Line Dredger
BRGM	Bureau de Recherches Géologique
BTEX	Benzene, toluene, ethylbenzene and xylenes
CAD	Contained Aquatic Disposal
CDF	Confined Disposal Facility
CDM	Contaminated Dredged Material
CDS	Cutter Suction Dredger
DC	Direct Current
EGCO	ElectroChemicalGeoOxidation
ECRT	Electrochemical Remediation Technology
ESTCP	Environmental Security Technology Programme
GD	Grab Dredger
HDMMC	Hamburg Dredged Material Management Concept
IADC	International Association of Dredging Companies
IC	Induced Complexation
MNR	Monitored Natural Recovery
PAH	Polyaromatic hydrocarbons
PCB	Polychlorinated biphenyl
SD	Suction Dredger
TBT	Tributyltin
TCE	Trichloroethylene
TPH	Total Petroleum Hydrocarbons
TSHD	Trailing Suction Hopper Dredger
USEPA	United Stated Environmental Protection Agency
WP	Work Package

1 Introduction

1.1 Project Background

As part of working towards meeting its environmental objectives, Defra is seeking to understand the magnitude of risks to sensitive receptors (e.g. aquatic ecology and human health) or impacts (e.g. on the way that water bodies are managed) posed by contaminated sediment in England. Defra’s requirements included a systematic review of the contamination status of sediments associated with water bodies through the application of a risk assessment approach. This process is intended ultimately to provide the basis for a comprehensive review of the potential mitigation options available for addressing those locations where the risks may be significant.

The Project’s overall aim is to provide a sound evidence base on contamination in in-situ sediments, which can underpin the development of tools and methods that will help Defra, the Environment Agency and other bodies engaged in regulation and protection of water quality. This will enable these bodies to make evidence-based decisions for funding to deliver maximum value for money in addressing risks to water quality, in particular to meet Water Framework, Marine Strategy Framework and Habitats Directives requirements.

This project is seeking to analyse and assess the risk posed by in-situ contaminated sediments and to identify practical and cost effective mitigation measures that can be applied, when needed, as part of a national risk assessment and management approach.

1.2 Project Structure

The project is divided into two workstreams; which are subdivided into a number of work packages (WP):

- **Workstream A: Need for Action:** This workstream gathers evidence of in-situ sediment contamination in England and undertakes an assessment of the risks that this could pose; and,
- **Workstream B: Developing Interventions:** This workstream gathers evidence on the range of interventions that can be used to address the issues posed by in-situ contaminated sediments, and undertakes an economic assessment.

Figure 1.1 shows the progression of tasks within each workstream, as well as the interactions between each workstream. This report presents the findings of **Work Package 1B** (WP1B).

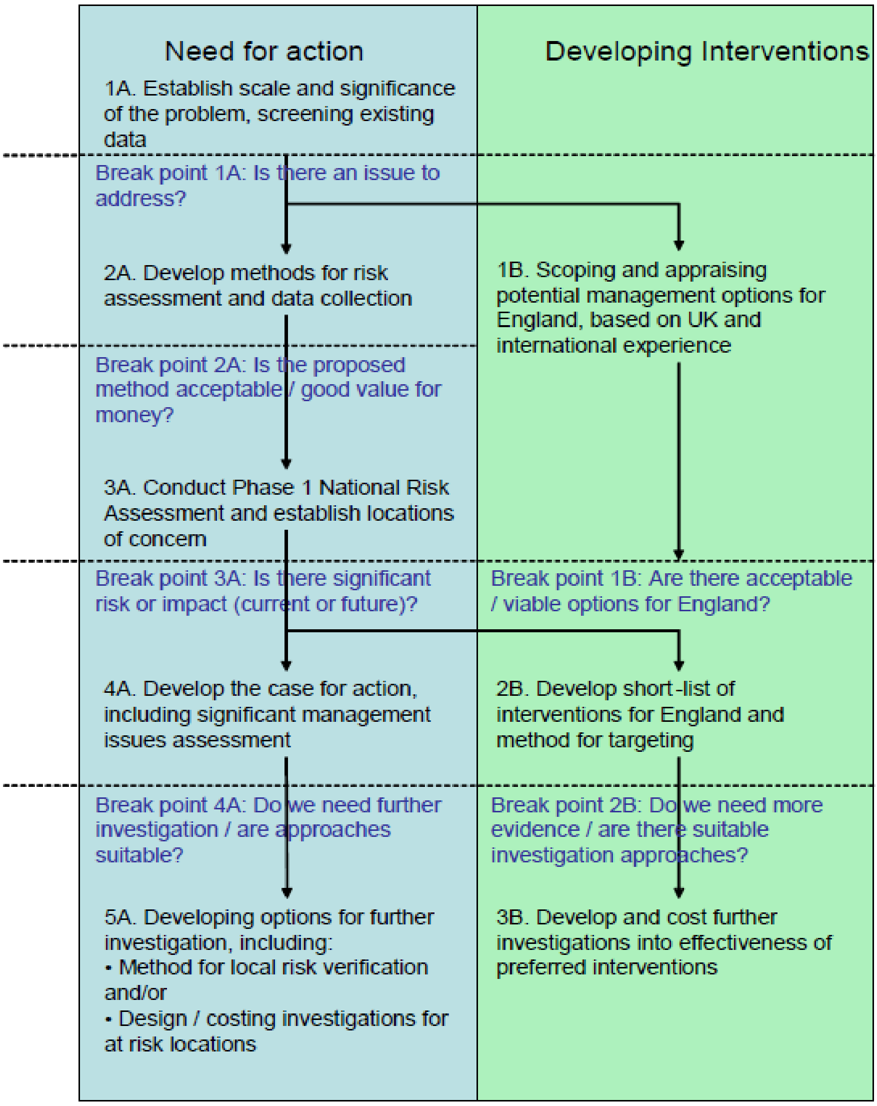

Figure 1.1 Structure of Work Packages

1.3 Workstream B

As discussed in **Section 1.2**, and demonstrated in **Figure 1.1**, workstream B aims to gather evidence to further develop management and intervention techniques for in-situ contaminated sediment. This work stream is divided into three WPs, each with its own specific aim for the project:

- **Work package 1B:** WP1B is the focus of this report and aims to collate, review and analyse existing management and intervention techniques for in-situ contaminated sediment (see **Section 1.4** for more information).
- **Work package 2B:** WP2B aims to develop an approach for identifying the most suitable intervention and management techniques for in-situ contaminated sediment, and determine how these should be selected or targeted in England.
- **Work Package 3B**: WP3B aims to define further, the work or data collection necessary to refine or evaluate the intervention and management options identified in the previous WPs. This includes adding further techniques to the short list, if necessary, or improving the quality of information about those already shortlisted.

1.4 Work Package 1B

WP1B focuses on the collation, review and analysis of intervention and management techniques which impact upon or are used to manage / treat in-situ contaminated sediment. The WP considers these options in terms of their advantages, disadvantages and cost-effectiveness. Case studies from both within and outside of the UK were used to highlight where the techniques identified have been applied.

The work for this package has been divided into three tasks, as follows:

1. Review and evaluate existing interventions and management techniques for managing in-situ contaminated sediment in the UK and internationally;
2. Investigate how land and water management techniques have the potential to improve or exacerbate the risks/impacts associated with in-situ contaminated sediment ; and,
3. Identify new innovative techniques for the management of in-situ contaminated sediment.

1.5 Report Structure

The remainder of this report comprises the following sections:

Section 2: Review of management and intervention measures for managing in-situ contaminated sediment;

Section 3: Investigation of how land and water management activities have the potential to improve or exacerbate the risks/impacts associated with in-situ contaminated sediment;

Section 4: Potential and methods for generating new innovative techniques for the management of *in-situ* contaminated sediment;

Section 5: Conclusions and recommendations; and,

Section 6: References.

2 Review of Management and Intervention Measures for Managing In-situ Contaminated Sediment

Scope of task:

Undertake a review of activities whose specific objectives is to manage contamination in in-situ sediments. This review includes the collation of reports that detail intervention and management activities from the UK and international sources. Benefits, constraints and cost-effectiveness of the activities are also outlined.

The findings of this task will support subsequent work on WP2B and WP3B and the development of a short-list of detailed, costed, potential interventions for England as well as a method for targeting these nationally or locally.

2.1 Introduction

In the UK, there are currently no intervention and management techniques aimed solely at reducing the impact of in-situ contaminated sediments for environmental benefit alone. Dredging is the only commonly used technique; however, this is usually as an indirect consequence of the need to maintain navigable waterways, or for works associated with development of ports and harbours or as a flood defence measure. Dredging activities are unlikely to remove all contaminated sediment and, unless the contaminant sources are targeted, contaminated sediments will continue to be deposited into the marine environment. In addition, there continues to be the issue of where the contaminated sediment can be disposed of once dredged, in some cases it is returned to the marine environment at a designated disposal site, in others it is disposed of inland at a landfill site.

There is a requirement for effective and cost-efficient management of in-situ contaminated sediment in England, not only to ensure that contamination of in-situ sediment is not exacerbated further but to also ensure that all objectives set out under environmental legislation including the Water Framework Directive (WFD), Habitats Directive and Marine Strategy Framework Directive (MSFD) are met.

The first task of WP1B considers intervention and management techniques for in-situ contaminated sediment which have been adopted in the UK and internationally. The advantages, disadvantages and cost-effectiveness of these techniques have also been assessed to determine their applicability for use in England.

2.2 Methodology

WP1B has primarily drawn upon the information provided in the Defra funded project ‘Contaminated Dredged Marine Sediments: Developing a Management Framework – ME1104’ which was undertaken in 2007. WP1B has reviewed and updated the information from the 2007 project in line with developments in the management and intervention of in-situ contaminated sediments. The previous work has been further developed in this report through the consideration of in-situ contaminated sediment in the wider freshwater environment and through the undertaking of a cost benefit analysis of the management and intervention techniques identified.

The list of techniques was compiled through a review of guidance documents, scientific research papers and technical documents, and consultation with the Project Steering Group and internal technical staff. In addition, a search of the internet was carried out.

2.3 Summary of Management and Intervention Techniques for Managing In-situ Contaminated Sediment

This task identified 13 intervention and management techniques for in-situ contaminated sediments for review and analysis. These techniques are:

- *Primary management/intervention techniques*
    1. In-situ capping;
    2. Dredging;
    3. Excavation;
    4. Monitored Natural Recovery;
    5. Immobilisation (in-situ); and,
    6. Electrochemical Remediation;

- *Secondary management/intervention technique*
    7. Immobilisation (ex-situ);
    8. Dewatering;
    9. Contained Aquatic Disposal;
    10. Confined Disposal Facilities;
    11. Landfarming;
    12. Landfill Disposal; and,
    13. Soil Washing.

The following tables provide an overview of each technique and describe their economic and environmental advantages, disadvantages and their cost-effectiveness. A summary of the tables and the information they contain is provided below:

- **Table 2.1**: Overview of the management and intervention techniques for in-situ contaminated sediment
- **Table 2.2:** Suitable environment for application of the intervention and management techniques
- **Table 2.3:** Advantages and disadvantages of the intervention and management techniques
- **Table 2.4:** Cost effectiveness (qualitative and quantitative costs) of the intervention and management techniques

Table 2.1 Overview of the Management and Intervention Techniques for In-situ Contaminated Sediment

Overview of Technique
Primary management/intervention techniques
In-situ Capping
In situ capping is the placement of a subaqueous covering or 'capping' of clean[1] material over contaminated sediment to chemically and biologically isolate it from the aqueous environment (Förstner and Apitz, 2007). Caps are generally constructed of granular material such as clean sediment, sand, or gravel. More complex cap designs can include geotextiles, liners and other permeable/impermeable elements in multiple layers. The minimum thickness of the cap is dependent upon; the physical and chemical properties of the contaminated sediments, the potential for bioturbation of the cap by aquatic organisms, the potential for consolidation and erosion of the cap material and the type(s) of cap material(s) used (United States Environmental Protection Agency (USEPA), 2005). Depending on the nature of the contaminants and sediment, a cap is designed to reduce the risk of further contamination of the sediment through the following primary functions: 1. Physical isolation of the contaminated sediment sufficient enough to reduce exposure due to direct contact and to reduce the ability of burrowing organisms to move contaminants to the surface; 2. Stabilisation of contaminated sediment and erosion protection of sediment to reduce re-suspension; and, 3. Chemical isolation of contaminated sediment to reduce the release of dissolved contaminants into the water column. *Other Considerations* An understanding of site specific conditions, in terms of the physical environment and sediment characteristics, is critical to predicting the feasibility and effectiveness of in-situ capping. Site conditions can affect all aspects of a capping project, including design, equipment and cap material selection and monitoring and management programmes. A variety of information about the project site and sediments is, therefore, needed to prepare an in-situ capping design. Conventional minimum required cap thickness for chemical isolation from the overlaying water column maybe highly variable, from the order of 10cm to 60cm (Reis *et al.*, 2007).

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[1] *Where sediment is referred to as ‘clean’ in this report, it is assumed that it is at acceptable level. Where the term 'acceptable' is used, it refers to the allowable quality standards and guidelines as detailed in the relevant legislation.*

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Dredging

Dredging involves mechanically grabbing, raking, cutting or hydraulically scouring the bottom of a waterbody to dislodge the sediment. Once dislodged, the sediment may be removed from a waterbody either mechanically with buckets or hydraulically by pumping, or by hydrodynamic processes (USEPA, 2005). There are three main types of dredging, as described below:

Hydraulic Dredging
Hydraulic dredgers make use of centrifugal pumps to remove sediment (through raising or horizontal transport). The three main groups of hydraulic dredgers are: Suction Dredgers (SD), Cutter Suction Dredgers (CSD) and Trailing Suction Hopper Dredgers (TSHD) (Bray, 2008)

Mechanical Dredging
Mechanical dredging makes use of mechanical excavation equipment for cutting and raising material. The three main groups of mechanical dredging can be identified as: bucket line dredgers (BLD), backhoe dredgers (BHD) and grab dredgers (GD) (Bray, 2008).

Hydrodynamic Dredging
Hydrodynamic dredging is where material is lifted into the water and is transported away by the currents (agitated dredging) or under the influence of the natural gravity forces (water injection dredging) or a mechanical push from the equipment (underwater plough or sweep bar) (Bray, 2008).

Other Considerations:

Prior to undertaking dredging activities, consideration of the physical environment (e.g. local bathymetry, currents and tides, bottom conditions, sediment particle size distribution and presence of structures) and local waterbody uses and infrastructure should be made.

Excavation

Excavation of contaminated sediment also involves the physical removal of sediment, although it differs from dredging as it is undertaken in the dry. Excavation isolates the contaminated sediment from the overlying waterbody by pumping or diverting water from the area, managing any continuing inflow, followed by sediment excavation using conventional dry land equipment (USEPA, 2005).

Prior to pumping out the water, the area needs to be isolated using the following technologies:

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- Sheetpiling/cofferdams;
- Geotubes, inflatable dams;
- Re-routing the waterbody using temporary dams or pipes; or,
- Permanent relocation of the waterbody.

Other Considerations

Similar considerations need to be made for excavation of contaminated sediments as for dredging, with the exception of those relating to in water effects (including local bathymetry and currents and tides. In addition, the following will need to be considered:

- Where bedrock or hard strata is present sheet piling will may not be viable;
- Where sheet piling is considered, the potential hydraulic impacts of the diverted flow should be considered;
- Following isolation and dewatering of an area, the sediment can be soft. In this case, support of the excavation equipment can be problematic should the underlying material not have the strength to support the equipment. Weight of equipment and strength of the sediment, therefore need to be considered in the design phase; and
- Levels of contaminants within the diverted water will also need to be determined to ensure that contaminants are not spread during excavation activities.

Monitored Natural Recovery

Monitored Natural Recovery (MNR) is a remediation technique that uses ongoing, naturally occurring processes to contain, destroy, or reduce the bioavailability or toxicity of contaminants in sediment (Environmental Security Technology Programme (ESTCP), 2009). The most common natural risk reduction processes are the following (listed from generally most to least preferable, though all potentially acceptable as a basis for selecting MNR):

1. Contaminant is converted to a less toxic form through transformation processes, such as biodegradation or abiotic transformation;
2. Contaminant mobility and bioavailability are reduced through sorption or other processes binding contaminants to the sediment matrix;
3. Exposure levels are reduced by a decrease in contaminant concentration levels in the near-surface sediment zone through burial or mixing in-place with cleaner sediment (a similar concept to in-situ capping); and,
4. Exposure levels are reduced by a decrease in contaminant concentrations levels in the near surface sediment zone through dispersion of particle bound contaminants or diffusive or advective transport of contaminants to the water column.

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Naturally occurring processes may include physical, biological and chemical mechanisms: *Physical Processes (sedimentation, advection, diffusion, dilution, dispersion, bioturbation, volatilisation):* Physical processes do not directly change the chemical nature of contaminants. Physical processes may bury, mix, dilute or transfer contaminants to another medium. Physical processes may reduce contaminant concentrations in surface sediments and thus reduce the risk associated with sediment (USEPA, 2005). Sedimentation reduces the risk posed by contaminants by physically isolating contaminants in place (similar to in-situ capping) (ESTCP, 2009). Other physical processes, such as erosion, dispersion, dilution, bioturbation etc. may reduce contaminants concentrations in sediment as a result of transferring the contaminants to another medium or dispersing over a wider area. The longevity of sedimentation depends upon the physical stability of the new sediment bed. Physical processes within sediment can operate at vastly different rates. Some may occur faster than others but may have a limited effect on risk. In general, processes which transport contaminants in bulk movements (e.g. erosion, dispersion, bioturbation) occur at faster rates than processes in which contaminants are transported by diffusion of volatilisation. Some physical processes are continuous, whereas, others are seasonal or episodic. Transport and deposition of cleaner sediment in a waterbody can cause the natural burial of contaminated sediments in low flow environments. Natural burial may reduce the availability of the contaminants to aquatic plants and animals and, therefore, may reduce toxicity and bioaccumulation. Although bioturbation by burrowing organisms may promote mixing and dilution of contaminated sediment with the newly deposited cleaner sediment, for bioaccumulative contaminants, it may also result in continued bioaccumulation into the food web until contaminant isolation occurs (USEPA, 2005). *Biological Processes (biodegradation, bio-transformation, phytoremediation, biological stabilisation):* As with physical processes, biological processes also depend on site-specific conditions and are highly variable. During biodegradation, a chemical change is facilitated by microorganisms living within the sediment. The usefulness of biodegradation as a management technique is limited to the fact that the greater the molecular weight of the organic contaminants, the greater partitioning to sorption sites on sediment particles, and the lower the contaminant availability to microorganisms. Some degradation of organic compounds with high molecular weights occurs naturally in sediment with anaerobic and aerobic microorganisms. Degradation rates vary with sediment depth partly due to the change from aerobic to anaerobic conditions. These changes frequently occur at depths of a few millimetres to a few centimetres where sediments have substantial organic content and conditions are relatively quiet. Longer residence times of contaminants in the sediment also usually result in increased sequestration. These processes reduce the availability of the organic compounds to

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microorganisms and, therefore, reduce the extent and rates of biodegradation. However, this can also reduce the availability of the contaminant to receptors living in the sediment and at higher trophic levels. Phytoremediation can be used to remediate contaminated sediments due to the uptake of metals and organic compounds by plants. This technique is still an emerging concept and is discussed in more detail in **Section 4** of this report as an innovative technique for the management of in-situ contaminated sediment. *Chemical Processes (oxidation/reduction, sorption or other processes resulting in stabilisation or reduced bioavailability) :* Chemical processes in sediment are important for metals. The mobility, toxicity and bioavailability of metals is heavily influenced by many environmental variables, including salinity, pH, alkalinity, sediment grain size, redox conditions and the amount of sulphides and organic carbon present in sediments (USEPA, 2005). Much of the current understanding of the role of chemical processes in controlling risk from in-situ contaminated sediments is focused on the important geochemical changes resulting from changes in redox potential that can affect the bioavailability of metal and organic metal compounds. Formation of relatively insoluble metal sulphides under reducing conditions can often effectively control the risk posed by metal contaminants if reducing conditions are maintained. *Other Considerations* MNR involves leaving sediments in place and relying on effective source control and ongoing natural processes to reduce the environmental risks posed by contaminated sediments. Monitoring of a site is required to assess whether risk reduction and ecological recovery by natural processes are occurring as expected. Not all natural processes results in risk reduction of contaminated sediment. Some may increase or shift risk to other locations or receptors. Therefore, the processes that contribute to risk reduction should be identified and evaluated prior to implementing MNR. Natural recovery can be combined with engineering approaches to manage contaminated sediment, e.g. installing flow control structures to encourage deposition of sediment, by the placement of a thin layer of additional clean sediment or additives to enhance sorption or chemical transformation. MNR can also be combined with dredging or in-situ capping of other areas of a site. The need for the following should be considered when selecting MNR: • Detailed understanding of the natural processes that are affecting sediment and contaminants at the site; • A predictive tool (e.g. modelling) to predict future effects of these processes;

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- A means to control any significant ongoing contaminant sources;
- An evaluation of ongoing risks during the recovery period and exposure control; and
- Ability to monitor the natural processes and/or concentrations of contaminants in sediment/biota to determine whether recovery is occurring at the expected rate.

Immobilisation (in-situ and ex-situ)

Immobilisation alters sediment's physical and/or chemical characteristics to reduce the potential for contaminants to be released from the sediment to the surrounding environment. The principal contaminant loss pathway reduced by immobilisation is contaminant leaching to groundwater and/or surface water (Van der Kooji, 1999).

Immobilisation techniques are closely linked to the pH of sediment and its natural buffering capacity. Marine sediments usually have higher buffering capacities than soils. A high buffering capacity reduces the need for additives because the pH of the sediment is less likely to be reduced as a result of chemical reactions post dewatering. The addition of an immobilising agent will reduce the mobility of contaminants but not remove them from the sediment; however the environmental risk is reduced. Additives include cement, calcium aluminates, fly-ash, bentonite, lime and phosphates. Immobilisation techniques can be applied both in-situ and ex-situ.

Thermal Immobilisation

Thermal immobilisation removes/destroys organic contaminants, through the breakdown of organic contaminants at high temperatures. The process can produce a number of products, including bricks, light weight aggregate and artificial basalts (Defra, 2010).

Thermal immobilisation can be applied to organic, inorganic compounds and metals in fine grained sediment.

Chemical Immobilisation

Physico-chemical treatment processes remove, change or stabilise contaminants in contaminated sediment. Following dewatering of contaminated sediments, they can be treated with a range of additives in order to stabilise them for beneficial use and/or immobilise contaminants. This technique aims to reduce leaching, erosion, dispersion and bioavailability of contaminants by altering the physical and chemical properties of the sediment (Defra. 2010).
Chemical immobilisation can be applied to some organic compounds (including tributyltin (TBT)), inorganic compounds and metals. Mostly silts and clays can be treated for re-use and sands can be stabilised.

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Other Considerations Immobilisation techniques can be applied both in-situ and ex-situ. Ex-situ treatments can be conducted using mobile mixing plant on land or on a floating pontoon (Defra, 2010). The effectiveness of the immobilisation for a particular sediment is difficult to predict and can only be evaluated using laboratory tests. With this in mind, although there are clear beneficial uses of stabilised sediments, in the Netherlands, the authorities have placed restriction on the allowable organic matter due to limited leaching tests. Additionally, there is some concern over the potential long term effects with respect to construction stability and poor water chemistry due to the generally higher organic contents of dredged material, in comparison with clays and silts (Defra, 2010).
Electrochemical
Electrochemical remediation involves the application of a low density direct current to a pair of positive (anode) and negative (cathode) electrodes placed in the sediment to mobilise contaminants (Gardner, 2005). The contaminants within the electric field are transported to the anode or to the cathode where they can be removed by various methods. Electrodialysis methods (which utilise the transport of ions between solutions through ion-exchange membranes) can only be applied to ex-situ sediments, whereas electrokinetic methods are accomplished by placing electrodes directly into in-situ sediment, and removing contaminants which have precipitated or have collected at the electrode (Gardner, 2005). Electrochemical Remediation Technologies (ECRTs) utilises a direct current(DC)/alternating current (AC) passed between an electrode pair (anode and cathode) in sediment to attempt to either mineralise organic contaminants through an ElectroChemicalGeoOxidation (ECGO) process, or complex, mobilise, and remove metal contaminants deposited at the electrodes through Induced Complexation (IC), as described below (USEPA, 2004): *ECGO* Using a low voltage, low amperage DC/AC current, an induced polarisation field is created within the sediment. The electrical current results in redox reactions which cause desorption of the contaminants from the sediments. Empirical evidence indicates that reaction rates are inversely proportional to grain size, such that ECRTs remediate faster in finer-grained materials typically found at contaminated sediment sites. Within sediment, in addition to the local electrode reactions, redox reactions occur simultaneously at interfaces within the sediment-water-contaminant system (USEPA, 2004). Contaminated sediments which have undergone ECGO include total petroleum hydrocarbon (TPH), benzene, toluene, ethylbenzene and xylenes (BTEX), trichloroethylene (TCE), polyaromatic hydrocarbons (PAHs), phenols, and polychlorinated biphenyl (PCBs).

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IC

Metal remediation may be achieved when redox reactions, created by the same low voltage/amperage current described above, desorb the contaminants from the sediment and create ionic metal complexes that are significantly more mobile. These mobile ions move readily to the electrodes, where they are electrically contained by the induced direct current, and migrated to the electrodes where they are chemically deposited. Following treatment, the electrodes are removed and disposed of, or the deposited metals are recycled (USEPA, 2004).

Contaminated sediments which have undergone IC include arsenic, chromium, copper, lead, nickel, and zinc

Other Considerations

The majority of electrochemical remediation is undertaken in-situ; however, it is also feasible that ex-situ treatment could be carried out with adapted infrastructure. Although electrochemical remediation technologies are not a new concept, the technologies are not widely used and large scale application has not been widely adopted by industry. To date most work with electrochemical treatment is confined to bench, pilot or small scale field experiments (Defra, 2010).

Electrochemical treatment technologies have been shown to have variable results for both fresh and marine water sediment sources and have the potential to remove metals, radionuclides and some organic compounds. Much of the available data were collected from experiments with soils rather than sediments but theoretically many of the principles are transferable to marine sediments (Defra, 2010).

The efficiency of electrochemical treatment of soils depends upon sediment type, mineral composition and pore fluid conditions (Defra, 2010).

Secondary management/intervention technique

Dewatering

Dewatering is the removal of water from sediment material, following the physical removal of the sediment. There are three types of dewatering methods commonly used: natural (gravity), mechanical and Geobags (Defra, 2010).

Natural dewatering

Natural dewatering is the most efficient treatment method for large volumes of contaminated sediments following their removal. Once removed (either by dredging or

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excavation), the material is laid out in windrows on dewatering (lagoon) fields to enable drying and consolidation. The sediments are mechanically turned (usually using a mechanical excavator). Further layers are added at intervals when the previous layer has reached the desired level of dewatering. The majority of the water content evaporates; the remaining water is drained from the fields through a series of drains containing filters and plastic pipes and is pumped to a, e.g., waste water treatment plant.

The best results have been shown to be with sandy sediments and, in terms of costs, natural dewatering is the best dewatering method for silts.

Mechanical dewatering

Mechanical dewatering requires the input of energy to squeeze, press, or draw water from contaminated sediment. Although this method is more energy dependent, it requires less space and time and can be undertaken on mobile dewatering plants near to where the sediment has been removed.

Mechanical dewatering is conducted using filter presses or belt presses of which there are various types, each including storage and conditioning tanks for the dredged material. The presses use filters to separate the liquid from the sediment and collects the solids as filter cakes which are separated for disposal. Conditioning materials, such as lime or cement, can be added to absorb water and improve the physical characteristics of the treated material.

Geobags/Filtration tubes

Contaminated sediment can be deposited or pumped into bags (Geobags) or tubes (Filtration tubes) made of woven geotextile material that allows water to drain out whilst retaining the solids. Following sufficient drying and consolidation, the retained fine grained material in the filtration tubes continue to consolidate by desiccation, while residual water vapour escapes through the small pores of the fabric. Bags or tubes can be stacked several layers high in a dewatering basin and the dried material can then be disposed of to landfill in the bags or removed and handled in bulk.

Other Considerations

As well as for the management of contaminated sediment, Geobags have been used throughout the world for the protection of riverbanks and hydraulic structures (weirs, dams, culverts etc.) from severe scouring and erosion (Wahed *et al*., 2009).

A key consideration for the treatment of contaminated sediment by dewatering is the management of the waste water that is produced. Effluent from sediment treatment processes is often contaminated with metals, inorganic and organic particles. In the Port of Hamburg, this has been undertaken through the removal of suspended particles by sedimentation aided by flocculation. A combination of sedimentation, nitrification and oxidation processes reduces the organic contaminated in the waste water (Defra, 2010).

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Contained Aquatic Disposal
Contained Aquatic Disposal (CAD) involves placing contaminated sediment into a CAD cell, which is then refilled with contaminated dredged material (CDM) and capped, typically with clean sand. CAD cells may be constructed from (1) naturally occurring bottom depressions; (2) sites from previous mining operations, such as beach nourishment borrow sites; or (3) new dredging operations created expressly for the containment structure (Fredette, 2009). These facilities involve open water disposal and typically comprise excavated pits or depressions in the seabed that receive CDM from plant such as split-bottom barges or, in deeper water (~70m), via a vertical pipe from an anchored vessel. CAD disposal cells can reduce the risk from CDM disposal by confining the sediments to a small footprint and isolating CDM. These factors can eliminate and/or reduce exposure pathways thereby reducing risk to both natural environmental receptors and human health (Defra, 2010). As CAD disposal areas are ‘open facilities’, during backfilling operations, and until they are capped, the CDM is not fully isolated from the receiving environment (Defra, 2010). *Other Considerations* The hydrodynamic regime (i.e. waves and currents) is a key consideration in the use of CADs for placement of CDM. They can be designed with bunds to reduce the risk of mobilisation of CDM from the seabed pit (Defra, 2010). For those CAD cells constructed in coastal and estuarine locations, a submerged artificial wall (ring dike) may be necessary to provide sufficient protection of CDM placed in the pit (Defra, 2010). Whilst many CAD cells are capped at the end of their operational life (i.e. once they have been filled with CDM), there is the option to leave the pit un-capped where the CDM will still be relatively isolated from the adjacent environment (Gardner *et al*., 2005), or the inclusion of a cap will result in the loss of cell capacity, along with the cost associated with capping (Fredette *et al*., 2000). Dredging can result in the ‘bulking up’ of sediment as water is entrained during the dredging process resulting in overall greater volumes of CDM than the in-situ (bedded) volume. Such bulked material may have different properties to bedded sediment and may be more easily mobilised from within the pit. However, there are dredging techniques, such as backhoes and special grabs that can excavate sediment with minimal water entrainment, so that they largely maintain their in-situ characteristics. Following CDM placement, the finer sediments would; however, consolidate as increasingly greater volumes of material are placed on top (Defra, 2010).

Overview of Technique

Because the upper layers of the CDM in the CAD cells will be below the seabed surface, physical forces will affect the surrounding seabed before mobilising sediment within the CAD facility and in practice it is likely that when the adjacent seabed is being re-suspended, the CAD area will act as a sediment receptor and substantial erosion of CDM is unlikely. The risk of CDM mobilisation even in uncapped CAD cells is, therefore, much reduced and probably a better alternative to disposal in capped open sea sites, which may be readily affected by natural events such as storms and anthropogenic impacts, including bottom trawling, anchor damage or disturbance by the downwash from ship's propellers (Defra, 2010)

The CAD cells have been used successfully at several locations around the world, including Hong Kong; Los Angeles, California, USA; Bremerton, Washington, USA; Newark, New Jersey, USA; Boston; Hyannis, Massachusetts, USA; and Providence, Rhode Island, USA (Fredette, 2009).

Confined Disposal Facilities

Confined Disposal Facilities (CDFs) are purpose built engineered structures for the containment of CDM with the purpose of controlling potential releases to the surrounding environment (Apitz and Black, 2010). The use of CDFs is widespread in locations where there are constraints on space to receive CDM and such facilities are now well developed and tested in locations overseas.

There are three main types of CDF which can be constructed in ‘upland’ sites (similar to a traditional landfill), in near shore areas where one or more of the engineered walls (dikes) are in water or as island depots surrounded by water. CDM is normally at least partially stored under water in island and nearshore CDFs and such storage, especially if the overlying water is anoxic, helps prevent the mobilisation of metals (Defra, 2010).

Other Considerations

Despite being engineered from relatively impermeable material (e.g. clay) there are several potential contaminant loss pathways from CDFs. Pathways include spills of effluent during filling operations, surface run-off after heavy rain, migration of leachate to ground water and loss of certain contaminants such as volatile organics to air. Nevertheless, it is possible to use operational controls on site to limit contaminant pathways from CDFs and these may include the selective placing of CDM followed by uncontaminated sediment layers to ‘sandwich’ contaminated layers; placement of a final capping layer comprising uncontaminated sediment; placement below water to keep the CDM anaerobic (low dissolved oxygen) that reduces the potential for mobilisation of contaminants such as metals to the dissolved phase (Defra, 2010).

In the UK, one of the most common forms of CDF is the use of disused docks in port areas; whereas in the USA and other part of Europe, 'island' or 'open water' CDFs are widely used (Apitz and Black, 2010).

Overview of Technique

The use of CDFs is well established and tested at many locations including Netherlands and Norway. CDFs are one of the most widely used CDM disposal options in the USA (Defra, 2010).

In Europe various methods, including the use of stiff clays and geotextile bags (see dewatering technique for further information on Geobags), are used to ensure an impermeable container, although this impacts on the cost of disposal (Apitz and Black, 2010).

Landfarming

Bioremediation (in aerobic conditions) is a suitable treatment technology to remove PAHs and mineral oil from soil and sediments. Several methods are available, which fall into two groups: active landfarming and passive landfarming. Landfarming is considered a promising technology with regards to remediating large quantities of PAH and mineral oil contaminated sediments (Harmsen *et al*., 2007).

Passive Landfarming/Ripening

In common with aerobic bioreactors, the use of landfarming relies upon oxygenating sediments over time to achieve the reduction of organic contaminants to acceptable residual concentrations; the effectiveness is directly proportional to time. This technique is most suitable for easily aerateable sediments, i.e. low in clay content and well drained; however, the technique can be applied to clay soils if organic matter is present. Sediments with a high clay content must be deposited in thin layers (Defra, 2010).

Passive landfarming, whereby no or limited activity is employed in the maturation process is much slower than active landfarming in which optimisation techniques are used to reduce the time involved to that comparable with a bioreactor; however, the passive method is capable of treating both rapid and slow degrading compounds (Defra, 2010).

Ripening is the name often given to dewatering the sediments and developing of the correct soil structure and is often necessary prior to landfarming, although it can be conducted concurrently in the passive process. The expected timescales for dewatering are between several months and several years (see the dewatering technique previously described for more information). Due to the long time-scales (decades) and large areas involved in passive landfarming, another beneficial use must be made of the site in order to make it economically viable (Defra, 2010).

Active Landfarming

Active landfarming involves additional activity to promote the speed of treatment compared to passive landfarming. Two main factors that affect the speed of the

Overview of Technique

treatment are the availability of the contaminants and the time taken for diffusion of the organisms to the contaminated parts of the sediment. Promoting vegetation growth substitutes active dewatering which is more time efficient once a level of good vegetation coverage is achieved. Metals will not be reduced ‘naturally’ using landfarming techniques and stabilising agents (such as lime or gypsum) must be added to the soil to decrease their availability (Defra, 2010).

Landfill Disposal

Landfill disposal involves the onshore disposal of contaminated sediment in designated landfill sites by means of burial. In terms of contaminated marine sediment, landfill disposal is considered when it is unable to be disposed of at sea, although there remains restrictions in this area with respect to the type of waste individual land fill sites can accept. In the UK, these sites are licensed by the Environment Agency. Dredged contaminated river sediments are either disposed of into landfill or within adjacent land (e.g. in building earth bunds).

Waste that is sent to landfill may need to be treated (typically dewatering) prior to disposal, but there is the risk of leakage to groundwater and issues associated with exposure to air. Risks of air pollution from transport may also be high if hazardous waste is involved, as there are few sites licensed to receive hazardous waste (Defra, 2010).

Soil Washing

Soil washing is an effective treatment *ex-situ* technique that can be used on-site to remove a wide range of both organic and inorganic contaminants from soils. This technology can be applied to the treatment of soils, sandy sediments, sewer sediment and construction debris; it is particularly effective for soils with a high granular content (DEC, 2010).

Sediment grain size is a significant factor that controls the capacity for sediments to retain contaminants. Finer sediment fractions (silt and clay) have a greater adsorbing capacity, owing to larger surface area and, therefore, retain higher concentrations of sediments than coarse fractions (sand and gravel). Soil washing technology, therefore, involves the wet separation of coarse sediment fractions from the fine fractions (Pensaert *et al*., 2013).

Removal of the coarse sediment results in the finer material being collected in a filter cake, which can be isolated for controlled disposal; thereby reducing the volume of contaminated soil needed to be disposed of to landfill. This method also allows a significant proportion of the original material to be considered for re-use as clean sand and aggregate. In more advanced forms of the soil washing process the gravel and sand fractions can be taken through additional processes to scrub the mineral surfaces to improve the contaminant removal (Roger, D. *pers comms*., 2nd October 2015). Following initial removal from the environment through either dredging or excavation, the process of soil washing involves the following stages:

Overview of Technique
Preliminary Treatment • Removal of metal fragments using overhead magnetic belts. • Screening of gravels using a vibrating wet sieve, this gravel is then ejected out of the plant onto a waterproof surface and sent for final disposal to landfill. *Gravel Washing Unit* • The stone and gravel fraction is cleaned in the gravel washer module by scrubbing and counter flow washing. • This fraction is then sent to storage bays where it undergoes assessment to determine whether it can be reused as a secondary construction material. *Sand Decontamination* • Separation of the fine fraction from the coarser sand fraction using hydroclones and upstream classification. • After dewatering, the clean sand can be reused, e.g., as raw materials for construction. *Sludge Treatment* • The sludge fraction, separated during previous process, is further dewatered in a filter press by the addition of chemical agents to generate a ‘filter cake’ that can be easily managed and transported to landfill for disposal. *Process Water Treatment* • Some mobile plant also has on-site water treatment and recirculation facilities.

Table 2.2 Suitable environment for application of intervention and management techniques

Intervention/Management Technique	Suitable Environment Technique can be Used			
	River	Estuary	Coastal	Comments
Primary Technique				
In-situ capping	✓	✓	✓	In situ capping has been applied in riverine, estuarine and coastal environments but must not be exposed to highly erosive environments, such as currents, waves, navigational propeller wash or to upwelling from groundwater. Site conditions well suited for capping include the following: • Suitable types and quantities of cap materials are readily available; • Anticipated infrastructure needs (e.g. piers, pilings, buried cables) are compatible with cap; • Water depth is adequate to accommodate the cap with uses of surrounding water body (e.g. navigation, flood control); • Hydrodynamic conditions are not likely to compromise cap; • Rates of groundwater flow in cap area are low; and, • Contaminated sediment has sufficient strength to support the cap.
Dredging	✓	✓	✓	Dredging can be undertaken in all environments (riverine, estuarine and coastal); however, the type of dredging method used may differ between environments depending on site characteristics. Site conditions well suited to dredging: • Suitable disposal site(s) nearby and with capacity (this could be either onshore or offshore disposal sites; • Existing shoreline areas and infrastructure to accommodate dredging needs; • Adequate water depth to accommodate dredging; and • Contaminated sediment overlies clean or cleaner sediment to allow for over-dredging.
Excavation	✓	✓	✓	Excavation is typically performed in streams, shallow rivers and intertidal areas. Excavation is unable to be undertaken in near/offshore environments.
Monitored Natural Recovery	✓	✓	✓	MNR can be undertaken in all environments, providing that the site conditions are viable for MNR to occur. This will require monitoring of the area. Sites conditions well suited for MNR include the following: • Sites with low to moderate risk of contamination, i.e. contaminant concentrations are low and cover diffuse areas; • Anticipated land uses or new structures are not incompatible with natural recovery; • There is a reasonable degree of certainty that natural recovery processes will continue at rates that will contain, destroy, or reduce the bioavailability or toxicity

Intervention/Management Technique	Suitable Environment Technique can be Used			
	River	Estuary	Coastal	Comments
				of contaminants within an acceptable time frame; • Expected human exposure is low and/or reasonably controlled; • Site contains sensitive environments that could be irreversibly damaged by capping or dredging; • Sediment bed is reasonably stable; and • Sediment is resistance to re-suspension.
Electrochemical	✓	✓	✓	In situ electrochemical remediation of contaminated sediments can be used in all environments.
Immobilisation	✓	✓	✓	In-situ immobilisation of contaminated sediments can be used in all environments.
Secondary Technique				
Immobilisation	n/a			Immobilisation is more effective in low flow conditions, where the flow can be diverted whilst the treatment takes places (Defra, 2010).
Dewatering	n/a			Dewatering is usually undertaken ex-situ following dredging/excavation of material. Land availability is a key requirement for this technique. Mechanical dewatering requires an energy input, for example via a mobile dewatering plant.
Contained Aquatic Disposal	✓	✓	✓	CAD can be used in all environments, however certain restrictions apply. For example, where the capping of the cell is required, site specific conditions, in terms of the physical environment and sediment characteristics, is critical to predicting the feasibility and effectiveness of the capping.
Confined Disposal Facilities		✓	✓	CDF is typically used in coastal and estuarine environments.
Landfarming	n/a			Both passive and active landfarming techniques require land availability (which may be significant depending on the quantity of sediment to be treated). Another requirement is time, with these techniques requiring a long time scale for full remediation.
Landfill Disposal	n/a			Designated landfill sites with burial facilities are required for the disposal of contaminated sediments. The sediments must also be dewatered prior to disposal.
Soil Washing	n/a			Soil washing is an ex-situ technique which can be used to treat contaminated sediment from all environments. Mobile plant is often used; therefore treatment can usually take place on, or very close to, site.

Table 2.3 Advantages and disadvantages of the intervention and management techniques

Advantages	Disadvantages
In-situ Capping (USEPA, 2005; Defra, 2010 and Reis et al., 2007)	
• Quickly reduces exposure of sediment to contaminants. • Requires less infrastructure, material handling, dewatering, treatment and disposal. • Quickly reduces the exposure to the contaminated sediment. • Provides a clean substrate for recolonisation by bottom dwelling organisms. • Changes in bottom elevation could create a more desirable habitat; specific cap design may enhance or improve habitat substrate. • The potential for contaminant re-suspension are typically lower for in-situ capping than for other techniques, such as dredging/excavation. • In-situ capping projects use conventional equipment and locally available materials, and can be implemented more quickly and be less expensive than other techniques. • Less disruptive on local communities as much smaller area of land based facilities is needed.	• The contaminated sediment remains in the aquatic environment where contaminants could become exposed or be dispersed if the cap is disturbed or if the contaminants move through the cap. • Capping may provide an unwanted habitat, e.g. to provide erosion protection it may be necessary to use coarse cap material that are different from native soft bottom materials, which may alter the biological community. • In some cases, it may be desirable to select capping material that discourages colonisation by native deep-burrowing organisms to limit bioturbation and release of underlying contaminants. • Monitoring is necessary at capping sites during and immediately after construction, followed by long term, less frequent intervals. There is therefore associated long term monitoring costs associated with capping. • Future uses of the waterbodies may be limited. • Increased road and rail traffic associated with the transportation of capping material.
Dredging (USEPA, 2005; Reis *et al.*, 2007; Bray, 2008; and Defra, 2010)	
• Completely removes contaminants, thereby no future issues. • Removal of contaminated sediment reduces the uncertainty associated with in-situ capping predictions of sediment bed or cap stability and the potential for future exposure of contaminants. • Increases flexibility regarding future use of the waterbody. • Allows for treatment and/or beneficial reuse of dredged material. • Immediate reduction of risk compared with other techniques which may take longer for remediation. as contaminants are removed..	• Implementation is usually more complex and costly due to the removal technologies themselves and the need for transport, staging, treatment and disposal. • High costs associated with treatment technologies. • Disposal capacity may be limited in available landfill sites. • Operations and effectiveness may be affected by utilities, surface and submerged infrastructures, overhead restrictions and narrow channel widths. • Level of uncertainty associated with estimating the extent of residual contamination following removal. • Contaminant losses through re-suspension and volatilization. Re-suspension of sediment from dredging normally results in releases of both dissolved and particle associated contaminants in the water column. Re-suspended material may be re-deposited at the dredging site or, if not controlled, transported elsewhere within the waterbody.

Advantages	Disadvantages
	• Temporary destruction of benthic habitat within the dredged area.
Excavation (USEPA, 2005 and Defra, 2010)	
• Excavation operations can be undertaken with greater visual assistance than dredging. • Removal of contaminated sediment is usually more complete (i.e. residual contamination tends to be lower when sediment is removed in the dry). • Bottom conditions (e.g. debris) and sediment characteristics (e.g. grain size) require less consideration. • Reduced potential for contaminated sediment re-suspension.	• Site preparation takes longer and is more costly than for dredging, due to the installation of cofferdams and sheet pile walls for dewatering or water diversion. • Excavation is limited to relatively shallow areas. • There is an increased risk of exposure of contaminated sediments to humans. • As with dredging, the contaminated sediment will require appropriate disposal. Depending on the method chosen, this may require pre-treatment, with which there will be an associated cost.
Monitored Natural Recovery (USEPA, 2005 and Defra, 2010)	
• Low implementation costs (most costs are associated with monitoring). • Non-invasive; involves no man made physical disruption to the existing environment and surrounding community.	• Although low implementation costs, the site investigations to characterise and evaluate MNR and long-term monitoring activities can cost more than those associated with dredging and capping. • Leaves contaminants in place, the risks of re-exposure of the contaminants remains. • Time frame for natural recovery may be slower than for other more active technologies. • There are a number of areas of uncertainty, including the ability to predict future sedimentation rates and predict rates of contaminant flux through the sediment.
Immobilisation (Reis *et al.*, 2007 and Defra, 2010)	
Thermal • Can produce beneficial secondary products which partly off-sets the process costs. Secondary products include: o Bricks; o Light-weight aggregates; and o Artificial basalt. • Can be used for all contaminants.	*Thermal* • The immobilisation process is very energy intensive and complex. The energy consumed using CDM during the thermal immobilisation process is generally higher in comparison to using natural clay due to the high water content in CDM. *Chemical* • The long term viability of this technique has not been tested. • Only suitable for some contaminants (metals and TBT). • Requires pre-treatment, commonly dewatering (see below for associated

Advantages	Disadvantages
Chemical - Although this technique does not remove contaminants from CDM, the contaminants are bound to additives less mobile and, therefore less bioavailable. - There are no costs associated with the disposal of the CDM. - Produces beneficial secondary material. These include: o Use as land covers (e.g. for disused landfill sites) o Use in construction material. The treated CDM can be used for the production of aggregates (mainly with the addition of cement). These aggregates are usually used for road material. o Capping material for abandoned mines or CDFs.	disadvantages)
Dewatering (Defra, 2010)	
Natural: The overall energy consumption of the natural dewatering process is low. The energy is consumed during the use of cranes or special windrow turners to handle or move sediments. As a result, the costs associated with natural dewatering are low. Treats large volumes and has high production rates. *Mechanical:* - Higher dry matter content than with natural dewatering giving higher volume reduction and increased beneficial use. - The plant is mobile and can be used in-situ if required. - Use of filter presses means that limited surface space is required in comparison to natural dewatering. - Mechanical dewatering is not affected by weather conditions, unlike natural dewatering. - The total volume of CDM is reduced using filter presses as it is possible to achieve higher dry matter content compared to natural dewatering (40-45% up to 65-80%). The volume reduction will depend on the content of fine grained particles in the dredged CDM.	Natural dewatering requires large amounts of space and time (months – years). The time required depends on the local weather conditions (i.e. wind, rain and sunshine) and the required level of dewatering given the composition of the CDM. There are risks associated with the treatment of effluent that is produced from the dewatering process. The waste water that is produced will need to be managed in a way to ensure that there is no risk of the contamination spreading. There are additional costs associated with this management.

Advantages	Disadvantages
• Produces marketable end products (soil/clay) which can be used as construction material. *Geobags:* • Low energy costs associated with treatment using Geobags • Treats large volumes and has high production rates. • Produces marketable end products (soil/clay) which can be used as construction material. • Suitable for use for a wide range of sediments.	
Electrochemical (Gardner *et al*., 2005 and USEPA, 2007)	
• Uniquely suited for CAD and CDF contaminated storage techniques. • ECRTs' are suitable for all sediment types, especially clay or silt. • Creates a limited waste stream. • The ECRTs process can theoretically be implemented anywhere that an electrode array can be installed. • The technologies (ECGO and IC) have been reported as effective in unsaturated and saturated zones in sediments for metals and organics, including free-phase organics. • There are currently no other viable in-situ methods for treating inorganic and organic compounds in porous media simultaneously. • Ionic contaminants are absorbed to sediment particles and are often not available for removal by the simple flushing action of water. The pH shift produced by the electrolysis of the water effectively desorbs contaminating ions. • In clayey sediments, hydraulic flow through pores can be extremely limited. Electrokinetic remediation is an effective method of inducing movement of water, ions and colloids through fine-grained sediment. • The process is competitive in cost and remediation effectiveness to other methods currently in use. • Environmental effects are considered to be lower than other technologies.	• The electrokinetic process is limited by the solubility of the contaminant and the desorption of contaminants from the soil matrix. Heavy metals in metallic states are difficult to dissolve and separate from sediment. Organic compounds may be tightly bound to natural organic matter. The process is also not efficient when the target ion concentration is low and non-target ion concentration is high. • Acidic conditions and corrosion of the anode may create difficulties in in-situ efforts. • Precipitation of species close to the electrode can impede the remediation process. • Separate groundwater treatment may be required, although this is unlikely. • The particle surface area and sediment to water ratio are key parameters in determining the technologies' effectiveness. Therefore, the sediment grain size is a potential limitation of this technology. • Depth and placement is limited by the installation technology. • Corrosion of the electrode leads can be an issue.

Advantages	Disadvantages
Contained Aquatic Disposal (Fredette, 2009 and Defra, 2010)	
• CAD cells are considered economically viable. • CAD cells can provide a suitable environment for the use of certain types of in-situ remediation techniques. • Legislation often favours CAD cells, as they are often near the dredging location in inland waters (e.g., within the confines of rivers, harbours, estuaries, and bays), whereas open water capping alternatives often involve consideration of deeper-water, offshore sites which are regulated by further stringent legislation. • The CAD cell alternative results in fewer transportation effects than do most other open water alternatives because of relatively shorter transport distances and the use of barges. • The general public has greater comfort with the CAD cell concept. • Environmental and human health risk assessment of the CAD cell alternative has shown that it can provide one of the lowest risk options compared with other alternatives. Relative to upland (land based) disposal, there is less re-handling of material and fewer contaminant transfer pathways: upland disposal can result in greater contact with humans, volatile emissions, and groundwater pathways. • CAD cells, even when uncapped, result in a reduced surface area for contaminant release and less potential for direct contact by humans and biological resources, resulting in lower risks. • CAD cells can usually be constructed by using readily available, conventional construction equipment. Mechanical dredging equipment, especially clamshell bucket dredges, is most readily compatible with CAD cell construction. • Compared to other disposal options including open sea capping and CDFs, the use of CADs can result in less handling of contaminated material and fewer contaminant transfer pathways. • CADs are suitable for CDM containing most contaminant types	• Sand caps have a high permeability, which is well understood that due to diffusion, the flux of contaminants can be significant. Release of many contaminants from CAD cells has been measured to reach tons per year. • In regions where clamshell dredges are less commonly available, the challenges of creating a CAD cell with hydraulic equipment can severely limit design options. These include the inability to create steep CAD wall side slopes and the inability to dredge much deeper than 20m. • The CAD cell selection can be limited by subsurface geological conditions, especially the depth to bedrock. In addition, when the width of the area in which the CAD cell is proposed is narrow, such as in a channel, the necessary side slopes for wall stability may limit the effective depth to which a CAD cell can be constructed. • Other construction issues associated with CAD cells include evaluating effects to existing infrastructure, planning for sufficient storage volume, surging of material outside the CAD cell during filling, and applying a cap. • Sizing a CAD cell to closely match the dredging volume creates a risk that the cell will be filled before the dredging is completed. This can occur when the dredging volume was underestimated because of survey inaccuracies or when additional sediment was deposited into the area after the volume survey was completed. The capacity of the cell can also be affected when water is added to the sediment during the dredging process (bulking), creating a greater volume than initially expected. • Although not likely, the potential effect to aquifers or the potential for groundwater flow to transport contaminants should be considered. Usually, the sediments being placed into the CAD cell will be fine grained with relatively low permeability. In that event, groundwater flow is likely to be diverted around the cell rather than through it. • Consideration will need to be made to climate change and its implications on the use of this technique. i.e. sea level rise and increased frequency and intensity of storms.

Advantages	Disadvantages
without the need for treatment. • Natural bathymetry can be used for CAD i.e. depressions in the seabed. In these cases, no mechanical excavation is required.	
Confined Disposal Facilities (Apitz and Black, 2010 and Defra, 2010)	
• CDFs offer a suitable environment for the treatment of CDM without the complications of the material being submerged. • CDFs are suitable for CDM containing most contaminant types without the need for treatment. • The use of structures, such as disused docks, can reduce costs, but they may require engineering to ensure contaminant pathway containment. Once such a facility is full, capping can allow the beneficial use of the dock surface. • On-land confinement structures are not exposed to the hydrodynamic forces. • CDFs can be landscaped in several ways to be used, e.g. for recreation uses and nature reserves.	• Although the use of old facilities removes the need to specifically construct a CDF (and thus reduce costs), such an approach is clearly limited by their availability. There is the potential for both air emissions and leachate leaking to surface or groundwater with CDFs. However, this can be reduced with well-designed landfills with conservatively safe barriers, leachate collection and treatment, and adequate caps. • Disposal of CDM in CDF may result in a greater level of handling by site workers and contaminants transfer via pathways to groundwater resources compare to CADs and open water disposal. • Salts can accumulate at the surface of the dredged material, especially on the edge of cracks, created when the dredged material dries out. Rainfall events tend to dissolve and remove these salt accumulations. Certain metal contaminants may also become dissolved and transported out of the CDF by surface runoff. This can result in a risk to human health and local biodiversity. Space consumption can be a disadvantage of CDF, especially if navigational routes are compromised or space is at a premium. For nearshore CDFs, a large area of foreshore is required and this may conflict with other users such as nature conservation, navigation and tourism.
Landfarming (Harmsen *et al*., 2007 and Defra, 2010)	
• Landfarming reduces the amount of CDM requiring disposal • Secondary products can include reusable CDM for building material as well as clean sediments. • Results of intensive landfarming can be comparable with a bioreactor. High degradation percentages can be obtained.	• Requires a large amount of space. • A period of 1-2 years is necessary for intensive landfarming and passive landfarming may last several decades. The time required can be a problem in densely populated areas. • The energy consumption ranges from the energy used in normal agricultural practice (passive landfarming) to the high energy consumed in intensive landfarming. Emissions from landfarming are comparable to a bioreactor but less readily controlled. • Only suitable for a few types of contaminants, PAHs and mineral oil. Unlikely to be

Advantages	Disadvantages
	suitable to marine sediments, as these are likely to contain metals and organotins (including TBT).
Landfill Disposal (Defra, 2010)	
• For contaminated dredged sediment that cannot be deposited at sea and for lower volumes, the costs of landfill are generally less than the cost for disposal in a CDF. • Can be seen as space saving compared to CFDs as the landfill is already established.	• The generally small number of landfills permitted to accept hazardous wastes is a practical limitation to their use for CDM disposal. • Restrictions on the types and concentrations of contaminants going to landfill means that this may not be a viable option for some types of CDM. • Pre-treatment of the CDM may be required (typically dewatering) prior to disposal, with associated disadvantages and cost. • Risks of air pollution during transportation can also be an issue • Landfill space is already at a premium and further use will only exacerbate the scale of the problem.
Soil Washing (DEC, 2010 and Pensaert *et al., 2013*)	
• Provides a cost effective alternative to disposal at landfill. Soil washing can be undertaken on relatively small sites and is economically viable for small volumes of material in areas with high disposal costs. • Under ideal conditions, it can be used to divert significant amounts of granular material away from landfill and to increase the likelihood of its beneficial re-use for construction purposes or in land restoration schemes. • Soil washing is able to treat a larger range of contaminants than other treatment technologies. • Soil washing is a relatively time efficient process and can be undertaken for projects with strict programme schedules. • Soil washing can be used to treat both marine and terrestrial contaminated sediment. • Suitable for use in sensitive residential areas and can often reduce the overall environmental impact associated with site remediation (e.g. issues related to noise and dust pollution as a result of transport).	• For the process to be viable, the original sediment has to comprise recoverable coarse material, in addition to fine material. Where fines alone represent more than 40% of the total mass, the resulting proportions of recyclable material and waste material may not be favourable when justifying the economics of the treatment. • Constant external water supply required.

2.4 Case Studies

Table 2.4 summarises case studies of the techniques for the intervention and management of contaminated sediment.

Table 2.4 Case studies of the techniques for the intervention and management of contaminated sediment

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
Marine					
Port of Antwerp	The Netherlands	• Dredging • Mechanical dewatering	Dumping sites at the Port of Antwerp had reached full capacity and other techniques for disposing of CDM were, therefore, required. The port invested in pilot testing, followed by the full scale installation of a facility that allows for the separation, dewatering and stockpiling of CDM. CDM is treated at the facility by the following methods: • Sediment is dredged from the docks in the port and discharged into an acceptance cell. • The sludge is pumped to a sand separation unit where the coarse material is removed; this material is stockpiled for re-use. • The remaining material (or sludge) is discharged into buffering ponds, where it is thickened. • The sludge is then dewatered using membrane chamber filter presses until a content of 65% dry matter is achieved. • This process produces filter cakes which are transported to a nearby disposal site. • The filtrate produced from dewatering is collected and pumped to a wastewater treatment plant.	The separated 'clean' sand fraction can be re-used (e.g. construction of landscape dykes, road surfaces), the filter cakes containing the majority of the pollutants are taken for disposal at a nearby disposal site. Further recycling of these filter cakes would be required to produce re-usable products (e.g. bricks, tiles, cement, gravel).	Vandekeybus *et al* (2010)

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
Port of Tyne	UK	• Dredging • Capping	The Port of Tyne was refused a licence for the offshore disposal of CDM. The port, therefore, had to seek alternative disposal options. A trial capping project was agreed for approximately 100,000 tonnes of CDM from three wharves on the Tyne. The project involved in the following stages: • A backhoe dredger was used to dredge the 3 priority areas within the estuary. • The CDM was placed into towed split hopper barges to remove and transport to the offshore disposal ground. • The material was taken for disposal at the Souter Point licenced offshore disposal site. • Once all CDM was deposited, the silt cap was placed using a trailer suction hopper dredge, however, the fluidised silt appeared to disperse rapidly and 70% was lost to the wider disposal site. • It was decided to suspend the placement of silt and place sand instead. A sand cap of 1.5m was created, which comprised of some 144,000 tonnes (90,000m^3) of sand.	It took 4 months from the initial placement of the CDM in December 2004 until the cap was placed (in April 2005) due to adverse weather interrupting disposal operations. CDM was exposed on the seabed for up to 4 months and is likely to have contributed to the spread of thin layers of CDM. Future placement should be undertaken in good weather conditions to ensure that the cap is placed as soon as possible after the placement of the CDM. The project proved that using careful backhoe dredging and accurate split hopper barge positioning, it is possible to drop consolidated blocks of CDM within a defined area, even during winter. However, placement of silts was ineffective as they were widely dispersed. Post dredge analyses showed significant TBT and metal contamination remained below the dredged depths but navigational access to the berths was available.	Blake (2009)
Port of Hamburg	Germany	• Dewatering	The Hamburg Dredged Material Management Concept (HDMMC) was developed in 1980 to address the growing need to incorporate environmental best practise into dredging	Once the silt fraction is dewatered, it is either sent to two special silt disposal sites, Francop and Feldhofe, or it is used as a mineral	Defra (2010)

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
			operations and maintain operational capability of the Port of Hamburg. The primary objective of the HDMMC is the beneficial use of the sand fraction and where possible, the silty sediment or treated silt fractions. Where silt cannot be put to beneficial use it is disposed of; for this purpose two landfill sites with a total capacity of 18 million m^3 were constructed. The landfill were constructed in flushing fields, which enable the waste water to be captured, this is then treated in a treatment plant. The HDMMC treats 1.25-1.45 $million^3$ of CDM annually. The treatment technologies include a dewatering facility at Moorburg, the treatment process at this site includes the following: • Moorburg is a 100ha site consisting of 31 dewatering fields of about 2-4ha each. • The site has the capability to treat approximately $200,000m^3$ annually. • The sediments are laid out on the fields to an average height of 1.3m. The site is situated on a conventionally flushed field and groundwater is additionally protected using a silt layer with a drainage layer at its surface. • Following a settling period for the silt of a few weeks, the supernatant water is removed. Following this, the actual drying period begins. • Drying fissures’ are the first indication that the silt surface is dried and this is then removed and stacked for further drying.	sealing on landfill sites.	

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
			• Depending on the required technical specification for the end-product the stacking process continues. • Generally the required solid content is 55-60% by weight which, in Hamburg takes a period of approximately 9 months to 1 year.		
Whatcom Waterway, Bellingham Bay	USA	MNR	Industrial activities began on and around the Whatcom Waterway site in Bellingham Bay in the late 1980s. Resulting industrial discharges to Whatcom Waterway primarily included mercury from a chlor-alkali plant, wood pulping, wood waste and degradation products from log rating and phenol from pulp mill wastewater. The primary natural recovery processes ongoing at Whatcome Waterway is physical isolation. Evidence to support this was obtained through the deployment of sediment traps and the analysis of bathymetric data to determine sedimentation rates. Sediment coring was also undertaken; this data identified historical recovery between 1996 and 2007. The data indicated that sedimentation occurs at a rate of approximately 1.6cm per year A remediation and feasibility study was undertaken in 2000 which demonstrated that physical isolation processes were generally consistent throughout most of the site, especially deep-water areas where wind/wave forces are minimal.	Based on the documented historical natural recovery, as indicated by decreasing mercury concentrations and measures toxicity reduction in sediments, MNR has been a successful remedy at Bellingham Bay	ESTCP (2009)

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
			This information was used to identify remedies for the sediment as part of the 2007 Cleanup Action Plan. MNR was selected for Starr Rock and offshore low-energy areas of the Whatcom Waterway.		
Hong Kong CAD	Hong Kong	CAD	Since, December 1992 CDM has been disposed in a series of purpose-built seabed pits and exhausted borrow pits located to the East of Sha Chau (ESC; an island lying off the present international airport at Chek Lap Kok). The land area of Hong Kong is relatively small (comprising approximately 1,064 km^2 of which 40% is classed as Country Park where development is highly regulated) and land-based disposal of CDM is highly impractical. Recognising the constraints on disposal of CDM and need for environmental protection, trials were undertaken to ascertain the efficacy of disposal of CDM in seabed pits (CAD facilities). Extensive disposal trials were conducted using uncontaminated sediment and Acoustic Doppler Current Profilers (ADCP) used to track suspended material and the ESC area was selected in 1992 as the preferred CDM disposal site in Hong Kong. The ESC site has several hydrological attributes that provide a suitable location for CDM disposal. The water is comparatively shallow (~6-8m) and the tidal currents are relatively slow (typical velocity is approximately 0.3m s^{-1}). During filling	*Constraints* Disposal of CDM into CADs located in deep water (>20m) and high tidal currents can result in unacceptable losses during placement if plant such as split bottom barges used (unacceptable CDM losses can, however, be overcome by use of deep submerged pipelines for CDM placement). Presence of CDM may result in a 'no go zone' on the seabed resulting in constraints to future seabed infrastructure (e.g. pipes, cables). Uncontaminated cap material is required to cap the CDMS in place at the end of the operational life of the CAD. Monitoring of cap with possible re-capping may be required to ensure cap integrity. Other seabed users (e.g. bottom trawlers) may impact cap integrity. *Opportunities* The backfilling of deep seabed pits with CDMS followed by capping returns the seabed to its former state and is a useful beneficial use of	Defra (2010) Nicholson *et al.* (2004) Fredette, (2006)

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
			operations, CDM placed in the CAD is still exposed to the overlying water and when the pit is backfilled to a certain level (to about 3-6m from the seabed level) the CDM is capped with inert material to isolate the contaminated material from the adjacent environment and also return the seabed to its former state. The ESC disposal facility is probably the largest CAD site used for disposal of CDM in the world and several studies have concluded that it represents the most appropriate environmentally acceptable option for placement of CDM in Hong Kong.	CDM. CADs can be constructed close to the dredging location (e.g. within the same tidal basin) and the shorter transport distances and use of barges for disposal are likely more cost-effective than longer transport routes to landfill and consequent greater use of petrol and inherent air quality issues. Compared to open sea disposal with capping, CADs are often also more easily accepted by the general public as CADs provide more ‘comfort’ to people as they appear to provide a high level of protection from natural events including storms and waves (Fredette, 2006). Compared to other disposal options including open sea and CDFs, use of CADs for disposal of CDM results in less handling of contaminated material and fewer contaminant transfer pathways (Fredette, 2006). For example disposal of CDM in upland CDF facilities may result in greater level of handling by site workers and contaminants transfer via pathways to groundwater resources.	

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
				Cost In many cases, the seabed pit will have been used for the purpose of aggregate extraction and hence costs will be covered during the winning of marine aggregate resources. Where CADs are purpose-built and dredging of the seabed is required, the cost is usually about 2-3 times higher (in some cases this may be considerably higher) than open sea disposal but it is often found that the additional costs are acceptable when balanced with public acceptance, agreement with regulators and expediency (Fredette, 2006). Capping and any environmental monitoring to ensure no impacts in the receiving environment may entail major cost implications.	
Oslofjord	Norway	CAD	The marine sediment contamination in Norway is so serious that in 120 areas restrictions have been placed on the consumption of fish and fish products from fjords and harbours over an area covering 1200km^2. In the Oslo fjord, there are naturally occurring deep water basins (50-150m deep) and the current velocity is about 3cm/s. A naturally formed deep sea basin with a capacity to hold	To ensure that water quality is not impacted during CDM placement an on-line monitoring system is operated using buoys that monitor turbidity and water currents. Additionally, water samples are periodically taken and passive samplers (polymer strips) and sediment traps deployed to measure dissolved contaminants and	Defra (2010)

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
			about 700,000m3 of CDM was identified. Dredged CDM (salt is added to the CDM to increase the specific gravity and improve sedimentation) is transported to the CAD area by barge and pumped down to 70m into the CAD facility using a vertical pipe.	suspended solids. When backfilling operations are completed, a cap will be placed over the CDM.	
Port of Taranto	Italy	Soil washing	The expansion of cargo operations at the Logistics Platform in the Port of Taranto required capital dredging to be undertaken. Areas of contaminated sediment were identified in the proposed dredge area. In order to reduce the amount of sediment that would be disposed to landfill and to recover sand and gravel, soil washing was deemed necessary. Contaminated sediment was removed from four areas within the port by a mechanical dredger.	Approximately 6,500m^3 of contaminated sediment was dredged and subsequently treated in the shore based soil wash plant, with sand and gravel removed and the fine fraction filter cakes and organic fraction taken to landfill.	DEC (2014)
Freshwater and Land-based					
New Merwede River	The Netherlands	• Excavation • Capping • Thermal immobilisation	This was a pilot project conducted by The Netherlands Directorate-General for Public Works and Water Management in preparation for the large-scale clean-up operation of the New Merwede River. The pilot project was undertaken in a groyne section of the river. The remediation activities included the following: • The top layer of sediment was remediated through removal by excavating up to 1.5m. • A clean layer of sediment was deposited on top of the contaminated sediment left behind.	Following thermal immobilisation, 95 % of the material could be reused as sand or basalt. More than 95% of the relatively volatile compounds, such as Cd, Pb, Zn and As evaporated and ended up as deposits in air ducts, filter residues of the purification system and silts of the wet gas scrubbing. PAHs almost completely disappeared as a result of scorching.	Van der Kooji (1999)

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
			- A small part of the excavated material underwent thermal immobilisation. This process consisted of separation of sand, dewatering, drying and thermic immobilisation of the silt fraction. - The sand fraction which was separated was planned for use in civil works. - The sludge fraction had to be further processed by the following: o Dewatering and drying to 95% dry solid; and, o Melting the dried sludge and adding of material to lower the melting point. o After cooling basalt was formed.	Only Cr and Cu were found to have remained in the final products.	
Electrochemical Remediation Study	USA	- Electrochemical	In this study several chemical and physical parameters were investigated to determine the effectiveness of electrochemical remediation on contaminated sediments from New York Harbour (USA), Haakonsvern Harbour (Denmark), the Gowanus Creek (USA), Newtown Creek (USA), and the Cocheco River (USA).	Several bench-scale studies, and a thorough literature review of past research, indicate success for the mobilisation of metals in sediments when subjected to an applied electric field. Comparing past work using electrodialytic experiments to the current study using electrokinetic experiments, the electrodialytic setup produced more effective results due to the use of electrolyte solution compartments that attract the metal complexes rather than expecting the metals to plate directly to an electrode to be removed. However, the electrodialytic method can only be applied to ex-situ sediments,	Gardner *et al.* (2005)

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
				where the electrokinetic method is accomplished by placing electrodes directly into in-situ sediment. Probably the most significant conclusion to come of this research was that the availability was found to increase for certain metals after treatment of the sediments. Acidification of the sediments caused by treatment resulted in higher water dissolution of elements at the sediments achieved pH, compared to the untreated sediment.	
De Slufter CDF	The Netherlands	CDF	De Slufter is a nearshore CDF close to the Port of Rotterdam and the industrial area known as Maasvlakte in the Netherlands. Started as a diked, subaquatic nearshore CDF 25m below sea level in 1987, twenty years later it is filled to sea level and in the future will be filled to 25m above sea level.	At present sand separation and clay production for reuse are taking place. This could offset some costs. In addition, energy-producing windmills are installed on the dikes. Once it is fully filled De Slufter will be used for recreation and nature activities guarded by a system for monitoring contaminants in perpetuity.	International Association of Dredging Companies (IADC) (2010) Defra (2010)
The Francop CDF	Germany	CDF	An upland CDF is an engineered structure used to store CDM above groundwater levels and is bounded by a dyke. In many respects, upland CDFs are not too dissimilar to a standard landfill in their construction and operation. Only dewatered sediment is disposed in the CDF. An upland CDF was constructed in the Francop district of Hamburg to receive highly	There is the potential for both air emissions and leachate seeping to groundwater with these CDFs. There is, therefore, a need to monitor contaminant emissions around the CDF after CDM disposal operations have ceased and the disposal facility has been put to other uses. Once	Defra (2010) Detzner (2004). Detzner *et al.* (1994)

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
			contaminated CDMS arising from the Elbe at the Port of Hamburg. The Francop CDF has the capacity to hold 7Mm^3 of dewatered CDM and covers an area of 120 ha. The CDF is located in an agricultural area adjacent to a river and with a height of about 38m. Prior to disposal in the CDF, CDMS is sorted and dewatered in a treatment installation using hydrocyclones and a series of screen and belt presses to reduce water content in a facility termed the METHA (Mechanical Separation of Harbour Sediments) that separates the contaminated silt fraction from uncontaminated sand and dewaters the silt slurry. The CDM is placed in the CDF in layers with alternate sand drainage layers. Silt layers (1.5.m thick) alternate with 0.3m wide sand drainage layers. To reduce contaminant leakage to groundwater the CDF base is sealed. Because of the natural self-sealing properties of silt, dewatered silt with a low permeability is used as a sealing material at the CDF base and a 2.5mm thick double high density polyethylene liner. The CDF is surface sealed with a 1.5m thick layer comprised of dewatered silt, sand and soil to reduce contaminant emissions to air. The final cover system comprises a loam soil (barrier to plant roots) and an arable soil layer that is	completed, upland CDFs can be landscaped and used for recreational purposes and the Francop CDF will form a park facility for use by the general public. *Opportunities* These disposal facilities are highly regulated, isolated from most pollution pathways and can be used for highly contaminated CDM. There is also experience in their use in countries including the USA and Germany. When the capacity of the CDF has been exhausted and the seal cultivated with vegetation and any emissions have ceased, the site may be converted for recreational use (e.g. park facilities) by the general public. *Costs* The CDF cost about €70M (in 1993) and costs for disposal of CDM including long-term monitoring at the CDF site range between €10-75/m^3. High overall costs associated with upland CDFs as disposal is at the end of the treatment chain involving dredging – separation of sand from contaminated silt – dewatering – transport – disposal.	

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
			cultivated for landscaping purposes. The seepage water arising from the CDF is treated in a wastewater treatment installation that removes contaminants before water is discharged to the River Elbe.		
Kreekraksluize	The Netherlands	Landfarming	Landfarms were started on a semi-field scale in Kreekraksluizen, (The Netherlands). Initial experiments started in 1990 on fields with a drainage layer of 30cm. Each field was 2,037m. A layer of approximately 50cm of dredged sediment was applied to each field; the layers were reduced to about 30cm after dewatering. The sediment layer was intensively treated to stimulate biodegradation during the first few years using either: cultivation (tillage) or no cultivation, and addition of wood chips and sludge from a sewage treatment plant containing PAH-adapted microorganisms. The sediments originated from the Geul Harbor in Rotterdam and the Zierikzee Harbor, Zeeland. In 1993 the sediments from the different experimental fields were combined and used to start two new experimental fields containing the Geul Harbor and Zierikzee sediment, with a layer of approximately 60 cm dewatered sediment. These sediments were further treated passively (passive landfarming). In June 1994, the landfarm was extended by adding two fields for the treatment of sediment from the Petroleum Harborin Amsterdam and	Biodegradation was observed to occur in all field plots, but there were no significant differences between the treatments. It was found that between 1990 and 1993 the concentration of PAH and mineral oil in Geul Harbor and Zierikzee sediment decreased from 52 to 3.7 and from 65 to 18mg kg^{-1} dry matter, respectively. Ultimately, it was found that both PAHs and mineral oil were degraded during the course of 10 to 15 years of landfarming. In the upper layer of the vegetated landfarms, aerobic conditions had been achieved in the first summer. Therefore, the fastest initial degradation occurred in this layer.	Harmsen *et al*. (2007)

Site	Country	Management/ Intervention Technique	Description of Activity	Key Outcomes	Reference
			sediment from the harbour in Wemeldinge, also situated in the province of Zeeland. In these fields an original layer of sediment of approximately 1m was used. In one replicate field of each sediment, dewatering was stimulated with vegetation (passive landfarming), while two other replicate fields were intended for intensive cultivation in the first period of intensive landfarming.		
Port of Bremen	Germany	Landfill	The Port of Bremen dredges about 300,000m^3 of sediment annually that is contaminated with a range of metals, organic contaminants and TBT. Cost for the dredging and disposal of the CDM are about £7-10m per year.	Dredged sediment is dewatered and stabilised in (ripening) fields within one year. Following the dewatering process, CDM is deposited in sealed landfill (silt mounds; upland CDF). Excess water is collected via drainage layers and diverted to a treatment plant; cost for the dredging and disposal of the CDM are about £10-13M per year.	Defra (2010)

2.5 Cost-effectiveness and cost-benefits of intervention and management of in-situ contaminated sediment

2.5.1 Method for conversion of figures to 2014

In order for cost figures to be comparable it was necessary for them to be in the same currency and to be adjusted to account for inflation. The literature reviewed presents figures from between 2005 and 2011 as well as figures in both Euros and USD which are not directly comparable.

Figures were converted from Euros and USD to GBP using historic exchange rates[2]. The average exchange rate for the year from which the figure is quoted was used, e.g. if a figure of $2 is quoted from 2007, this was multiplied by the average conversation rate for 2007 (£1 = $0.5034) to give a value of £1.01.

To ensure figures from different years are comparable, the average Consumer Price Index (CPI)[3] for 2014 was divided by the CPI of the year from which the figure is quoted, e.g. 128 (CPI for 2014) divided by 104.7 (CPI for 2007). The result of this calculation provides a multiplier (1.223) which was then used to uplift the 2007 value by multiplying the two (e.g. £1.01 multiplied by 1.223 to give £1.23). Although the CPI is not specifically related to costs associated with treatment of contaminated sediments, it is used here to give an indication of the extent to which costs have increased between the date of the costs and 2014

2.5.2 Costs

Overview

This section considers the costs of intervention techniques for in-situ contaminated sediments from source to the marine and freshwater environment focusing on the costs associated with interventions to reduce the amount of contaminants reaching the marine and freshwater environment, and interventions to reduce (in-situ) or remove (ex-situ) contaminants. The section presents the references used to identify costs, focusing on monetary estimates where these are available. Each intervention is assigned a rating to reflect the magnitude of costs (from low to very high). The ratings have been assigned by our project team, using expert judgement but are, to the extent possible, based on information from the reviewed documents.

Interventions for Reducing Contaminants at Source

Table 2.5 provides a summary of key information on the costs of interventions to reduce contaminants at source. The majority of the information is drawn from experience of treatment methods for contaminated water. It should be noted that costs vary significantly according to contaminant concentrations and flow rates, so average values are difficult to identify. Where possible, the factors affecting the variability of the costs are included. However, in most cases such information was not provided in documents reviewed for this project. Likewise, whole life costs were only available from some sources, with others giving just costs associated with construction (and no operation and maintenance costs) that would enable whole life costs to be estimated.

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[2] http://stats.oecd.org/Index.aspx?datasetcode=SNA_TABLE4
[3] http://www.ons.gov.uk/ons/index.html

Table 2.5 Summary of information on costs for reducing contaminants at source

Intervention	Reference	Costs (all 2014 values)	Rating
Active treatment of contaminated water source	Confidential source	Active treatment plant requiring pumping of water and addition of reagents to treat contaminated water with a flow rate of around 20 l/s: £1 million to £1.5 million for initial construction (also requires monitoring and operational costs).	MEDIUM to HIGH
Passive treatment of contaminated water source	Confidential source	Passive treatment of contaminated water (gravity fed) with flow rate of around 1 l/s: up to £500,000 for initial construction (also requires monitoring costs). Passive treatment of contaminated water (gravity fed) with flow rate of around 15-20 l/s: around £1 million for initial construction (also requires monitoring costs). Passive treatment of contaminated water (pump fed) with flow rate of around 15-20 l/s: £1 million to £1.5 million for initial construction (also requires monitoring and operational costs).	LOW to HIGH
Combined active and passive treatment of contaminated water source	Environment Agency (2015)	Whole life costs for an intervention to treat contaminated water involving pumping, temporary chemical treatment during construction with passive treatment thereafter: £7 million.	VERY HIGH
Notes: costs per m^3 have not been identified. Where sources are not specified, costs are based on expert judgement and are likely to vary significantly according to the individual situation.			
Definition of ratings for costs: LOW: up to £500,000 per site MEDIUM: >£500,000 to £ 1 million per site HIGH: >£1 million to £2 million per site VERY HIGH: >£2 million per site			
A site is assumed to be a water treatment site where a point source discharge is treated OR where there are several point sources in close proximity to each other, they may all be piped to one site and treated together.			

Interventions to Deal with Contaminated Sediments In-Situ

Table 2.6 provides a summary of key information on the costs of interventions used in-situ. All costs have been converted to pounds sterling and uprated to 2014 values. References used to identify costs can be found in **Appendix A**. A rating has been assigned to the costs to reflect the range of costs across the various interventions. The definition used to determine the appropriate rating is given in the final row of **Table 2.6.** This rating is used alongside information on effectiveness (**Section 2.5.2**), benefits and dis-benefits (**Section 2.5.2)** to help identify which interventions appear to be the most cost-effective and cost-beneficial (**Section 2.5.4**).

Table 2.6 Summary of information on costs for interventions to deal with contaminated sediments in-situ

Intervention	References	Costs (all 2014 values)	Rating
In-situ capping	Apitz and Black (2010)	£39 per m^3 (plus monitoring costs) (open sea with capping).	HIGH
Dredging	Greenpeace (2010)	Special equipment is needed for contaminated sediments, costs vary from £3-£14 per m^3 of sediment to be removed, depending on health risks, labour demands, logistics and scope of the work to be done (Netherlands).	LOW to MEDIUM
Excavation	Bureau de Recherches Géologique RGM (2010)	£5 to £47 (first and fourth quartiles per m^3 of soils excavated); £7 to £12 (low to high average per m^3 of soils excavated). (France)	LOW to HIGH
Monitored Natural Recovery	Bureau de Recherches Géologique RGM (2010)	£11 to £62 (first and fourth quartiles per m^2 of treated surface water); £19 to £24 (low to high average per m^2 of treated surface water). (France)	MEDIUM to HIGH
Immobilisation (in-situ)	Apitz and Black (2010)	In-situ chemical: £52 to £87 per m^3 In-situ biological: £13 to £26 per m^3	Chemical: HIGH Biological: MEDIUM
Electrochemical Remediation	Defra UK (2010)	Not established, a barrier has very high costs (including high energy and complex apparatus) [note relates to electrokinetic treatment and from title of report looks like this is ex-situ rather than in-situ) (France)	VERY HIGH
<u>Definition of ratings for costs:</u> MEDIUM: £11 to £30 per m^3 HIGH: >£30 per m^3 VERY HIGH: >£100 per m^3			
Note: Information was available only on a per m^3 basis with no data on the volumes of materials that these costs relate to			

Interventions to Deal with Contaminated Sediments Ex-Situ

Table 2.7 presents costs information for interventions used ex-situ. As above, the costs have all been converted to pounds sterling and uprated to 2014 so they can be more easily compared. A rating has again been assigned based on the definition provided in the final row of **Table 2.7.**

Table 2.7 Summary of information on costs for interventions to deal with contaminated sediments ex-situ

Intervention	Reference	Costs (all 2014 values)	Rating
Immobilisation (ex-situ)	Greenpeace (2010)	Chemical immobilisation requires high investment and therefore high throughput (>100,000 m^3 per year). Costs are then typically £24/m^3 of dredged material (Netherlands). Thermal immobilisation (only undertaken on pilot experiments with the high costs meaning that installations have not been realised). The costs for energy and transport are the main elements in the operational costs. A minimum of 500,000 m^3 throughout per year is needed to reach costs of around £33 per m^3 of dredged material (Netherlands).	MEDIUM MEDIUM
Dewatering	Apitz and Black (2010	Natural dewatering: £8 to £21 per m^3	LOW to MEDIUM

Intervention	Reference	Costs (all 2014 values)	Rating
		Mechanical dewatering: £8 to £26 per m^3 (Belgium)	MEDIUM to HIGH
Contained Aquatic Disposal	-	£5 to £31 per m^3 (plus monitoring costs)	LOW to HIGH
Confined Disposal Facilities	Greenpeace (2010)	Building costs for large depots in the Netherlands £152 million (a minimum of £1.90 per m^3 of dredged spoil) (Netherlands).	LOW to MEDIUM
	Greenpeace (2011)	Costs of storing contaminated dredged spoil in large depots is around £9 per m^3 sediment. In the Netherlands (such as IJsselook, Slufter and Hollands Diep), private depots cost around £18 per m^3 sediment.	
	Apitz and Black (2010)	£9 to £60 per m^3	LOW to HIGH
Landfarming	Greenpeace (2010)	Land must be bought or rented. These can be the largest costs. Operational costs for a throughput of 100,000 m^3 of dredged materials are around £9 per m^3 (Netherlands)	LOW
	Apitz and Black (2010)	£9 to £32 per m^3	LOW to HIGH
	BRGM (2010)	£23 to £66 (first and fourth quartiles per m^3 of soils excavated) £25 to £34 (low to high average per m^3 of soils excavated) (converted to per m^3 from per metric ton) (France)	MEDIUM to HIGH
Landfill Disposal	Apitz and Black (2010)	£1 to £205 per ton [£2 to £480 per m^3 assuming 2 tons per m^3)	LOW to VERY HIGH
Soil washing	DEC (2011)	£146 per m^3 (€167 per m^3 in 2011) (note: this is the maximum cost as this cost includes costs of dredging and construction of temporary storage basins).	HIGH (lower end of range used since it is known that costs are maximums)
	DEC (2012)	£66 per m^3 (€80 per m^3 in 2012) (note: this is the maximum cost as this includes costs of dredging and construction of working area and is associated with testing of the facility).	
	DEC (2014)	£371 per m^3 (€464 per m^3 in 2014) (note: this is the maximum cost as this includes costs of dredging of independent hot spot areas to target highest contaminated (red sediment)).	
	DEC (2013)	£35 per m^3 (€42 per m^3 in 2013) (note: this is the maximum cost based on 60,000 m^3 that was treated but a further 140,000 m^3 was dredged)	
Definition of ratings for costs: LOW: £1 - £10 per m^3 (conversion from tons assumes 2 ton per m^3) MEDIUM: £11 to £30 per m^3 HIGH: >£30 per m3 VERY HIGH: >£100 per m^3			
Note: Information was available only on a per m^3 basis with no data on the volumes of materials that these costs relate to unless stated			

2.5.3 Effectiveness

Overview

This section considers the relative effectiveness of interventions. It is noted that effectiveness is highly dependent on a number of factors, such as the type of contaminant, the type of sediment, whether the intervention is at source or once contaminants have been deposited in the sea, the conditions in which organisations looking to reduce or remove contaminants are working, the timescale over which interventions are being considered, and whether interventions are applied singly or in combination. The section presents a summary of information collected on effectiveness of interventions from the documents reviewed. As with costs, a rating is assigned to each intervention to give an indication of relative effectiveness (from low to very high). This is based on the qualitative and quantitative descriptions of effectiveness which follows the effectiveness ratings provided by Apitz & Black (2010)[4].

Interventions for Reducing Contaminants at Source

Table 2.8 provides an overview of information collected on the effectiveness of the interventions for reducing contaminants at source. The effectiveness of any intervention will, of course, vary according to the concentration of the contaminant(s) and the flow rate of the water. **Table 2.8** provides indicative ratings of effectiveness based on expert judgement.

Table 2.8 Summary of information on effectiveness for reducing contaminants at source

Intervention	References	Effectiveness	Rating
Active treatment of contaminated water source	Coal Authority (2014) Taylor *et al* (2005)	Active treatment may be used as a short term solution, or where insufficient land is available for passive treatment. Chemical dosing can be tailored to ensure sufficient levels of contaminants are removed to meet water quality standards (e.g. WFD good/good potential status). Active treatment systems can be engineered to deal with any acidity and flow rate. Regular monitoring and maintenance is required.	LOW
Passive treatment of contaminated water source	Coal Authority (2014)	Where the treatment plant is gravity fed, there are no long term pumping costs and minimal maintenance is required. Desludging may only be needed every other year, with the reedbeds themselves potentially lasting for around 25 years There is a time lag between constructing the scheme and it being fully operational and effective at removing contaminants (any reedbeds need time to establish).	MEDIUM to HIGH
Combined active and passive treatment water source	Environment Agency (2015)	Tests undertaken in the laboratory and the field suggest that up to 99% of the contaminant should be removed by the treatment plant. Long term costs are reduced by removing the active treatment plant once the passive scheme is fully operational.	MEDIUM
Definition of overall ratings for effectiveness: LOW: no sustainability + small economic + no/small environmental + no/small social, or just one medium others none/small MEDIUM: some sustainability + medium economic, environmental and social Some sustainability + one small, one medium, one high from economic, environmental, social HIGH: some sustainability + at least two high economic, environmental, social VERY HIGH: some sustainability + all high economic, environmental, social			
Note: effectiveness ratings are based on Apitz & Black (2010). Insufficient detail provided on the performance of each measure to allow for development of an alternative rating system so this has been used as the basis for assessment within this study for consistency across interventions			

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[4] The specific definitions are not given in Apitz & Black. However, this source covers the majority of interventions as so it used as the basis for assessing effectiveness, benefits and dis-benefits to make best use of the available data

Interventions to deal with contaminated sediments in-situ

Table 2.9 provides a summary of the information collected from the reviewed reports on effectiveness of the interventions in-situ. As already noted, it is difficult to determine effectiveness without also considering the type and concentration of contaminant that needs to be treated, the type of sediment involved, the conditions in which the intervention is to be used and any combination of interventions that could be used. However, an indicative rating has been assigned based on expert judgement drawing on the qualitative information on likely effectiveness.

Table 2.9 Summary of information on effectiveness for interventions to deal with contaminated sediments in-situ

Intervention	References	Effectiveness	Rating
In-situ capping	USEPA (2005) Reible (no date)	Affected by: physical site conditions, sediment characteristics, waterway use and infrastructure and habitat alterations. Also dependant on e.g. thickness of cap, etc. Conventional sediment capping with sand or similar material can be very effective over long times with strongly sorbing contaminants but in some cases proper placement or long term cap stability are difficult to ensure and transport mechanisms may exist that cause more rapid reductions in effectiveness.	MEDIUM
Dredging	USEPA (1993) USEPA (2005) USEPA (1993)	Level of uncertainty associated with residual contamination can be high, with this likely to be greatest where there are cobbles, boulders or buried debris; in high energy environments; at greater water depths; and where more highly contaminated sediment lies near the bottom of the dredge thickness or overlies bedrock or a hard bottom (these factors can also make sediment removal more expensive). Contaminant resuspension may be redeposited at the dredging site or transported downstream, where not controlled. Mechanical dredging leads to high levels of resuspension, particularly of fine particles which are often the most contaminated. Hydraulic dredging has lower resuspension rates but can be damaged and clogged by debris. Pneumatic dredging produces higher solid concentrations and cause less resuspension of bottom materials. Dredging minimises the uncertainty associated with future environmental exposure as the contaminant is removed but can cause residual contamination	MEDIUM
Excavation	USEPA (2005)	Level of uncertainty associated with residual contamination can be high, with this likely to be greatest where there are cobbles, boulders or buried debris; and where more highly contaminated sediment lies near the bottom of the excavation depth or overlies bedrock or a hard bottom (these factors can also make sediment removal more expensive). Removal of contaminated sediment is usually more complete than with dredging however excavation is	HIGH

Intervention	References	Effectiveness	Rating
		usually limited to a relatively shallow area.	
Monitored Natural Recovery	USEPA (2005)	Leaves untreated contaminants in place, some risk of contaminants being re-exposed or dispersed, risk of contaminated sediment reaching the surface leading to unacceptable risks. Most effective in depositional environments after source control actions and active remediation of any high risk sediment have been completed.	LOW
Immobilisation (in-situ)	USEPA (2005)	Leaves untreated contaminants in place, some risk of contaminants being re-exposed or dispersed, risk of contaminated sediment reaching the surface leading to unacceptable risks. Most effective in depositional environments after source control actions and active remediation of any high risk sediment have been completed.	MEDIUM
Electrochemical Remediation	National Risk Management Research Laboratory (2007) Yeung and Gu (2011)	Lack of a reduction in contaminants from this intervention (could be due to operational problems). Effectiveness of this intervention is diminished by sorption of contaminants on soil particle surfaces and various effects induced by hydrogen and hydroxide ions generated at the electrodes. Can use other techniques to enhance effectiveness.	LOW
Definition of overall ratings for effectiveness: LOW: no sustainability + small economic + no/small environmental + no/small social, or just one medium others none/small MEDIUM: some sustainability + medium economic, environmental and social Some sustainability + one small, one medium, one high from economic, environmental, social HIGH: some sustainability + at least two high economic, environmental, social VERY HIGH: some sustainability + all high economic, environmental, social			

Interventions to Deal with Contaminated Sediments Ex-Situ

Table 2.10 sets out the information collected on effectiveness for interventions used on contaminated sediments ex-situ.

Table 2.10 Summary of information on effectiveness for interventions to deal with contaminated sediments ex-situ

Intervention	Reference	Effectiveness	Rating
Immobilisation (ex-situ)	Greenpeace (2010)	Thermal immobilisation is constrained by the scale required to make the process economically viable.	LOW (data gaps – assumed worst case)
Dewatering	Englis and Hunter (no date)	When properly employed, the application of mechanical and dewatering technologies have proven effective in managing the solids handling needs of a dredging project.	HIGH
Contained Aquatic Disposal	Palmerton *et al* (no date)	Effectiveness relies in part on physical and chemical containment of the contaminated material while limiting losses of material during placement and capping.	MEDIUM
Confined Disposal Facilities	Olsta (no date)	Highly effective at retaining the sediment solids and moderate concentrations of attached contaminants.	MEDIUM

	Portland Harbour Superfund Site (2013)	Concentration of contaminant which can be effectively contained depends on the contaminant type, i.e. highly mobile and/or toxic contaminants have a lower acceptable concentration level at CDFs.	
Landfarming	Harmsen *et al* (2007)	In passive landfarms potentially limiting factors are: availability of appropriate microorganisms, supply of oxygen for the biodegradation process, and bioavailability of the pollutants to the microorganisms. In heavily contaminated sediment PAH and mineral oil degradation becomes limited following depletion of the accessible fractions by microorganisms. This is not as much of a problem in optimised bioreactors as in passive landfarms. Can create air-filled pores to improve the effectiveness of passive Landfarming.	MEDIUM
Landfill Disposal	-	Assumed effective as removes contaminants at site but depends on the controls at the landfill site.	HIGH
Soil washing	DEC (2010)	Treatment effectiveness: - PAH: 80-90% - mineral oil: >90% - cyanides: 65-75% - heavy metals: 65-75%	HIGH

<u>Definition of overall ratings for effectiveness:</u>
LOW: no sustainability + small economic + no/small environmental + no/small social, or just one medium others none/small
MEDIUM: some sustainability + medium economic, environmental and social
Some sustainability + one small, one medium, one high from economic, environmental, social
HIGH: some sustainability + at least two high economic, environmental, social
VERY HIGH: some sustainability + all high economic, environmental, social

2.5.4 Other Benefits and Dis-Benefits

Overview

As well as the effectiveness of the measures in dealing with contaminants at source, or reducing or removing them once deposited, there are other factors that affect the extent to which any intervention may be more or less desirable. These include environmental, social and economic benefits (advantages) and dis-benefits (disadvantages). Such factors are important to consider when looking to prioritise interventions. This section presents a summary of the review of information on wider benefits and dis-benefits (i.e. all the other benefits and dis-benefits that are associated with an intervention, but excluding effectiveness). The sources reviewed provided general information on the benefits and dis-benefits but this was not in enough detail to allow further quantification and monetisation of the benefits and dis-benefits. As a result, a qualitative rating is assigned in line with the approach used when assessing the costs.

An overall rating is assigned taking account of the various levels of benefits (and dis-benefits) associated with each intervention. This gives an indication of the relative level of overall benefits/dis-benefits of each intervention, based on the information collected from the reviewed documents. There are overlaps between this section and the other sections as benefits can include the low cost of an option or the effectiveness of it. These have been included when considering the overall rating for the benefits of each intervention as they are important benefits when determining which actions to undertake, however it is important to be aware of the overlap and the potential for double counting.

Interventions for Reducing Contaminants at Source

Table 2.11 provides the main dis-benefits of reducing contaminants at source, whilst **Table 2.12** presents the different types of benefit, along with an overall rating. Note that there may be some overlap between the benefits in **Table 2.12** and the points on effectiveness in **Table 2.10.**

Table 2.11 Summary of information on effectiveness for interventions to deal with contaminated sediments ex-situ

Intervention	References	Dis-benefits
Active treatment of contaminated water source	Coal Authority (2014)	Active schemes may not be visually appealing, and do not provide any ecological benefits (other than improvements to the quality of the treated water). Active schemes require regular maintenance as well as chemical inputs Waste produced will require disposal relatively regularly (potentially several times each year)
Passive treatment of contaminated water source	-	Passive treatment schemes generally have a time lag between construction and full operation since wetlands require time to establish. Large areas of land may be required. Passive schemes may not be able to deal with highly contaminated sources where the contaminant concentration is significant
Combined active and passive treatment of contaminated water source	-	Large area of land is required. Contaminant concentration needs to be reduced sufficiently for passive treatment to be used

Table 2.12 Summary of information on benefits for reducing contaminants at source

Intervention	References	Benefits					Overall benefits rating
		Sustainability	Economic	Environmental	Social	Other	
Active treatment of contaminated water source	Coal Authority (2014) USEPA (2014) Environment Agency (2015)	None identified	Active schemes do not require much land. Local economic benefits associated with improving the quality of the environment.	Active schemes do not provide any ecological benefits (other than improvements to the quality of the treated water).	Active schemes may not be visually appealing.	Active treatment plant can be set up to deal with any contaminant concentration	LOW
Passive treatment of contaminated water source	Coal Authority (2014) Environment Agency (2015)	Desludging may only be needed every other year, with the reedbeds themselves potentially lasting for around 25 years. Scheme does not need chemical input to operate	Where plant is gravity fed, there are no long term pumping costs and minimal maintenance is required. Local economic benefits associated with improving the quality of the environment.	Gravity fed treatment plants have minimal carbon costs because there is no pumping. Passive schemes can provide biodiversity benefits through the creation of wetland habitats.	Wetlands may also provide recreational benefits.	None identified	MEDIUM to HIGH
Combined active and passive treatment of contaminated water source	Coal Authority (2014) Environment Agency (2015)	Passive aspect of scheme does not need chemical input to operate	Local economic benefits associated with improving the quality of the environment (3)	Wetlands can provide biodiversity benefits (1)	Wetlands may also provide recreational benefits (1)	Active treatment plant can be set up to deal with any contaminant concentration	MEDIUM

Definition of overall ratings for benefits:
LOW: no sustainability + small economic + no/small environmental + no/small social, or just one medium others none/small
MEDIUM: some sustainability + medium economic, environmental and social
Some sustainability + one small, one medium, one high from economic, environmental, social
HIGH: some sustainability + at least two high economic, environmental, social
VERY HIGH: some sustainability + all high economic, environmental, social

Interventions to Deal with Contaminated Sediments In-Situ

Table 2.13 summarises the main dis-benefits for in-situ interventions and **Table 2.14** provides a summary of different types of benefit, along with the overall benefit rating. Much of the information is based on the paper by Apitz & Black (2010) which does not explain how the definitions for the ratings have been determined, although it does reference Defra UK Limited (2010), which does provide further details on the sustainability, economic, environmental and social benefits. However, Defra UK Limited (2010) provides qualitative descriptions and it is not clear from this how the ratings have been defined. We have, therefore, provided a summary of the key information from Defra UK Limited (2010) to accompany the ratings assigned by Apitz & Black (2010). Additional research has been undertaken to fill gaps in the information. The additional information suggests that the ratings for environmental benefits may overlap with effectiveness for some of the interventions (but not for all). Also some of the ratings assigned appear to be slightly optimistic in terms of the social benefits that could be delivered. The original ratings and descriptions are included in the table below but some may need to be treated with caution.

Table 2.13 Summary of information on dis-benefits for interventions to deal with contaminated sediments in-situ

Intervention	References	Dis-benefits
In-situ capping	Vandekeybus *et al* (2010)	Community concerns relating to: increased traffic, loss of resources/harvesting opportunities, increased flooding, disturbance of the aquatic habitat, cap material source issues, loss of boat, anchoring access, doubts about effectiveness, impacts of construction (e.g. loss of privacy, tourism impacts), impacts on property values, problems of cap placements and long-term effectiveness of cap
Dredging	Environment Agency (2013) National Academy of Sciences (2007)	Ecological impacts through physical removal of habitat and disruption Problems of exposure during dredging, re-suspension and release could lead to increase in contaminant. Could lead to negative impacts on health and quality of life of the local community
Excavation	USEPA (2005)	Site preparation is more lengthy and costly than for dredging and the process is limited to only relatively shallow areas.
Monitored Natural Recovery	Vandekeybus *et al* (2010)	Community concerns relating to: the long timeframe for recovery, the ongoing human and ecological exposure, doubts about the effectiveness, extended loss of resources and use, perception as a 'do nothing' remedy, impact on property values.
Immobilisation (in-situ)	Ringeling (1998)	Cold immobilisation requires additives and acidity (e.g. acid rain) can lead to the mobilisation of heavy metals, this process does not remove organic contaminants and there is no clear market for the final product
Electrochemical remediation	Niroumand (2012)	Working depth is limited by availability of drilling technology to install the electrodes. This process is also limited by the solubility of the contaminants and desorption of contaminant from the soil matrix. Acidic conditions and corrosion of the anode create difficulties in-situ and precipitation of species close to the electrode impedes the process

Table 2.14 Summary of information on benefits for interventions to deal with contaminated sediments in-situ

Intervention	References	Benefits					Overall benefits rating
		Sustainability	Economic	Environmental	Social	Other	
In-situ capping	Apitz and Black (2010) Defra UK (2010) National Academy of Sciences (2007)	None identified	Medium Eliminates need for transport, treatment and disposal at storage site so energy, space and production of by-products is negligible.	No further improvement May be a reduction in sediment and contaminant losses to water column if toxic sediments remain capped Fewer land based facilities are needed for material handling.	Small Possible recreational benefits from improved sediment/water quality. Quickly reduces exposure to contaminants, requires less infrastructure for material handling and disposal, low risk of resuspension of contaminant, less disruptive of communities.	Performance can be better predicted, more easily quantified and it is quicker to implement than dredging.	LOW
Dredging	National Academy of Sciences (2007) USEPA (2005)	None identified	None identified	Removal of contaminants reduces risk of ecological impacts in long term.	Removes contaminants permanently thereby reduces human health risk , as well as the potential for psychological consequences of not removing. Does not limit the use of the waterbody.	Relatively quick	LOW
Excavation	USEPA (2005)	None identified	None identified	Likely to be similar to dredging	Likely to be similar to dredging	Equipment operators and oversight personnel can more easily see the removal operation, removal of the contaminated sediment	MEDIUM

						is more complete and fewer waterborne contaminants are released.	
Monitored Natural Recovery	USEPA (2005)	None identified	Relatively low implementation costs (primarily associated with monitoring).	Non-invasive, typically no man-made physical disruption to existing biological community.	No construction or infrastructure required therefore less disruptive of communities and no contaminants are transported through communities.	None identified	MEDIUM
Immobilisation (in-situ):	Apitz and Black (2010) Defra UK (2010) Ghosh (2012)	Site recovery	High In-situ chemical: high In-situ biological: medium Potential sale of secondary material; no disposal costs. Potential for low cost	Major change In-situ chemical: major change In-situ biological: small change Contaminants less mobile and less bioavailable. Less disruption to benthic habitats.	High In-situ chemical: high In-situ biological: small Perception of positive benefit due to environmental benefit	Suitable for shallow or constricted locations, can be combined with capping and dredging	In-situ chemical: VERY HIGH In-situ biological: LOW
Electrochemical Remediation	Niroumand *et al* (2012)	None identified	Competitive cost	None identified	None identified	Can treat inorganic and organic compounds in porous media simultaneously	LOW

Definition of overall ratings for benefits:
LOW: no sustainability + small economic + no/small environmental + no/small social, or just one medium others none/small
MEDIUM: some sustainability + medium economic, environmental and social
Some sustainability + one small, one medium, one high from economic, environmental, social
HIGH: some sustainability + at least two high economic, environmental, social
VERY HIGH: some sustainability + all high economic, environmental, social

Interventions to Deal with Contaminated Sediments Ex-Situ

Table 2.15 presents the dis-benefits of ex-situ contaminant interventions, while **Table 2.16** presents the benefits information for the ex-situ interventions. As with **Table 2.14**, this also shows the ratings taken from Apitz & Black (2010) expanded to include some of the qualitative descriptions from Defra UK Limited (2010). Again, it is important to note that there may be some overlap between the environmental benefits noted in **Table 2.16** and the effectiveness ratings assigned in **Section 2**. Furthermore, the description of economic, environmental and social benefits may be optimistic, particularly in the case of the social benefits (e.g. where there is the suggestion of social benefits due to quarrying being reduced from reuse of treated contaminated sediments). As such, the benefits should be treated with caution.

Table 2.15 Summary of information on dis-benefits for interventions to deal with contaminated sediments ex-situ

Intervention	References	Dis-benefits
Immobilisation (ex-situ)	Apitz and Black (2010)	This process has high treatment costs, releases flue gas emissions and has high energy consumption
Dewatering: Natural/mechanical	-	None identified
Contained Aquatic Disposal	Palmerton *et al* (2010)	Potential loss of contaminated material during placement, difficulties of accurately placing the cap material, particularly over the less dense contaminated material
Confined Disposal Facilities	IADC (2010) Sheldrake (2011)	High costs and difficulties of finding suitable locations. Also loss of bottom habitat and the potential for contaminant releases during filling if not properly conducted. There is the potential for long-term release of contaminants
Landfarming	Harmsen *et al* (2007)	Degradation of contaminants affected by the availability of appropriate microorganisms, supply of oxygen and bioavailability of pollutants to microorganisms
Landfill disposal	Webb and Keller (no date)	Requires transportation to the site
Soil washing	DEC (2010)	None specifically identified; however, does include dewatering and reports lower dust/noise compared to other techniques that require higher volumes of transportation (the latter being specifically associated with washing of soils rather than contaminated sediments).

Table 2.16 Summary of information on effectiveness for interventions to deal with contaminated sediments in-situ

Intervention	References	Benefits					Overall benefits rating
		Sustainability	Economic	Environmental	Social	Other	
Immobilisation (ex-situ)	Apitz and Black (2010) Defra UK (2010) Smith *et al* (2009)	Thermal immobilisation: clean product. Reduction in volume.	High Beneficial use of secondary material; no disposal costs.	Major change Compliant with emissions standards; immobilises organic and inorganic contaminants.	High Reduction in use of natural resources; no need for disposal in landfill.	None identified	HIGH
Dewatering: natural	Apitz and Black (2010) Defra UK (2010)	Reduced volumes	Medium Transport handling can be reduced; outputs acceptable for beneficial use.	Major change Limited surface area needed, can get high dry matter content	High Potentially reduces need for primary aggregates.	Creates aerobic conditions for microbial degradation of many contaminants.	HIGH
Mechanical		Reduced volumes	Outputs can be used as construction material.	Energy consumption is low; emissions to air are negligible.	Potentially reduces need for primary aggregates.		HIGH
Contained Aquatic Disposal	Apitz and Black (2010) Defra UK (2010)	None identified	Medium Shorter transport distances; potential to generate income from sale of materials from seabed pit; can follow polluter-pays principle.	Small change Result in less handling of contaminated materials so fewer contaminant transfer pathways.	Medium Perceived as offering higher level of protection by public from natural events including storms and waves.	None identified	MEDIUM
Confined Disposal Facilities	Apitz and Black (2010) Defra UK (2010) Sheldrake (2011)	Recreational space	High Considered more economical than landfill; separation techniques can produce sellable	Small change On-land structures are not exposed to forces from vessels; risk to the environment is low	Medium Can be landscaped and use for recreation or as nature reserves.	Facilitates dredging projects.	MEDIUM

Intervention	References	Benefits					Overall benefits rating
		Sustainability	Economic	Environmental	Social	Other	
			products, e.g. sand; follows polluter pay principle.	Potential for creation of shallow water, wetland and riparian habitat.			
Landfarming		Clean product, biomass	Medium Reduces disposal costs and site can be used to grow biomass, e.g. willow in Netherlands. Relatively low cost	Small change High degradation percentages possible.	Medium Biomass production can reduce use of natural resources.	None identified	MEDIUM
Landfill Disposal	Apitz and Black (2010) Defra UK (2010) Webb and Keller (no date)	None identified	Small Costs generally lower than in a CDF.	No further improvement Eliminates future impacts on water quality, fish habitat and endangered species without causing additional harm to surrounding neighbours and businesses.	Small Permitting requirements and public opposition are eliminated (compared to CAD/CDF).	None identified	LOW
Soil washing	DEC (2010) DEC (2011)	Clean product, reduced volumes	Medium Transport handling can be reduced; outputs acceptable for beneficial use.	Major change Area needed is small; can get high dry matter content.	High Sediments can be reused, e.g. for beach nourishment.	Can be effective even with small volumes.	HIGH

Definition of overall ratings for benefits:
LOW: no sustainability + small economic + no/small environmental + no/small social, or just one medium others none/small
MEDIUM: some sustainability + medium economic, environmental and social
Some sustainability + one small, one medium, one high from economic, environmental, social
HIGH: some sustainability + at least two high economic, environmental, social
VERY HIGH: some sustainability + all high economic, environmental, social

3 Investigation of how land and water management activities have the potential to improve or exacerbate the risks/impacts associated with in-situ contaminated sediment

Scope of task:

Examine how management of land and water in the UK has the potential to improve or exacerbate the risks or impacts associated with in-situ contaminated sediment.

Collate a list of land and water management activities that have the potential to affect sediment/contaminant input or sediment movement into and/or within the aqueous environment. Evaluate these activities according to their potential to impact upon these aspects.

3.1 Introduction

Many activities that are carried out within river catchments and coastal waters may affect the pathways by which contaminants are able to cause harm (or which presents a possibility of such harm being caused). This task considers the way in which these activities could affect sediment disturbance and how their management in the UK has the potential to improve or exacerbate the risks or impacts from contaminated sediment. Management activities that have the potential to affect contaminated sediment include:

- Dredging (e.g. navigation)
- Introduction of flood defence structures
- Changes to existing defences
- Introduction/removal of river structures (e.g. weir removal and deculverting)
- River Bank Works, including other river restoration activities, including in-channel habitat enhancements and the reinstatement of natural geomorphological processes.
- Beach nourishment
- Sustainable Drainage Systems (SuDS)
- Control of invasive species
- Fishing
- Vessel speed limits
- Changes in land use
- Changes to the way in which structures are operated

3.2 Methodology

Intervention and management techniques to land and water, whose primary focus is not the management of in-situ contaminated sediment, was compiled through a review of guidance documents (including land use practises detailed in the Sediment Matters Handbook (Environment Agency, 2011)), scientific research papers and technical documents, as well as am internet search. Furthermore, each technique has been evaluated by expert opinion, to determine the degree to which the technique could affect in-situ contaminated sediment.

3.3 Summary of land and water intervention and management activities which may impact on in-situ contaminated sediment

Table 3.1 below describes how each of the activities identified could potentially improve or exacerbate the risks/impacts of in-situ contaminated sediment.

Table 3.1 Land and water management activities which have the potential to improve or exacerbate risks/impacts from in-situ contaminated sediment

Improve	Exacerbate
Capital and maintenance dredging (e.g. for construction, navigation, flood risk management)	
■ Dredging and disposal within the UK is well regulated, with strict measures applied to dredging activities and what material is permitted to be deposited at sea. Given this, dredging is considered to have the potential to improve the risks associated with in-situ contaminated sediment, where this leads to its removal and subsequent appropriate disposal (thereby removing the contaminated material). ■ For capital dredging projects, in particular, a sediment survey is normally required to determine the chemical quality of the material to be dredged. This provides valuable information on the quality of historic sediments in the area, which can be used to inform decision making on other projects. ■ Sediment surveys are required for maintenance dredging normally every three years. This provides useful information on whether there are existing contamination issues affecting sediment quality.	■ Capital dredging works, in particular, may expose and re-suspend historic sediments, which have the potential to be contaminated. ■ The process of dredging and overflowing the hopper to reduce fine content, results in the release of sediment that has the potential to be contaminated. ■ Dredging may alter sediment transport dynamics, thereby altering erosion patterns, potentially exposing contaminated sediment. ■ Dredging vessels may expose potentially contaminated sediment through propeller action and vessel wash. ■ Dredging may result in chemical and biological changes to water quality due to changes in contaminant levels (e.g. oxidation, reduction, degradation and concentration of contaminants by plants or animals).
Introduction of flood defence structures	
■ Creation of hard defences along river banks/coastline to reduce coastal flooding can prevent runoff from landfills and contaminated land (including contaminated dredged material placed on canal and river banks and in disposal lagoons adjacent to rivers and fly tipped wastes). ■ Creation of hard defences to prevent coastal erosion can prevent the release of potentially contaminated soil, in particular where landfills are at risk.	■ Flood defences can reduce the volume of sediment stored on a floodplain, increase volumes of sediment being transported downstream and potentially increase sediment deposition in undefended areas downstream. ■ Flood defence structures may change sediment transport dynamics, for example thought changes to channel/coastline mobility, thereby altering erosion patterns, potentially exposing contaminated sediment. ■ In-water works have the potential to expose and re-suspend potentially contaminated sediment. ■ Flood defence structures may change usage/number of vessels, thereby altering the mobilisation of sediments by propeller action and vessel wash.

Improve	Exacerbate
Removal of river structures (e.g. weir removal and deculverting)	
■ None identified.	■ Removal of river structures may leave land exposed to erosion. If river structures are located near contaminated land or land fill sites, where sediments are likely to contain elevated concentrations of contaminants, disturbance to the sediment may create contaminated surface water run-off. ■ Contaminated dredged material on canal and river banks and in disposal lagoons adjacent to rivers, and fly tipped waste may become exposed to the wider aquatic environment. This may lead to the creation of contaminated surface water run-off. ■ Deculverting may alter sediment transport dynamics, thereby altering erosion patterns, potentially covering exposing contaminated sediment. ■ Activities associated with the removal of river structures may disturb and remobilise potentially contaminated sediments.
Coastal infrastructure projects (not including linear defences)	
■ Infrastructure projects that have the potential to disturb sediment, in particular at depth, normally require a sediment survey to determine the chemical quality of the material. This provides valuable information on the quality of historic sediments in the area, which can be used to inform decision making on other projects. In addition, should these sediments need to be removed and appropriately disposed of, this would improve the risks with in-situ contaminated sediment. ■ Reclamation projects, such as a new port terminal, can be used to lock in contaminated sediments, which functions as a CDF (see previous task), thereby improving the risks with in-situ contaminated sediment.	■ Coastal infrastructure projects may alter sediment transport dynamics, thereby altering erosion patterns and potentially exposing contaminated sediment. ■ The formation of bays can reduce tidal mixing, thereby causing levels of contaminants within the water column to increase and contaminate the underlying sediment. ■ Construction activities can result in the re-suspension of potentially contaminated sediment. ■ Construction projects have the potential to result in accidental spills and leakages thereby contaminating sediment. ■ Increased surface run off associated with ground compaction and reduced permeability of surrounding land may affect sediment loading.

Improve	Exacerbate
Riparian infrastructure project (not including linear defences)	
■ The construction of weirs with silt traps can reduce the downstream transport of contaminated sediments. ■ The construction of raised beds using clean gravel augmentation, may act to contain and reduce erosion of contaminated sediments. ■ Hydroelectric power plants can reduce the downstream transport of contaminated sediments.	■ Freshwater infrastructure projects may change sediment transport dynamics, thereby altering erosion patterns and potentially exposing contaminated sediment. ■ Potential releases of contaminated sediments associated with the construction and removal of freshwater infrastructure. ■ Construction activities can result in the re-suspension of potentially contaminated sediment. ■ Construction projects have the potential to result in accidental spills and leakages thereby contaminating sediment.
River Bank Restoration/Reinforcement	
■ River bank restoration/reinforcement reduces erosion of the riverbank, thereby reducing the release of potentially contaminated sediment. ■ Restoring/reinforcing riverbanks reduces the mobilisation of deep stored, potentially contaminated, sediment which can be released by fluvial flood events (deep scouring). ■ Erosion and mobilisation of in-channel, potentially contaminated, sediment by channel migration will be reduced due to bank strengthening. ■ Bank reinforcement may also reduce the erosion of contaminated material by vessel wash.	■ In-river works have the potential to result in the re-suspension of potentially contaminated sediment.
Beach Nourishment	
■ Beach nourishment reduces/prevents erosion of the foreshore, thereby preventing the release of potentially contaminated sediment. ■ This activity provides a supply of clean sediment for transport, which may overlay potentially contaminated sediment.	■ None identified.

Improve	Exacerbate
SuDS	
■ SuDS may prevent the mobilisation of in-situ contaminated sediment by fluvial flood events by managing surface water. ■ The installation of SuDS, such as permeable surfaces, filter strips and detention basins, have the potential to drain surface water in a manner that reduces the risk of contaminated in-situ sediment entering water bodies from the source. Contaminant linkages between source and water body (likely to be site specific to tackle a localised contamination problem) that may be disrupted by SuDS include: □ Direct erosion of mineral deposits, entrainment of enriched soils through surface runoff, chemical leaching of enriched deposits. □ Direct erosion of mining spoil heaps by flowing water, entrainment by surface runoff, chemical leaching of enriched deposits, direct input of dissolved metals. □ Mine adit discharges to surface and groundwater. □ Erosion, disturbance and surface water runoff from landfills and contaminated land (including contaminated dredged material placed on canal and river banks and in disposal lagoons adjacent to rivers and fly tipped wastes). □ Leaks and spills from industrial sites. ■ SuDS may also prevent the accumulation of contaminants downstream of consented outfalls, the movement of existing contaminated in-channel and in-bank sediments via river water.	■ None identified.
Control of invasive and nuisance species	
■ Invasive species, such as signal crayfish (*Pacifastacus leniusculus*) and Chinese mitten crab (*Eriocheir sinensis*), burrow into river banks for shelter, causing bioturbation and therefore may release potentially contaminated sediment. By controlling these invasive species this risk is reduced.	■ None identified

Improve	Exacerbate
■ Rabbits and badgers burrowing in river embankments may result in the deterioration of channel banks and therefore release potentially contaminated sediment into the waterbody. Management such as ‘rabbit proofing’ embankments with wire fencing with strengthen the bank, reduces sediment input from this impact.	
Fishing	
■ Modern fishing practices that aim to reduce impacting upon benthic ecosystems would also reduce their potential to disturb potentially contaminated sediment.	■ Any fishing activities that impacts upon the seafloor (such as bottom trawling) have the potential to increase the mobilisation of potentially contaminated sediments. ■ Propeller wash from fishing boats may expose potentially contaminated sediment through propeller action and vessel wash.
Vessel speed limits	
■ Controlled speed limits will reduce the potential mobilisation of potentially contaminated sediment via propeller action and vessel wash.	■ None identified
Changes in land use	
■ None identified.	■ Diffuse inputs from new urban/built areas (road runoff, misconnections, misuse of surface water drains, pollution incidents, etc.) may increase contaminant input into water bodies. ■ Changes in land use type have the potential to exacerbate the availability of soil for erosion, the potential for runoff to be generated and the pathways available for delivery. ■ The timing of land use activities can also result in increased vulnerability of soils for erosion.

Improve	Exacerbate
Changes in operational management	
▪ The active management of structures to control flow rate (flow intervention) could help to control erosion rates and therefore reduce the potential mobilisation of contaminated sediments. ▪ Changing vessel discharge practices (such as ballast water, oil spills and anti-fouling paints) can reduce the potential to contaminate sediment.	▪ Reducing or ceasing management of structures, for example culverts, weirs and dredging regimes, may impact upon contaminated sediment transport potential and result in the contamination of sediment.

4 Potential and methods for generating new innovative techniques for the management of in-situ contaminated sediment

Scope of task:

A qualitative discussion on possible strategies which may include:

- Introducing techniques which are innovative in the UK (but which have been trialled in other countries)
- A cross-disciplinary approach to the application of remediation techniques from other fields to contaminated sediments
- More general methods for stimulating innovation in sediment remedial engineering

4.1 Introduction

For the purposes of this task, 'innovation' is defined as any remediation techniques that are:

- Not commonly used in the UK.
- Not commonly endorsed by Defra as a technique.

The previous sections (**Section 2.3** and **2.4**) identify that there are number of remediation techniques that are not widely used or implemented in the UK in a consistent or strategic approach. As such, all management interventions for managing in-situ contaminated sediments discussed in this document are considered for the implementation of innovative techniques.

Task 7 reviewed and evaluated existing interventions and management activities for managing in-situ contaminated sediments. **Task 8** reviewed and evaluated existing interventions and management activities which may impact on in-situ contaminated sediments.

Table 2.5 identifies a series of case studies for innovative techniques as identified in **Table 2.1**. As discussed, these are mostly innovative, as they represent a minority of techniques used as remediation techniques (outside of dredging / excavation).

4.2 UK Innovation

Techniques identified in **Table 2.5** that have been trialled in the UK predominantly revolved around dredging and capping (both in the marine and freshwater environments). In both instances (Port of Tyne and Rattlechain Lagoon) this is due to prohibitive costs associated with treatment of excavated materials. Capping is therefore seen as a temporary measure and a stop-gap until further research has identified new technologies and solutions.

In both instances, the solutions required further investigation regarding the underlying causes and significant investment into monitoring. The scale of these case studies is relatively small in comparison to the other international case studies.

4.3 International Innovation

Table 2.5 also identifies a series of examples of innovative techniques from other countries. These include:

- The Netherlands
- Germany
- USA
- Hong Kong

In each of these instances, the scale of the operation is significantly larger than the UK. In particular, this indicates that finance is not a constraint for the implementation of techniques involving large centralised locations for dewatering or CAD pits. In the UK, there are few examples for the requirement of a large-scale dewatering facility due to the scale of the treatment requirements, in particular with reference to the riverine / freshwater environment.

There are few examples of centralised drying beds in the UK. One such example is at Bubbenhall in Warwickshire. This is co-funded and supported by the Canal & River Trust that accepts wet non-hazardous dredgings and dries them for acceptance as landfill material or capping material. This is one of the first of its kind in the UK and is a culmination of requirements for various dredgings on the River Avon and River Severn. At this stage, there are no reportable results as the trials are ongoing and it is too early in the programme, however, Land & Water are working closely with the Canal & River Trust in producing a research paper in the near future.

The lack of implementation in the UK means that there is a lack of case studies to test the regulatory processes that currently exist in the UK and if they restrict our ability to manage contaminated sediment risks or impacts in an innovative method. The implementation of the few case studies in the UK demonstrates that the responsible authorities are prepared to facilitate the legislative policy environment to enable their use. To further this wider implantation there is a requirement to disseminate the results of the ongoing trials to provide justification for further investment and associated regulatory approaches.

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5 Conclusions and Next Steps

WP1B has identified a number of management and intervention techniques that can be applied to manage in-situ contaminated sediment in the aquatic environment. Given the variety of the management and intervention techniques identified and the different types of problems that they target, the nature of the contamination issue needs to be fully understood before recommendations for appropriate techniques can be provided. Where techniques have been compared on their cost-effectiveness, it is noted that it is difficult to compare *ex-situ* techniques on a like for like basis as these techniques are heavily influence by transportation and disposal costs.

The drivers for the successful use of interventions, management actions and remediation activities appear to be the inter-related factors of need, scale and cost. Need is generally associated with commercial development or land management for purposes other than environmental improvement. At this stage there are no obvious legislative barriers to the application of most (if not all) of the measures used in other countries to England. However, the need to identify the owner of a sediment contamination 'problem' and to potentially apply the polluter pays principle would be a significant issue in circumstances where there was no clear commercial driver.

WP1B has provided a basis for discussions which will be undertaken as part of the WP2B. This report will be used as a reference document for WP2B which will develop this information further to collate a short list of detailed, costed potential interventions and identify the most appropriate/suitable management and intervention techniques which can be applied in different scenarios.

6 References

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7 Appendix A

7.1 Additional Information on the Cost-Benefit Analysis

Technique	Costs rating[a]	Effectiveness rating[b]	Other benefits ratings[b]	Dis-benefits rating[c]
Primary management techniques				
In-situ capping	High	Medium	Low	Very High
Dredging	Low to Moderate	Medium	Low	Very High
Excavation	Low to High	High	Medium	Very High
MNR	Moderate to High	Low	Medium	Medium
Immobilisation (in-situ)	Chemical: High Biological: Moderate	Medium	In-situ chemical: Very High In-situ biological: Low	Chemical: Low Biological: Low
Electrochemical Remediation	Very High	Medium	Low	Medium
Secondary management technique				
Immobilisation (ex-situ)	Moderate	High	High	Low
Dewatering	Mechanical: Moderate to High (Belgium) Natural: Low to Moderate	Natural: High Mechanical: High	Natural: High Mechanical: High	Natural dewatering: Medium Mechanical dewatering: Low
CAD	Low to High	Medium	Medium	Very High
CDF	Low to High	Medium	Medium	Very High
Landfarming	Low to High	Medium	Medium	Very High
Landfill Disposal	Low to Very High	LOW	LOW	Very High

Definitions:

[a] Covers £/m^3 cost (£2014), environmental costs and social costs. LOW: £1 - £10 per m^3 ; MODERATE: £11 to £30 per m^3; HIGH: >£30 per m^3; VERY HIGH: >£100 per m^3

[b] Based on combination of definitions as given in Apitz & Black (2010) LOW: no sustainability + small economic + no/small environmental + no/small social, or just one medium others none/small; MEDIUM: some sustainability + medium economic, environmental and social; Some sustainability + one small, one medium, one high from economic, environmental, social; HIGH: some sustainability + at least two high economic, environmental, social; VERY HIGH: some sustainability + all high economic, environmental, social

[c] Based on combination of definitions as given in Apitz & Black (2010) LOW: no further deterioration/small + small; "MEDIUM: no further deterioration/small + medium; HIGH: small + high; major change + medium; VERY HIGH: major change + high

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Technique	Costs rating[a]	Effectiveness	Other benefits	Dis-benefits rating[c]	Overall cost-	Overall cost-

		rating[b]	ratings[b]		effectiveness[d]	benefit[e]
Primary management techniques						
In-situ capping	10	7	1	1	0.7	0.9
Dredging	3	7	1	1	2.3	3.0
Excavation	4	13	7	1	3.3	5.3
Monitored Natural Recovery	7	1	7	13	0.1	3.0
Immobilisation (in-situ)	Chemical: 10 Biological: 4	7	In-situ chemical: 20 In-situ biological: 1	Chemical: 20 Biological: 20	Chemical: 0.7 Biological: 1.75	Chemical: 4.7 Biological: 7
Electrochemical Remediation	20	7	1	13	0.4	1.1
Secondary management technique						
Immobilisation (ex-situ)	4	13	13	20	3.3	11.5
Dewatering	Mechanical: 7 Natural: 3	Natural: 13 Mechanical: 13	Natural: 13 Mechanical: 13	Natural dewatering: 13 Mechanical dewatering: 20	Natural dewatering: 1.8 Mechanical: 4.3	Natural dewatering: 5.5 Mechanical: 15.3
Contained Aquatic Disposal	5	7	7	1	1.4	3.0
Confined Disposal Facilities	5	7	7	1	1.4	3.0
Landfarming	5	7	7	1	1.4	3.0
Landfill Disposal	11	13	1	1	1.2	1.4

Definitions:

[a] Covers £/m^3 cost (£2014), environmental costs and social costs LOW = 1 (based on mid point of £5 per m^3); MODERATE = 4 (based on midpoint of £20 per m^3); HIGH = 10 (based on £50 per m^3); VERY HIGH = 20 (based on £100 per m^3).

[b] LOW = 1; MEDIUM = 7; HIGH = 13; VERY HIGH = 20

[c] LOW = 20; MEDIUM = 13; HIGH = 7; VERY HIGH = 1

[d] Effectiveness rating divided by cost rating

[e] Sum of Effectiveness, benefits and dis-benefits divided by costs rating

Where a range is given, the mid-point is used. Where there is no data, assumed LOW for effectiveness and other benefits and very high for dis-benefits (i.e. worst-case).

Overall cost-benefit rating matrix

1.1	2.2	5.5	22
1.35	2.7	6.75	27
1.65	3.3	8.25	33
2.05	4.1	10.25	41

<2 = LOW; 2-4= MEDIUM; 4-10 = HIGH; >10 = VERY HIGH