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In Situ Contaminated Sediments

Work Package 2B Report

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In Situ Contaminated Sediments Work Package 2B

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REPORT

In Situ Contaminated Sediments Project

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1 Introduction

1.1 Objectives of the In Situ Contaminated Sediments Project

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 national risk assessment approach. This process is intended ultimately to provide the basis for a comprehensive review of the potential mitigation options available for addressing issues at 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 the regulation and protection of water quality. This knowledge will enable these bodies to make evidence-based decisions for funding priorities 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.

Details of the project scope, definition of *in situ* contaminated sediments and project structure are provided in the Work Package 1A Report (Royal HaskoningDHV, 2015).

1.2 Project Structure

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

- **Work Stream A: Need for Action:** This work stream gathers evidence of in-situ sediment contamination in England and undertakes an assessment of the risks that this could pose; and
- **Work Stream B: Developing Interventions:** This work stream gathers evidence on the range of intervention options (i.e. sediment management and remediation measures) 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 work stream, as well as the interactions between each work stream.

This report presents the findings of **Work Package 2B** (WP2B).

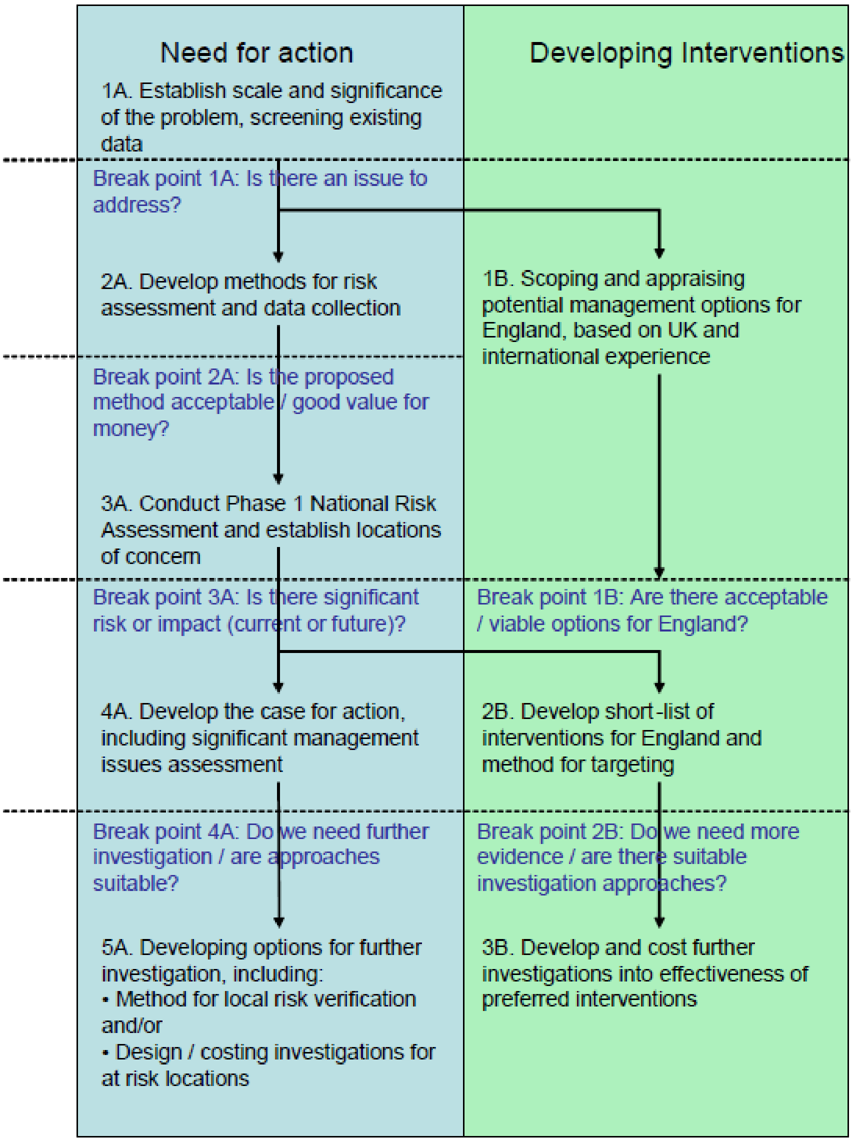
1.3 Work Stream B

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

- **Work package 1B:** WP1B aims to collate, review and analyse existing management and intervention options for in-situ contaminated sediment;
- **Work package 2B:** WP2B aims to develop an approach for identifying the most suitable intervention options for in-situ contaminated sediment, and determine how these should be selected or targeted in England; and

- **Work Package 3B**: WP3B aims to define further, the work or data collection necessary to refine or evaluate the management and intervention options identified in the previous work packages. This includes adding further techniques to the short list, if necessary, or improving the quality of information about those already shortlisted.

Figure 1.1 Structure of Work Packages



1.4 Objectives of Work Package 2B

The objective of WP2B is to use the information gathered under WP1B to develop an appraisal framework (i.e. a selection tool) for identifying and assessing the most appropriate intervention options (or package of options) for contaminated sediments.

To address this objective, WP2B uses a stepped options assessment procedure to compares the relative performance of the various in situ and ex situ intervention options (identified in WP1B) against a range of technical, financial (in the form of costs) and sustainability (in the form of environmental, social and economic benefits) performance criteria.

1.5 Report Structure

This report is divided into the following sections:

- **Section 2**: Options assessment procedure;
- **Section 3**: Intervention options;
- **Section 4**: Performance criteria;
- **Section 5**: Performance assessment;
- **Section 6**: Options selection tool; and
- **Section 7:** Conclusions.

2 Options Assessment Procedure

2.1 Context

WP2B aims to use previously collated information from WP1B and other relevant, readily available sources to provide an appraisal framework (i.e. a selection tool) for identifying the most suitable interventions (or packages of interventions) for different contaminated sediment scenarios.

To meet this aim, an appraisal framework is presented in the form of an options assessment procedure. This procedure builds in and expands upon the previously collated technical, financial and environmental, social and economic information on the intervention options and performance criteria to develop a set of performance matrices. The performance matrices are then tested to illustrate how they can be used as a selection tool to identify the most suitable intervention options for specific contaminated sediment decision-making scenarios (i.e. formulated problems).

2.2 Problem Formulation

An options assessment needs to be set in context with a particular contaminated sediment scenario (i.e. the 'problem') and the need for intervention. Through problem formulation, the decision-maker frames the contaminated sediment scenario by defining what the concerns are and how they could / should be addressed by intervention.

As a minimum, problem formulation conceptualises the single high level objective of intervention (e.g. clean up of in situ contaminated sediment conditions by the most cost-effective, environmentally acceptable removal and ex situ treatment and/or disposal intervention option(s)).

More detailed problem formulation leads to a transparent and shared understanding of:

- The contaminated sediment problem including the physical and chemical characteristics of the contaminated sediment and the risks it poses to the surrounding environmental, social and economic conditions if left in situ without intervention; and
- The objectives of intervention and the resulting change to the in situ sediment conditions taking into account sustainability objectives (e.g. regulatory compliance, human health and ecological risk minimisation, waste minimisation, non-renewable resource consumption minimisation, etc.), sustainability principles (precautionary principle, polluter pays principle) and the statutory duties and/or non-statutory policies of the decision-maker.

2.3 Procedure Outline

The procedure comprises a stepped assessment that mimics some, but not all, of the key steps of multi-criteria analysis (**Figure 2.1**).

The procedure's initial steps entail the identification and description of the in situ and ex situ intervention options for contaminated sediment (**Section 3**), and the environmental, social and economic performance criteria and scoring systems for assessing the intervention options (**Section 4**).

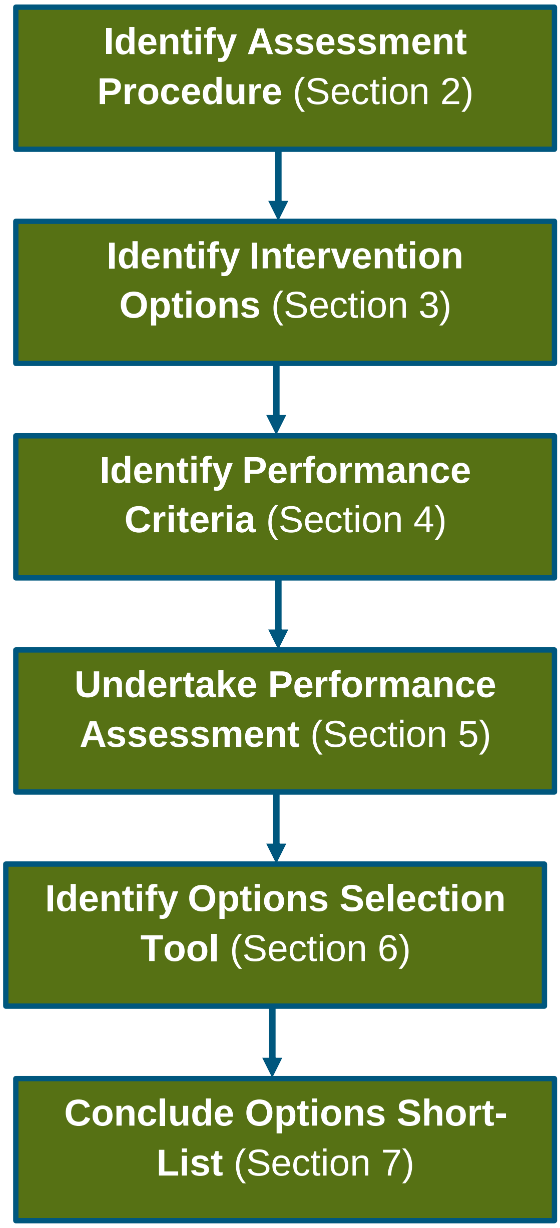
With this information in place, the procedure's next step entails the scoring of the intervention options against each of the performance criteria to create a series of performance matrices (**Section 5**). The performance matrices contain performance scores that are presented using a basic, consistent scale and are supported by supplementary comments to facilitate of the selection of potentially suitable intervention options. The performance scores are made in relation to quantified data (e.g. intervention costs based on published reference materials) and qualified information (e.g. intervention results based on recorded observations) drawn from WP1B and additional referenced data and information sources, which are identified in the performance matrices (**Tables 5.1 to 5.5**).

The performance matrices inform the selection tool for determining the most suitable intervention option(s). They facilitate a transparent, informed, multi-criteria performance-based assessment and an audit trail for decisions. It is acknowledged that the performance matrices leave decision-makers with the task of assessing the extent to which their specific objectives can be met by the selected intervention options and, therefore, the performance matrices are tested in the context of external influences (i.e. issues that may be critical to a particular project and, therefore, the selection of intervention options).

The options selection tool involves a tiered assessment process. This is a two-stage process that initially selects the intervention options available for a particular contaminated sediment scenario (e.g. maintenance dredging in an operational port) and then selects the most suitable option(s) for further investigation using the performance matrices (**Section 6**).

The options short-list indicates the potential interventions - or packages of interventions (i.e. intervention chains) that are most likely to be used for managing contaminated sediment (**Section 7**).

Figure 2.1 Options Assessment Procedure for WP2B



3 Intervention Options

This section identifies the various intervention options available for contaminated sediment. It draws upon the information contained within the WP1B Report, which has drawn upon the information contained within a number of key references including previous Defra research (e.g. Defra, 2010) and published industry guidance.

3.1 Types of Intervention Options

The WP1B Report identified two overarching types of intervention options for contaminated sediment:

- In situ intervention options that involve an intervention relating to in situ contaminated sediment in its original location (e.g. in the bed of a river, estuary or sea); and
- Ex situ intervention options that involve an intervention relating to the ex situ contaminated sediment in a new location (e.g. in another part of the bed of a river, estuary or sea, or on land).

3.2 Roles of Intervention Options

Both the in situ and ex situ intervention options have different objectives and outcomes and, therefore, are identified in relation to the following intervention roles:

- Removal of contaminated sediment – various in situ options to remove contaminated sediment from its in situ location to an ex situ location, typically in advance of another management measure (i.e. treatment and/or disposal options);
- Pre-treatment of contaminated sediment – various ex situ options to prepare the contaminated sediment for subsequent treatment and/or disposal options;
- Treatment of contaminated sediment – various in situ and ex situ options to reduce, remove and/or immobilise contaminants; and
- Disposal of contaminated sediment – various in situ and ex situ options to dispose, contain and manage contaminated sediment.

3.3 In Situ Intervention Options

The WP1B Report identifies the following six options that involve an intervention to the in situ contaminated sediment (see Table 2.1 of the WP1B Report for more details):

- Removal options – physical methods to remove the contaminated sediment from its in situ location prior to the implementation of ex situ options (see **Section 3.3** below):
  - Dredging – use of specialist dredging plant in wet conditions to physically remove contaminated sediment from the surrounding aquatic environment; and
  - Excavation – use of conventional land-based excavation plant in dry conditions to physically remove contaminated sediment from the surrounding aquatic environment.
- Treatment options:
  - Monitored natural recovery – use of naturally occurring processes to physically, chemically and/or biologically prevent and/or reduce contaminated sediment exposure to the surrounding aquatic environment;

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    - In situ immobilisation – use of thermal or chemical techniques to physically or chemically remove, reduce or change contaminated sediment exposure the surrounding aquatic environment; and
    - In situ electrochemical remediation technologies (ECRTs) – use of electrical currents passing between electrodes to destroy organic contaminants using an electrochemical geo-oxidation (ECGO) process and mobilise and remove metals using an induced complexation (IC) process.
- Disposal options – physical methods to contain the contaminated sediment in situ:
    - In-situ capping (i.e. contained aquatic disposal) – placement of clean material to physically cover (i.e. 'cap') and isolate contaminated sediment from the surrounding aquatic environment (also known as in-situ contained aquatic disposal).

3.4 Ex Situ Intervention Options

The WP1B Report identifies the following seven options that involve an intervention to the ex situ contaminated sediment following dredging or excavation (see Table 2.1 of the WP1B Report for more details):

- Ex situ disposal options - physical methods to contain the contaminated sediment ex situ:
    - Ex situ capping (i.e. contained aquatic disposal);
    - Confined aquatic disposal; and
    - Landfill disposal.
- Ex situ pre-treatment options:
    - Dewatering – use of various techniques to remove water from the contaminated sediment including natural dewatering in lagoons by evaporation and drainage, mechanical dewatering using filter and belt presses, and Geobag dewatering by filtering through geotextile materials; and
    - Soil washing – particle separation – use of mechanical agitation to separate finer contaminated sediment from coarser uncontaminated sediment and reduce the volume of contaminated sediment subject to further treatment.
- Ex situ treatment options:
    - Soil washing (scrubbing) – use of mechanical agitation with or without a washing solution (comprising water (typically) and chemical additives (possibly)) to scrub contaminants from sediment by physical abrasion and/or chemical dissolution;
    - Ex situ immobilisation – use of thermal or chemical techniques to physically or chemically remove, reduce or change contaminated sediment exposure the surrounding ex situ aquatic or land environment; and
    - Land farming – use of bioremediation techniques to cultivate and enhance microbial degradation of contaminants in sediment either passively (under natural conditions) or actively (under enhanced conditions, for example, by using supplementary oxygen).

4 Performance Criteria

4.1 Introduction

This section identifies the technical, environmental and socio-economic performance criteria against which the intervention options for contaminated sediment will be assessed, and identifies the performance scoring approach taken for each of the criteria.

The performance criteria have been selected on the basis that they need to be relevant and add value to the option assessment procedure by facilitating the measurement of the comparative performance of the intervention options. In addition, they need to be broad enough to cover the options assessment context (e.g. project objectives and site-specific influences) while remaining sufficiently mutually exclusive to avoid double-counting.

To ensure that the performance criteria have been selected on a sound basis for informing WP2B, they have been selected from the following two Defra projects concerning intervention options for contaminated sediment, namely:

- Research and Support for Developing a UK Strategy for Managing Contaminated Marine Sediments. Task 5: Establishing Best Practice for Current Disposal and Treatment Options for Contaminated Dredged Marine Sediments. Prepared by Partrac et al. for Defra, and cited in this report as Defra (2010); and
- Developing the Evidence Base on the Need for Action to Address In-situ Contaminated Sediment in England. Work Package 1B - Scoping and Appraising Potential Interventions for England, based on UK and International Experience. Prepared by Royal HaskoningDHV for Defra, and cited in this report as Defra (2015).

The performance criteria include the following technical, environmental and socio-economic criteria for contaminated sediment identified in Defra (2010) and Defra (2015), namely:

- Sediment type (i.e. clay, silt, sand), which has been extended over the Defra (2010) sediment types to include gravel (see **Section 4.2**);
- Contamination level (i.e. low or high contamination), which has been extended over the Defra (2010) contamination levels to include moderate contamination (see **Section 4.3**); and
- Contaminant type (i.e. organic contaminants and inorganic contaminants (i.e. metals)), which has been extended over the Defra (2010) contaminant types to include organo-metal contaminants (see **Section 4.4**).
- Environmental conditions (i.e. the physical, chemical and/or biological conditions that influence the effectiveness of executing the intervention option and the effectiveness of the intervention option) (see **Section 4.5**);
- Cost-effectiveness (i.e. i.e. the costs of intervention measured in relation to the effectiveness of intervention) (see **Section 4.6**); and
- Cost-benefit (i.e. i.e. the costs of intervention measured in relation to the effectiveness of intervention combined with the environmental, social and economic benefits and dis-benefits of intervention) (see **Section 4.7**).

The number of performance criteria has been kept low to make the options assessment procedure focussed on the principal technical, environmental and socio-economic factors influencing assessment and decision-making.

4.2 Performance Criterion 1 – Sediment Type

4.2.1 Definition of Criterion

This criterion considers the performance of intervention options in relation to the following sediment types based on particle sizes (see Table 2.2 of the WP1B Report for more details).

- Clay (consolidated), comprising particle sizes below 0.004mm but consolidated into stiff / cohesive lumps, typically derived from capital dredging, and typically containing low to no contamination levels;
- Silt (including soft clay), comprising particle sizes below 0.004mm (soft clay) to 0.063mm, typically derived from maintenance dredging or clean up dredging / excavation, and typically containing high to no contamination levels;
- Sand and gravel, comprising particle sizes 0.063mm to 2mm (sand) and 2mm to 64mm (gravel), typically derived from capital dredging or targeted extraction for aggregate, and typically low to no contamination levels; and
- Mixed sediment types, comprising mixtures of particle sizes potentially below 0.004mm up to 64mm, typically derived from capital dredging, and typically containing high to no contamination levels.

The sediment types include silt and soft clay (which is most likely to be contaminated and trigger the need for intervention), and consolidated clay, sand and gravel (which are less likely to be contaminated and trigger the need for intervention). While this criterion considers these sediment types individually, in reality it is likely that contaminated sediment will comprise more than one sediment type (e.g. silt and soft clay mixed with sand and gravel), although one sediment type may be dominant.

Sediment type is an important performance criterion because sediment's potential to concentrate contaminants is strongly influenced by its range of particle sizes. Silts and soft clays comprise finer particles with high surface area to mass ratios and tend to contain higher organic matter content and, therefore, provide more attachment sites to concentrate contaminants (compared to coarser particles in sands and gravels). Further information is provided in Section 5 of the WP1A Report.

Sediment can contain a mixture of sediment types and exhibit narrow to broad particle size distributions (i.e. one to no dominant sediment type, respectively). Different sediment types and mixtures can require different intervention options, so the sediment type can influence the availability and selection of options; particularly ex situ options that are likely to require some form of dewatering and/or soil washing involving particle separation prior to treatment and/or disposal.

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4.2.2 Performance Scoring of Criterion

The performance scoring for the contamination level criterion is derived from the reviewed evidence and expert judgement on the key issues, and is identified in **Table 4.1**.

Table 4.1 Performance Scoring for the Sediment Type Criterion

Sediment Type Suitability	Characteristics	Performance Score
Very high	Suitable for all three individual sediment types and all mixes of sediment types	+ + +
High	Suitable for two individual sediment types and some mixes of sediment types	+ +
Medium	Suitable for two individual sediment types and no mixes of sediment types	+
Low	Suitable for one individual sediment type and no mixes of sediment types	-

4.3 Performance Criterion 2 – Contamination Level

4.3.1 Definition of Criterion

This criterion will be used to assess the performance of intervention options in relation to different chemical contamination levels (see Table 2.2 of the WP1B Report (Defra, 2015) for more details).

Contamination levels can be related to various sediment quality criteria, such as the two chemical Action Levels (cALs) established by Cefas in 1995 (with changes proposed in 2003) as part of a weight of evidence approach to determining the acceptability of dredged material for disposal at sea. According to the MMO (2015), dredged materials with contaminants:

- Below cAL1 are generally considered acceptable for disposal at sea, pending other considerations such as physical suitability for the disposal site and potential beneficial uses; and
- Above cAL2 are considered unacceptable for uncontrolled disposal at sea without special handling and containment.

Using the cALs, this criterion considers the suitability of intervention options in relation to the following contaminant levels:

- High contamination level defined as chemical contaminant(s) present at concentration(s) greater than cAL2;
- Medium contamination level defined as chemical contaminant(s) present at concentration(s) less than cAL2 but above cAL1; and
- Low contamination level defined as chemical contaminant(s) present at concentration(s) less than cAL1.

Contaminated sediment rarely contains one chemical contaminant and one contaminant level. Rather, it typically contains a mixture of contaminants and contaminant levels that reflects (the largely historical legacy of) upstream contamination point sources (e.g. industrial and sewage waste effluents) and diffuse sources (e.g. agricultural and urban storm water run-off).

As set out in the WP1B Report (Defra, 2015), the suitability of intervention options depends on their relative ability to control or reduce the contamination levels by removal (e.g. dredging and excavation), isolation (e.g. capping), stabilisation (e.g. thermal and chemical immobilisation), management (e.g. natural recovery), and reduction (e.g. soil washing and ECRT). Different intervention options have different contaminant removal and reduction efficiencies. These efficiencies are not particularly sensitive for intervention options that involve physical processes; that is, removal interventions (i.e. dredging and excavation), pre-treatment interventions (i.e. dewatering and soil washing – particle separation) and disposal interventions (i.e. capping, confined aquatic disposal and landfill disposal), but are sensitive for intervention options that involve specific physical, chemical and biological treatment processes to destroy, degrade or immobilise the contaminants; that is, treatment interventions (i.e. monitored natural recovery, soil washing – scrubbing, immobilisation, electrochemical remediation and land farming) (Defra, 2010). Therefore, this criterion can be important for selection if, for example, an intervention is being sought to remove or reduce the contamination level to achieve a target level for sediment re-use or disposal.

4.3.2 Performance Scoring of Criterion

The performance scoring for the contamination level criterion is derived from the reviewed evidence and expert judgement on the key issues, and is identified in **Table 4.2**.

Table 4.2 Performance Scoring for the Contamination Level Criterion

Sediment Type Suitability	Characteristics	Performance Score
Very high	Very high treatment intervention efficiencies (>75% removal / reduction / isolation) Suitable for addressing high contamination levels >cAL2	+ + +
High	High treatment intervention efficiencies (50-75% removal / reduction / isolation) Suitable for addressing moderate contamination levels >cAL1 and <cAL2	+ +
Medium	Medium treatment intervention efficiencies (25-50% removal / reduction / isolation) Suitable for addressing low contamination levels <cAL1	+
Low	Low treatment intervention efficiencies (<25% removal / reduction / isolation) Unsuitable for addressing contamination levels <cAL1	-

4.4 Performance Criterion 3 – Contaminant Type

4.4.1 Definition of Criterion

This criterion considers the suitability of intervention options in relation to the following chemical contaminant types:

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- Organic contaminants such as mineral oil, mononuclear aromatic hydrocarbons (benzene and its derivatives), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) in the form of various congeners, and organochlorine pesticides (OCPs) in the form of various compounds including dichlorodiphenyltrichloroethane (DDT) and its derivatives and hexachlorocyclohexane (HCH) and its isomers;
- Inorganic contaminants (i.e. metals) such as arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc;
- Organo-metal contaminants such as tri-butyl-tin (TBT) and its derivatives; and
- Mixed organic, metal and/or organo-metal contaminant types.

These contaminants typically exhibit low solubility and partitioning, high environmental persistence, high bio-concentration factors, and high acute and/or chronic toxicity for human health and/or ecological receptors. Contaminated sediment rarely contains one chemical contaminant and occasionally contains one contaminant type. Rather, it typically contains a mixture of contaminants and contaminant types that reflects (the largely historical legacy of) upstream contamination point sources (e.g. industrial and sewage waste effluents) and diffuse sources (e.g. agricultural and urban storm water run-off).

As set out in Section 2.3 (Table 2.1) of the WP1B Report (Defra, 2015), the suitability of intervention options depends on the contaminant types found in the sediment. Different contaminants can require different intervention options, so the individual contaminant types (and particularly the mix of contaminant types) can influence the suitability and, therefore, the selection of options. This is particularly important for treatment options involving specific physical, chemical and biological processes to destroy, degrade or immobilise the contaminants, such as immobilisation, ECRTs and land farming. This criterion can be important for selection if, for example, a treatment intervention is being sought to remove / reduce particular contaminant types (e.g. organo-metals) of mixes of contaminant types (e.g. organics and metals).

4.4.2 Performance Scoring of Criterion

The performance scoring for the contaminant type criterion is derived from the reviewed evidence and expert judgement on the key issues, and is identified in **Table 4.3**.

Table 4.3 Performance Scoring for the Contaminant Type Criterion

Contaminant Type Suitability	Characteristic	Performance Score
Very high	Suitable for all three individual contaminant types and all mixes of contaminant types	+ + +
High	Suitable for two individual contaminant types and some mixes of contaminant types	+ +
Medium	Suitable for two individual contaminant types and no mixes of contaminant types	+
Low	Suitable for one individual contaminant type and no mixes of contaminant types	-

4.5 Performance Criterion 4 - Environmental Limitation

4.5.1 Definition of Criterion

This criterion will be used to assess the intervention options' relative performance in terms of the environmental conditions at the following in situ and ex situ locations:

- Rivers including all freshwater inland waterways (i.e. rivers and canals) and lakes containing the in situ contaminated sediment or offering an ex situ option for the contaminated sediment;
- Estuaries including all salt water / brackish transitional waters containing the in situ contaminated sediment or offering an ex situ option for the contaminated sediment;
- Seas including all salt water coastal and marine waters containing the in situ contaminated sediment or offering an ex situ option for the contaminated sediment; and
- Land, including all terrestrial areas adjacent to the in situ contaminated sediment and offering an ex situ option for the contaminated sediment (e.g. river banks, port estates), or distant from the contaminated sediment and offering an ex situ option for the contaminated sediment (e.g. treatment facilities and landfill sites).

As set out in Section 2.3 (Table 2.2) of the WP1B Report (Defra, 2015), the suitability of intervention options can be restricted by environmental conditions (particularly physical environmental conditions) such as the depth of navigable water required to undertake in situ dredging, the availability of material for in situ and ex situ capping, the maximum flow or current velocity acceptable before the material used for in situ or ex situ capping is eroded, the land available to undertake ex situ treatments, the accessibility of contaminated sediment from river banks, and the accessibility of power supplies to undertake interventions (e.g. in situ EGRTs).

4.5.2 Performance Scoring of Criterion

The performance scoring for the environmental conditions criterion is derived from the reviewed evidence and expert judgement on the key issues, and is identified in **Table 4.4**.

Table 4.4 Performance Scoring for the Environmental Condition Criterion

Environmental Condition	Characteristics	Performance Score
Low limitation	Unrestricted in situ contaminated sediment access from bank side or via fully navigable water Unrestricted ex situ river / estuary / sea bed availability, land availability, treatment facility availability or landfill site availability within acceptable proximity of in situ contaminated sediment	+ + +
Medium limitation	Partially restricted in situ access from bank side or via partially navigable water Partially restricted ex situ river / estuary / sea bed availability, land availability, treatment facility availability or landfill site availability within acceptable proximity of in situ contaminated sediment	+ +
High limitation	Significantly restricted in situ contaminated sediment access from bank side or via partially navigable water	+

Environmental Condition	Characteristics	Performance Score
	Significantly restricted ex situ river / estuary / sea bed availability, land availability, treatment facility availability or landfill site availability within acceptable proximity of in situ contaminated sediment	
Very high limitation	Fully restricted in situ contaminated sediment access from bank side or due to non-navigable water Fully restricted ex situ river / estuary / sea bed availability, land availability, treatment facility availability or landfill site availability within acceptable proximity of in situ contaminated sediment	-

4.6 Performance Criterion 5 – Cost-effectiveness

4.6.1 Definition of Criterion

This criterion will be used to assess the intervention options' relative performance in terms of the cost of in situ and ex situ interventions for removing and/or reducing contaminants

The cost scores are based on the cost ratings identified in Section 2.5 of the WP1B Report (Defra, 2015). The cost ratings are derived from the reviewed evidence and expert judgement on costs for reducing and/or removing contaminants, focusing on monetary estimates per m^3 of contaminated sediment where these are available, or monetary scales (i.e. totals) where monetary estimates are not available. Cost is scored from low to very high as follows:

- Low = <£1 to £10 per m^3 or <£500,000 in total;
- Medium = £11 to £30 per m^3 or between £500,000 and £1 million in total;
- High = >£30 per m^3 or between £1 million and £2 million in total; and
- Very high = >£100 per m^3 or >£2 million in total.

4.6.2 Performance Scoring of Criterion

The performance scoring for the cost criterion is identified in **Table 4.5**.

Table 4.5 Performance Scoring for Cost-effectiveness Criterion

Cost	Characteristics	Performance Score
Low	Cost of <£1 to £10 per m^3 or <£500,000 in total	+ + +
Medium	Cost £11 to £30 per m^3 or between £500,000 and £1 million in total	+ +
High	Cost of >£30 per m^3 or between £1 million and £2 million in total	+
Very high	Cost of >£100 per m^3 or >£2 million in total	-

4.7 Performance Criterion 6 – Environmental, Social and Economic Benefit

This criterion will be used to assess the intervention options relative performance in terms of the benefits of in situ and/or ex situ interventions for removing and/or reducing contaminants, taking account of other environmental, social and economic benefits (i.e. desirable effects, advantages).

The benefit scores are based on the benefit ratings identified in Section 2.5 of the WP1B Report (Defra, 2015). The benefit ratings are derived from the reviewed evidence and expert judgement on effectiveness and other benefits of reducing and/or removing contaminants including environmental, social and economic benefits (i.e. advantages; e.g. biodiversity benefits). Benefit is scored from low to very high as follows:

- Low = no sustainability + small economic + no / small environmental + no / small social, or just one medium others no / small benefit;
- Medium = some sustainability + medium economic, environmental and social effectiveness, or some sustainability + one small, one medium and one high economic, environmental and social benefit;
- High = some sustainability + at least two high economic, environmental and social benefit; and
- Very high = some sustainability + all high economic, environmental and social benefit.

4.7.1 Performance Scoring of Criterion

The performance scoring for cost-benefit criterion is identified in **Table 4.6**.

Table 4.6 Performance Scoring for Cost-benefit Criterion

Cost-benefit	Characteristics	Performance Score
Very high	Some sustainability + all high economic, environmental and social benefit	**+ + +**
High	Some sustainability + at least two high economic, environmental and social benefit	**+ +**
Medium	Some sustainability + medium economic, environmental and social effectiveness, or some sustainability + one small, one medium and one high economic, environmental and social benefit	**+**
Low	No sustainability + small economic + no / small environmental + no / small social, or just one medium others no / small benefit	**-**

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5 Performance Assessment

5.1 Introduction

This section presents the performance assessment of the various intervention options as a series of performance matrices (**Tables 5.1 to 5.5**).

Each performance matrix comprises:

- Rows corresponding to the in situ and ex situ intervention options identified in **Section 3**;
- Columns corresponding to the performance assessment criteria identified in **Section 4**; and
- Performance scores in the body of the matrix corresponding to the scoring system identified in **Tables 4.1 to 4.6, Section 4**) corresponding to an informed assessment of each options' performance against the criteria; and
- Supplementary comments in the body of the matrix providing notes (including referenced evidence) about generic and/or specific aspects of the performance scores.

5.2 Evidence Base

The evidence base (i.e. cited references) used to inform **Tables 5.1 to 5.5** is drawn from the WP1B Report (Defra, 2015) - including the references identified in Appendix A of WP1B Report – and the references identified in **Section 8**.

5.3 Performance Matrices

The following performance matrices are provided:

- Performance matrix of intervention options against the sediment type criterion (**Table 5.1**);
- Performance matrix of intervention options against the contaminant type criterion (**Table 5.2**);
- Performance matrix of intervention options against the contamination level criterion (**Table 5.3**);
- Performance matrix of intervention options against the environmental condition criterion (**Table 5.4**);
- Performance matrix of intervention options against the cost criterion (**Table 5.5**); and
- Performance matrix of intervention options against the benefit criterion (**Table 5.5**).

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Table 5.1 Performance Matrix of Intervention Options for the Sediment Type Criterion

Intervention option	Performance for different sediment types				
	Clay	Silt	Sand + gravel	Mixed	Performance comments
Dredging	+ +	+ +	+ + +	+ +	Dredging is potentially suitable for all sediment types, but specialist equipment may be required to dredge well-consolidated clay or prevent contaminant release from silt (including soft clay) and mixed sediment.
Excavation	+ +	+ + +	+ + +	+ +	Excavation is potentially suitable for all sediment types, but specialist equipment may be required to dredge well-consolidated clay or prevent contaminant release from silt (including soft clay) and mixed sediment.
In situ capping	+ + +	+ + +	+	+ + +	Capping is potentially suitable for all sediment types (assuming cap is designed to prevent unacceptable sediment migration), but alternative interventions may be better suited to sand and gravel to avoid the loss of a potentially valuable (commercial) resource.
In situ monitored natural recovery	+ + +	+ +	+ + +	+ +	Monitored natural recovery is potentially suitable for all sediment types depending on the process utilised (i.e. transformation, sequestration, isolation, etc.) (Defra, 2010; ESTCP, 2009). Compared to softer, finer sediment types (i.e. silt and soft clay), cohesive clay and coarser sand and gravel sediment types form more stable bed conditions and, therefore, are potentially more suitable for MNR at locations where there is a pose less risk of sediment erosion and contaminant migration due to adverse environmental conditions (USEPA, 2014).
In situ immobilisation:					Thermal immobilisation is potentially suitable for all sediment types, but particularly fine sediment types (Defra, 2010; Bortone et al, 2004; Detzner et al, 2007).
• Thermal	+ +	+ + +	+ +	+ +	Chemical immobilisation is potentially suitable for all sediment types except consolidated clays because the chemical additives cannot reach contaminants in the clay's structure beyond the boundary layer (Wise and Trantolo, 1994; Wuana and Okieimen, 2011).
• Chemical	-	+ + +	+ +	+ +	
In situ ECRT:					ECRT is most suitable to silt) than sand and gravel because reaction rates (i.e. remediation rates) are inversely proportional to particle size (Defra, 2010; Niroumand et al, 2012; Ferrarese and Andreottola, 2008). ECRT is also suitable for soft clay, but less suitable for consolidated clay with limited hydraulic flow (Niroumand et al, 2012).
• ECGO	+	+ + +	+	+ +	
• IC	+	+ + +	+	+ +	

Intervention option	Performance for different sediment types				
	Clay	Silt	Sand + gravel	Mixed	Performance comments
Ex situ dewatering:					Dewatering is potentially suitable for all silt and sand and gravel, but not consolidated clay due to low hydraulic flow rates, but mechanical dewatering offers higher dewatering rates.
• Natural	-	+ +	+ +	+ +	
• Mechanical	-	+ + +	+ + +	+ +	
• Geobag	-	+ +	+ +	+ +	
Ex situ capping	+ + +	+ + +	+	+ + +	Capping is potentially suitable for all sediment types (assuming the cap is designed to prevent unacceptable sediment migration), but alternative interventions may be better suited to sand and gravel to avoid the loss of a potentially valuable (commercial) resource.
Ex situ confined aquatic disposal	+ + +	+ + +	+	+ + +	Confined disposal is potentially suitable for all sediment types (assuming the CDF is designed to prevent unacceptable sediment migration), but alternative interventions may be better suited to sand and gravel to avoid the loss of a potentially valuable (commercial) resource.
Ex situ landfill	+ + +	+ + +	+	+ + +	Landfill is potentially suitable for all sediment types (assuming the landfill site is designed to prevent unacceptable sediment migration), but alternative interventions may be better suited to sand and gravel to avoid the loss of a potentially valuable (commercial) resource.
Ex situ soil washing					
• Particle separation	-	+	+	+ + +	Particle separation is particularly suitable for separating mixed sediment (rather than sediment dominated by one particle size) so that the coarser uncontaminated sand and gravel can be separated from finer contaminated silt (including soft clay). Particle separation is less suitable for well-consolidated clay because the particles cannot be sufficiently separated, and for clay and silt when present in high proportions (30-50%) because the volume reduction does not justify the cost (DEC, 2010; Pensaert et al, 2013; ITRC, 1997).
• Scrubbing	+	+ +	+ + +	+ +	Scrubbing is potentially suitable for all sediment types (assuming no prior particle separation to separate uncontaminated sand and gravel), but contaminant removal efficiencies are higher with coarser sediment types (Defra, 2010; Akcil et al, 2015) and lower if trying to dissolve contaminants from clay.
Ex situ immobilisation:					Thermal immobilisation is potentially suitable for all sediment types, but particularly fine sediment types (Defra, 2010; Bortone et al, 2004; Detzner et al, 2007).

Intervention option	Performance for different sediment types				
	Clay	Silt	Sand + gravel	Mixed	Performance comments
• Thermal • Chemical	+ + -	+ + + + + +	+ + + +	+ + + +	Chemical immobilisation is potentially suitable for all sediment types except consolidated clays because the chemical additives cannot reach contaminants in the clay's structure beyond the boundary layer (Wise and Trantolo, 1994; Wuana and Okieimen, 2011).
Ex situ land farming: • Passive • Active	 - -	 + + + +	 + + + + + +	 + + + +	Land farming is more effective for readily aerated and free draining sediments, so is more suitable to sediments with a low clay content (assuming no prior soil washing to separate uncontaminated coarser sand and/or gravel).

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Table 5.2 Performance Matrix of Intervention Options for the Contaminant Type Criterion

Intervention option	Performance for different contaminant types				
	Organics	Metals	Organo-metals	Mixed	Performance comment
Dredging	+ + +	+ + +	+ + +	+ + +	Dredging is potentially suitable for all contaminant types (assuming the dredging method is designed to prevent unacceptable contaminant migration pathways).
Excavation	+ + +	+ + +	+ + +	+ + +	Excavation is potentially suitable for all contaminant types (assuming the excavation method is designed to prevent unacceptable contaminant migration pathways).
In situ capping	+ + +	+ + +	+ + +	+ + +	Capping is potentially suitable for all contaminant types (assuming the cap is designed to prevent unacceptable contaminant migration pathways).
In situ monitored natural recovery	+ +	+	+ +	+ +	MNR is potentially suitable for all contaminant types (assuming MNR appropriately manages the source control of contaminants, but some recovery processes are reversible such as the chemical transformation of metals and the sorption and perception of all contaminant types (ESTCP, 2009).
In situ immobilisation: • Thermal • Chemical	 + + + + +	 + + + + + +	 + + + +	 + + + +	Thermal immobilisation is potentially suitable for all contaminant types as it destroys organic and organo-metal contaminant types and binds metals within the structure of the end-product (Defra, 2010). Chemical immobilisation is potentially suitable for most (forms of) metals and for some organics and mixed contaminant types containing metals and organics (Evanko and Dzombak, 1997), but potentially not suitable for organo-metals (Fergusson, 2014) and mixed contaminants types containing organo-metals.
In situ ECRT: • ECGO • IC	 + + + -	 - + + +	 + + -	 + +	ECRTs offer the only in situ methods for treating organic compounds and metals simultaneously, but different ECRTs are required for treating different contaminant types - ECGO for mineralising organic compounds to inorganic substances, and IC for mobilising and removing metals – which means doubling up on the in situ treatment infrastructure (e.g. electrode arrays, power supplies, etc.) and operation and maintenance activities (Defra, 2010; Harmsen et al, 2007).
Ex situ dewatering:					Dewatering is potentially suitable for all contaminant types (assuming the dewatering process is designed

Intervention option	Performance for different contaminant types				
	Organics	Metals	Organo-metals	Mixed	Performance comment
• Natural • Mechanical • Geobag	+ + + + + + + + +	+ + + + + + + + +	+ + + + + + + + +	+ + + + + + + + +	to meet environmental permits for the discharged effluent).
Ex situ capping	+ + +	+ + +	+ + +	+ + +	Capping is potentially suitable for all contaminant types (assuming the cap is designed to prevent unacceptable contaminant migration pathways).
Ex situ confined aquatic disposal	+ + +	+ + +	+ + +	+ + +	Confined disposal is potentially suitable for all contaminant types (assuming the CDF is designed to prevent unacceptable contaminant migration pathways).
Ex situ landfill	+ + +	+ + +	+ + +	+ + +	Landfill is potentially suitable for all contaminant types (assuming the landfill site is designed to prevent unacceptable contaminant migration pathways).
Ex situ soil washing: • Particle separation • Scrubbing	 + + + + +	 + + + + +	 + + + +	 + + + +	Soil washing – particle separation – is potentially suitable for all contaminant types as most organics, metals and organo-metals are associated with fine particles which can be separated from uncontaminated coarse particles. Soil washing – scrubbing – is potentially suitable for most organics and metals, but potentially less suitable for organo-metals and, therefore mixed contaminant types (CL:AIRE, 2007).
Ex situ immobilisation: • Thermal • Chemical	 + + + + +	 + + + + + +	 + + + + +	 + + + +	Thermal immobilisation is potentially suitable for all contaminant types as it destroys organic and organo-metal contaminant types and binds metals within the structure of the end-product (Defra, 2010). Chemical immobilisation is potentially suitable for most (forms of) metals and for some organics and mixed contaminant types containing metals and organics (Evanko and Dzombak, 1997), but potentially not suitable for organo-metals (Fergusson, 2014) and mixed contaminants types containing organo-metals.
Ex situ land farming • Passive	+ + + +	- +	- +	+ +	Passive land farming is only suitable for some organic contaminants so performance is potentially (significantly) constrained if certain organic contaminants present, and/or if metals and/or organo-metals present are present (Defra, 2010; Harmsen et al, 2007).

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Intervention option	Performance for different contaminant types				
	Organics	Metals	Organo-metals	Mixed	Performance comment
• Active					Active land farming is potentially suitable for some organic contaminants and/or metals and organo-metals if immobilising additives are introduced through active land farming (Defra, 2010; Harmsen et al, 2007).

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Table 5.3 Performance Matrix of Intervention Options for the Contamination Level Criterion

Intervention option	Performance for different contamination levels			
	Low	Medium	High	Performance comment
Dredging	+ + +	+ +	+ +	Dredging is potentially suitable for all contamination levels, but specialist equipment may be required to prevent contaminant release from sediment with medium and high contamination levels.
Excavation	+ + +	+ +	+ +	Excavation is potentially suitable for all contamination levels, but specialist equipment may be required to prevent contaminant release from sediment with medium and high contamination levels.
In situ capping	+ +	+ + +	+ + +	Capping is potentially suitable for all contamination levels (assuming the cap is designed to prevent unacceptable sediment migration), but alternative interventions may be better suited to sediment with low contamination levels (e.g. in terms of cost-effectiveness).
In situ monitored natural recovery	+ + +	+ +	+	MNR is potentially suitable for all contamination levels (assuming MNR appropriately manages the source control of contaminants), but its performance is increasingly uncertain and environmentally risky for sediment with medium and high contamination levels if physical, chemical and biological processes may not achieve intervention objectives within a reasonable time period (Wise and Trantolo, 1994).
In situ immobilisation:				Thermal and chemical immobilisation is potentially suitable for all contamination levels, but immobilisation efficiencies may not be sufficient for high contamination levels (e.g. in terms of achieving the required reduction) and low contamination levels (e.g. in terms of cost-effectiveness). Treatment efficiencies can depend on the immobilisation method used and contaminant type(s) requiring treatment; for example, bench tests of TBT removal efficiencies have been recorded up to 43% for chemical immobilisation, up to 99% for thermo-chemical immobilisation, and greater than 99% for thermal immobilisation (Fergusson, 2014).
• Thermal	+ +	+ +	+	
• Chemical	+ +	+ +	+	
In situ ECRT:				ECRTs are potentially suitable for all contamination levels, but removal efficiencies may not be sufficient for high contamination levels (in terms of achieving the required reduction) and low contamination levels (e.g. in terms of cost-effectiveness). Treatment efficiencies can depend on the ECRT method used in relation to the contaminants present; for example, bench tests of organic contaminant removal have recorded up to 90% for PAH, 45-55% for TOC and 70-85% for TPH (Ferrarese and Andreottola, 2008). ECRT methods have remediate various contaminants to levels to below regulatory standards including VOCs, CVOCs, SVOCs, PAHs, PCBs, phenols, fuels, hydrocarbons, explosives, mercury, cadmium and lead (Niroumand et al, 2012).
• ECGO	+ +	+ +	+	
• IC	+ +	+ +	+	
Ex situ dewatering:				Dewatering is potentially suitable for all contamination levels (assuming the dewatering process is designed to meet environmental permits for the discharged effluent), but alternative interventions may be better suited to

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Intervention option	Performance for different contamination levels			
	Low	Medium	High	Performance comment
• Natural • Mechanical • Geobag	+ + + + + +	+ + + + + + + + +	+ + + + + + + + +	sediment with low contamination levels (e.g. in terms of cost-effectiveness).
Ex situ capping	+ +	+ + +	+ + +	Capping is potentially suitable for all contamination levels (assuming the cap is designed to prevent unacceptable sediment migration), but alternative interventions may be better suited to sediment with low contamination levels (e.g. in terms of cost-effectiveness).
Ex situ confined aquatic disposal	+ +	+ + +	+ + +	Confined aquatic disposal is potentially suitable for all contamination levels (assuming the CDF is designed to prevent unacceptable sediment migration), but alternative interventions may be better suited to sediment with low contamination levels (e.g. in terms of cost-effectiveness).
Ex situ landfill	+ +	+ + +	+ + +	Landfill is potentially suitable for all contamination levels (assuming the landfill site is designed to prevent unacceptable contaminant migration pathways), but alternative interventions may be better suited to sediment with low contamination levels (e.g. in terms of cost-effectiveness).
Ex situ soil washing: • Particle separation • Scrubbing	 + + + +	 + + + + +	 + + + + +	Particle separation is potentially suitable for all contamination levels. Scrubbing is potentially suitable for all contamination levels, but removal efficiencies may not be sufficient for high contamination levels (e.g. in terms of achieving the required reduction), but "general removal efficiencies for a range of contaminants in fine sediments are in the range 60 to 80%" (Defra, 2010). Treatment efficiencies for different contaminants have been recorded as follows: 47-95% for TPH, 76-98% for PAH, 70-96% for metals (CL:AIRE, 2007).
Ex situ immobilisation: • Thermal • Chemical	 + + + +	 + + + +	 + +	Thermal and chemical immobilisation is potentially suitable for all contamination levels, but immobilisation efficiencies may not be sufficient for high contamination levels (in terms of achieving the required reduction) and low contamination levels (e.g. in terms of cost-effectiveness). Treatment efficiencies can depend on the ECRT method used and contaminant type(s) requiring treatment; for example, bench tests of TBT removal efficiencies have been recorded up to 43% for chemical immobilisation, up to 99% for thermo-chemical immobilisation, and greater than 99% for thermal immobilisation (Fergusson, 2014).
Ex situ land farming: • Passive	 + / + +	 + / + +	 +	Land farming does not differentiate between contamination levels, but bioremediation efficiencies may not be sufficient for high contamination levels (e.g. in terms of achieving the required reduction) subject to the time available (passive land farming) and supplementary action (active land farming). Treatment efficiencies can be

Intervention option	Performance for different contamination levels			
	Low	Medium	High	Performance comment
• Active	**+ / + +**	**+ / + +**	**+**	influenced significantly by the availability of the contaminants; for example, in relation to active land farming “readily available PAHs are reported to be biodegraded between one and three years but less available PAHs can take between three and six years to be degraded by 50%” (Defra, 2010).

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Table 5.4 Performance Matrix of Intervention Options for the Environmental Conditions Criterion

Option	Performance for different environmental conditions				
	River	Estuary	Sea	Land	Performance comment
Dredging	+ +	+ +	+ + +	-	Dredging is potentially suitable for all water areas (but not land), but performance may be constrained by water depth and flows in rivers (e.g. due to low flows or seasonal flows) and, to a lesser extent, in estuaries (e.g. due to tides).
Excavation	+ +	+	+	-	Excavation is potentially suitable for all water areas (but not land), but performance may be constrained by limited access and reach of land-based excavation plant, particularly in estuaries and seas.
In situ capping	+	+ +	+ +	-	Capping is potentially suitable for all water areas (but not land) (assuming the cap is designed to tolerate environmental conditions), but performance may be constrained by site availability (e.g. space on the bed, depressions in the bed), particularly in rivers.
In situ monitored natural recovery	+	+	+	-	MNR is potentially suitable for all water areas (but not land), but performance may be constrained significantly by uncertainties about environmental conditions affecting (the control of) contaminants dependant on physical isolation (e.g. sediment erosion and/or deposition, contaminant migration) over the long time frames associated with this intervention option (ESTCP, 2009).
In situ immobilisation:					Performance potentially (significantly) constrained by physical environmental conditions hindering application and mixing of additives, chemical environmental conditions hindering immobilisation of contaminants, and physical environmental conditions causing erosion of immobilised sediments. Performance is more effective in low flow conditions (Defra, 2010).
• Thermal	+ +	+ +	+ +	-	
• Chemical	+ +	+ +	+ +	-	
In situ ECRT:					Performance potentially (significantly) constrained for application in larger areas (particularly in open estuaries and seas) by accessibility of power supply, small-scale of proven technological effectiveness and regular operation and maintenance inspection requirements, and potentially (significantly) constrained in in proximity to structures with cathodic protection systems that are vulnerable to corrosion during the operation of the electrochemical remediation system. Performance potentially significantly) constrained for large-scale application as there is limited evidence of effective ECRT for metals in saline reduced environments (Altaee et al, 2008) and variable results for ECRT for various contaminants in freshwater and saline environments (Defra, 2010).
• ECGO	+ +	+ +	+	-	
• IC	+ +	+ +	+	-	
Ex situ dewatering:					Natural, mechanical and Geobag dewatering are potentially suitable for land (but not water areas), but

Option	Performance for different environmental conditions				
	River	Estuary	Sea	Land	Performance comment
• Natural • Mechanical • Geobag	- - -	- - -	- - -	+ + + + + +	the performance of natural dewatering and, to a lesser extent, Geobag dewatering may be constrained by availability of sufficient land area within acceptable proximity of in situ contaminated sediment.
Ex situ capping	+	+ +	+ +	-	Capping is potentially suitable for all water areas (but not land) (assuming the cap is designed to tolerate environmental conditions), but performance may be constrained by site availability (e.g. space on the bed, depressions in the bed), particularly in rivers.
Ex situ confined aquatic disposal	+	+ +	+ +	-	Confined aquatic disposal is potentially suitable for all water areas (but not land) (assuming the CDF is designed to tolerate environmental conditions), but performance may be constrained by site availability (e.g. space on the bed, depressions in the bed), particularly in rivers.
Ex situ landfill	-	-	-	+	Landfill is potentially suitable for land (but not water areas), but performance may be constrained significantly by landfill volume available and rate at which contaminated sediment can be received, which means landfill may only be suitable for relatively small volumes of contaminated sediment.
Ex situ soil washing: • Particle separation • Scrubbing	 - -	 - -	 - -	 + + + +	Particle separation and scrubbing are potentially suitable for land (but not water areas), but performance may be constrained by availability of sufficient land area within acceptable proximity of in situ contaminated sediment.
Ex situ immobilisation: • Thermal • Chemical	 - -	 - -	 - -	 + + + +	Thermal immobilisation and chemical immobilisation are potentially suitable for land (but not water areas), but performance may be constrained by availability of sufficient land area within acceptable proximity of in situ contaminated sediment.
Ex situ land farming • Passive • Active	 - -	 - -	 - -	 + +	Passive land farming and active land farming are potentially suitable for land (but not water areas), but performance may be constrained significantly by availability of sufficient large land area within acceptable proximity of in situ contaminated sediment and over long time periods.

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Table 5.5 Performance Matrix of Intervention Options for the Cost and Benefit Criteria

Intervention option	Performance for cost and benefit		
	Cost	Benefit	Performance comment
Dredging	+ +	+	Medium dredging costs (£3-14 per m^3) depending on a number of variables including the need for specialist dredging equipment (Greenpeace, 2010). Low benefits largely associated with removing contaminants leading to reduced human health and ecology risks (National Academy of Sciences, 2007; USEPA, 2003).
Excavation	+ +	+	Medium excavation costs (£5-47 per m^3, predominantly £7-12 per m^3) (BRGM (2010). Low benefits largely associated with removing contaminants leading to reduced human health and ecology risks (National Academy of Sciences, 2007; USEPA, 2003).
In situ capping	+ +	+	High in situ capping costs (£39 per m^3) based on open sea capping without monitoring costs (Apitz and Black, 2010). Low benefits largely associated with avoiding transport and energy consumption and reducing contaminant exposure pathways (Apitz and Black, 2010; Defra, 2010; National Academy of Sciences, 2007).
In situ monitored natural recovery	+ + / +	+	Medium to high MNR costs (£11-62 per m^3, predominantly £19-24 per m^3) (Bureau de Recherches Geologique RGM (2010). Low benefits largely associated with relatively non-invasive and undisruptive intervention approach minimising impacts on biological communities (USEPA, 2005).
In situ immobilisation: • Thermal • Chemical	 + +	 + + / + + + + + / + + +	High in situ immobilisation costs (£52-87 per m^3) (Apitz and Black, 2010) for chemical immobilisation. The score for chemical immobilisation has been used to represent thermal immobilisation, but it is recommended that caution be applied. High to very high benefits largely associated with reduced contaminant mobility / bioavailability and undisruptive intervention approach minimising impacts on biological communities (Apitz and Black, 2010; Defra, 2010; Ghosh, 2012).
In situ ECRT: • ECGO • IC	 - -	 - -	High ECRT costs (not defined) (Defra, 2010) for ECRT has been used to represent both ECGO and IC, but it is recommended that caution be applied. Low benefits largely associated with potential to simultaneously treat organic and inorganic contaminants (Niroumand et al, 2012).
Ex situ dewatering:			Medium to high dewatering costs for natural dewatering (£8-21 per m^3) and mechanical dewatering (£8-26 per m3) (Apitz and Black, 2010). The score for mechanical dewatering has been used to represent Geobag dewatering, but it is recommended

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Intervention option	Performance for cost and benefit		
	Cost	Benefit	Performance comment
• Natural • Mechanical • Geobag	+ + / + + + + +	+ + + + + +	that caution be applied. High benefits largely associated with reduced volumes for further intervention, low energy consumption and emissions, and potential re-use options for resulting material (Apitz and Black, 2010; Defra, 2010).
Ex situ capping	+ +	+	Medium ex situ capping costs (£5-31 per m^3). Medium benefits largely associated with low transport and energy consumption and reducing contaminant exposure pathways (Apitz and Black, 2010; Defra, 2010).
Ex situ confined aquatic disposal	+ + / +	+	Medium to high ex situ CDF costs (£9-60 per m^3) (Greenpeace, 2010; Apitz and Black, 2010), with cost range depending on the cost for building a new CDF (if required) and variable storage costs. Medium benefits largely associated with low environmental risk and potential use of wider CDF area for recreation and/or nature conservation (Apitz and Black, 2010; Defra, 2010; Sheldrake, 2011).
Ex situ landfill	+	-	High landfill costs and high variability of landfill costs (£2-480 per m^3) (Apitz and Black, 2010). Low benefits largely associated with low environmental risk (Apitz and Black, 2010; Defra, 2010).
Ex situ soil washing: • Particle separation • Scrubbing	 + + +	 + + + +	High soil washing costs (£35 per m^3) (DEC, 2013) for scrubbing. Costs for scrubbing increase with additional, incremental effort required (e.g. additives used) to address multiple contaminant types and high contamination levels[15]. Due to the significant differences between scrubbing and particle separation, the score for scrubbing has not been used to represent particle separation. Instead, an alternative score has been suggested for particle separation, but it is recommended that caution be applied. High benefits largely associated with reduced volumes for further intervention and reduced transport and energy consumption, and potential creation of re-usable clean sediment (DEC, 2010; DEC, 2011).
Ex situ immobilisation: • Thermal • Chemical	 + +	 + + + +	High ex situ immobilisation costs for chemical immobilisation (c. £24 per m^3) and thermal immobilisation (c. £33 per m^3) (Greenpeace, 2010). High benefits largely associated with potential creation of re-usable by-products (also avoiding waste disposal) and reduced

Intervention option	Performance for cost and benefit		
	Cost	Benefit	Performance comment
			contaminant mobility / bioavailability (Apitz and Black, 2010; Defra, 2010; Smith et al, 2009).
Ex situ land farming • Passive • Active	 + / + + + / + +	 + +	Medium to high land farming costs (£35 per m^3) (DEC, 2013). The score for land farming has been used to represent both passive and active land farming, but it is recommended that caution be applied. Medium benefits largely associated with potential creation of re-usable biomass (also avoiding waste disposal).

6 Options Selection Tool

6.1 Introduction

This section describes the proposed two-staged process for selecting intervention options, taking into account the influences associated with particular contaminated sediment scenarios (e.g. maintenance dredging in an operational port).

The two-staged process comprises:

- Stage 1 - selecting one or more of the potentially suitable intervention chains to be taken forward into Stage 2 by excluding those intervention chains that are not suitable for achieving the objectives of a particular contaminated sediment scenario.
- Stage 2 - selecting one or more of the potentially suitable intervention options by using the performance matrices to short-list the most suitable intervention options for achieving the objectives of a particular contaminated sediment scenario.

6.2 Stage 1 – Selection of Potentially Suitable Intervention Chains

6.2.1 Context

The initial selection of potential intervention chains takes account of two key influences associated with a particular contaminated sediment decision-making scenario. These influences may be sufficiently strong that they affect the selection of potential intervention chains by necessitating or excluding the selection based on the options' intervention roles (see **Section 3.2** and **Table 6.1**).

Table 6.1 Intervention Roles

Intervention Roles	Corresponding Intervention Options
In situ removal	Dredging and excavation
In situ treatment	MNR, immobilisation and ECRT
In situ disposal	Capping
Ex situ pre-treatment	Dewatering and soil washing (particle separation)
Ex situ treatment	Soil washing (scrubbing), immobilisation and land farming
Ex situ disposal	Capping, confined aquatic disposal and landfill

The following influences are potentially critical for the Stage 1 selection of intervention chains based on intervention roles:

- The need (or choice) to remove the contaminated sediment (from an in situ to ex situ location); and
- The need (or choice) to pre-treat and/or treat the contaminated sediment (in an in situ or an ex situ location) to remove and/or reduce contaminants such that some or all of the resulting

sediment is sufficiently remediated or is suitable for re-using, recycling or recovering, in order to avoid and/or reduce the volume of sediment for disposal.

6.2.2 Influence of a Removal Intervention

Contaminated sediment may need to be removed from an in situ location for a variety of reasons. These reasons may or may not relate to contamination, but may necessitate a removal intervention because the contaminated sediment presents an unacceptable environmental risk (e.g. pollution effect), an unacceptable health and safety risk (e.g. toxicological effect), or an unacceptable navigational risk (e.g. vessel grounding).

Stage 1 option selection should take the removal intervention requirement into account as it will have a significant influence on the potentially suitable options to take forward into stage 2.

If a removal intervention is not required, then all non-removal in situ and ex situ intervention options are potentially available for taking forward into stage 2. While this situation may result in the selection of just one in situ treatment or disposal option, it may also result in the selection of a chain of intervention options (e.g. an in situ removal option, potentially followed an ex situ pre-treatment option, potentially followed by an ex situ treatment option, potentially followed by an ex situ disposal option), depending on the relative performance of these options (see **Table 6.2**).

If removal intervention is required, then an in situ intervention option and all ex situ options are potentially available for taking forward into stage 2. This situation may result in the selection of a chain of intervention options. The chain would start an in situ removal option to relocate the contaminated sediment from an in situ to an ex situ location, followed by one or more ex situ pre-treatment, treatment and/or disposal options, depending on the relative performance of these options (see **Table 6.2**).

6.2.3 Influence of a Disposal Intervention

Contaminated sediment may need to be wholly or partially pre-treated and/or treated to avoid and/or reduce the need for in situ and/or ex situ disposal for a variety of reasons. These reasons may or may not relate to contamination, and may require pre-treatment and/or treatment in order to comply with environmental regulations and principles, such as waste management requirements incorporating the concept of Best Practicable Environmental Option (BPEO) and the hierarchy of waste management options. In some cases, it may be practicable to sufficiently pre-treat and/or treat contaminated sediment such that all of it can be re-used, recycled and/or recovered and, therefore, none of it needs to be disposed of.

Stage 1 option selection should take the disposal intervention into account as it will have a significant influence on the intervention options to take forward into stage 2.

If a disposal intervention is available, then all in situ and ex situ disposal options are potentially available for taking forward into stage 2. While this situation may result in the selection of just one in situ disposal option, it may also result in the selection of a chain of intervention options (e.g. an in situ removal option, potentially followed an ex situ pre-treatment option, potentially followed by an ex situ treatment option, potentially followed by an ex situ disposal option), depending on the relative performance of these options (see **Table 6.2**).

If disposal is to be avoided or reduced, this situation may result in the selection of just one in situ treatment option, but may also result in the selection of a chain of intervention options (e.g. an in situ removal option, potentially by followed an ex situ pre-treatment option, potentially followed by an ex situ treatment option), depending on the relative performance of these options (see **Table 6.2**).

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Table 6.2 Stage 1 Potential Intervention Chains

Chain Reference	Initial Intervention	Subsequent Intervention	Subsequent Intervention	Subsequent Intervention
1	In situ treatment by MNR, immobilisation or ECRT			
2	In situ disposal by capping			
3	In situ removal by dredging or excavation	Ex situ pre-treatment by dewatering or soil washing – particle separation	Ex situ treatment by soil washing – scrubbing, immobilisation or land farming	Ex situ disposal by landfill
4	In situ removal by dredging or excavation	Ex situ pre-treatment by dewatering or soil washing – particle separation	Ex situ treatment by soil washing – scrubbing, immobilisation or land farming	(Ex situ disposal not required – all sediment can be re-used, recovered and/or recycled)
5	In situ removal by dredging or excavation	Ex situ pre-treatment by dewatering or soil washing – particle separation	Ex situ disposal by landfill	
6	In situ removal by dredging or excavation	Ex situ pre-treatment by dewatering or soil washing – particle separation	(Ex situ disposal not required – all sediment can be re-used, recovered and/or recycled)	
7	In situ removal by dredging or excavation	Ex situ treatment by soil washing – scrubbing, immobilisation or land farming	Ex situ disposal by landfill	
8	In situ removal by dredging or excavation	Ex situ treatment by soil washing – scrubbing, immobilisation or land farming	(Ex situ disposal not required – all sediment can be re-used, recovered and/or recycled)	
9	In situ removal by dredging or excavation	Ex situ disposal by capping or confined aquatic disposal		

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6.2.4 Selection Outcome

The outcome of stage 1 should be the selection of a range potentially suitable intervention chains (i.e. series of options) to be taken forward into stage 2. **Table 6.2** identifies nine potential intervention chains available for selection at the outset of stage 1.

UK experience relating to contaminated sediment indicates that some intervention chains are more likely to be selected over other intervention chains because of the relative state of the UK's knowledge and/or availability of equipment under each of the intervention roles, as summarised below.

In terms of the in situ removal intervention options:

- Dredging is well-established and various standard and specialist equipment is available in the UK, so this option is likely to feature in selected intervention chains where removal is required / chosen; and
- Excavation is well-established and various standard and specialist equipment is available in the UK, so this option is likely to feature in selected intervention chains where removal is required / chosen.

In terms of the in situ treatment intervention options:

- MNR – is not well-established and there is limited experience in the UK, so this option is less likely to feature in selected intervention chains where this particular type of treatment is suitable;
- Immobilisation – thermal immobilisation is fairly well-established and limited equipment is available in the UK, so this option may feature in selected intervention chains where this particular type of treatment is suitable;
- Immobilisation – chemical immobilisation is well-established and equipment is available in the UK, so this option is likely feature in selected intervention chains where this particular type of treatment is suitable;
- ECRT – ECGO is fairly well-established and equipment is available in the UK, so this option may feature in selected intervention chains where this particular type of treatment is suitable; and
- ECRT – IC is fairly well-established and equipment is available in the UK, so this option may feature in selected intervention chains where this particular type of treatment is suitable.

In terms of the in situ disposal intervention options:

- There has been only one trial of ex situ capping in the UK (Defra, 2015), so this option is less likely to feature in selected intervention chains.

In terms of the ex situ pre-treatment intervention options:

- Dewatering is well-established and equipment is available in the UK, particularly for mechanical dewatering which requires less space, so this option is likely to feature in selected intervention chains where this particular type of pre-treatment is suitable; and
- Soil washing – particle separation is well-established and equipment is available in the UK, so this option is likely to feature in selected intervention chains where this particular type of pre-treatment is suitable.

In terms of the ex situ treatment intervention options:

- Soil washing – scrubbing is well-established and equipment is available in the UK, so this option may feature in selected intervention chains where this particular type of treatment is suitable;

- Immobilisation – thermal immobilisation is fairly well-established and limited equipment is available in the UK, so this option may feature in selected intervention chains where this particular type of treatment is suitable;
- Immobilisation – chemical immobilisation is well-established and equipment is available in the UK, so this option is likely feature in selected intervention chains where this particular type of treatment is suitable;
- Land farming – passive is fairly well-established in the UK, so this option may feature in selected intervention chains where this particular type of treatment is suitable and sufficient land is available; and
- Land farming – active is fairly well-established in the UK, so this option may feature in selected intervention chains where this particular type of treatment is suitable and sufficient land is available.

In terms of the ex situ disposal intervention options:

- There are no contained aquatic disposal (e.g. CDF) sites in the UK, so this option is less likely to feature in selected intervention chains where disposal is required;
- There has been only one trial of ex situ capping in the UK, so this option is less likely to feature in selected intervention chains where disposal is required; and
- There are many landfill sites across the UK that are set up to receive a variety of wastes but they can only receive certain types and quantities of waste at certain rates, so this option may feature in selected intervention chains for the disposal of relatively small volumes of contaminated sediment (i.e. 1000m^3 to 10,000m^3), particularly sediment that has been subject to pre-treatment (notably dewatering) and, potentially, treatment. There are two examples of landfill sites in the UK that were silt lagoons dedicated to receiving dredged material from the Port of London and the Manchester Ship Canal, but this option is less likely feature in selected intervention chains unless a significant financial investment is required for the disposal of regular removals of relatively large volumes of contaminated sediment (i.e. 10,000m^3 to 100,000m^3) from one location.

Based on previous UK experience of managing contaminated sediment, the potential intervention chains are likely to involve one or more of the following interventions:

- In situ removal by either dredging or excavation;
- Ex situ pre-treatment involving either dewatering and/or soil washing using particle separation;
- Ex situ treatment involving either soil washing using scrubbing or immobilisation; and
- Ex situ disposal involving landfill, unless pre-treatment and/or treatment options generate re-use, recycling and/or recovery options that offset the need for disposal.

6.3 Stage 2 – Selection of Most Suitable Options

6.3.1 Context

The subsequent selection of the most suitable intervention chains takes account the key influences associated with the performance criteria. These influences may be sufficiently strong that they affect the selection of the most suitable intervention chains by necessitating or excluding the selection based on the options' performance assessments (see **Tables 5.1 to 5.5**).

Some interventions perform equally or similarly in relation to the various performance criteria. However, other interventions perform very differently. The following influences are potentially critical for the Stage 2 selection of intervention chains based:

- The contaminated sediment characteristics – notably the distribution of different contaminant types across different sediment types (i.e. particles); and
- The remediation objectives – notably the remediation limit for the residual contaminated sediment to be disposed of and/or the by-products to be re-used, recycled and/or recovered.

6.3.2 Influence of Contaminated Sediment

The characteristics of particular contaminated sediment scenario relate to the distribution of different contaminant types (i.e. organics, metals, organo-metals) across different particles (i.e. clay, silt, sand, and gravel, and other constituents such as organic matter). These characteristics can influence the choice of pre-treatment and/or treatment options (including specific processes within those options); for example:

- Soil washing using particle separation is much more suitable for separating mixed sediment (particularly mixed sediments with silt content below 40%) - rather than sediment dominated by one particle size - so that the coarser uncontaminated sediment can be separated from finer contaminated sediment; and
- ECRT using ECGO is more suitable for organic contaminants, while ECRT using IC is more suitable for metal contaminants, but neither is particularly suitable for mixed contaminants.

As a starting point, the performance matrices identify the assessments for the different sediment types (**Table 5.1**) and contaminant types (**Table 5.2**), and a basic comparison table can be generated for the ex situ pre-treatment and treatment options (see **Table 6.3**).

6.3.3 Influence of Remediation Objectives

The remediation objectives of a particular contaminated sediment scenario relate to the end-points of the intervention and the distribution of the sediment across ex situ disposal options and/or (albeit beyond the scope of intervention options) re-use, recycling or recovery end-points. These objectives can influence the choice of pre-treatment and/or treatment options (including specific processes within those options); for example:

- Various ex situ treatment options may not be able to meet the required remediation objective (e.g. contaminant removal / reduction target in a significant proportion of the contaminated sediment to justify their selection.

As a starting point, the performance matrices identify the assessments for the different contamination levels (**Table 5.3**), and a basic comparison table can be generated for the ex situ pre-treatment and treatment options (see **Table 6.3**).

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Table 6.3 Comparative Performance Matrix of Most Suitable Ex Situ Pre-treatment and Treatment Intervention Options

	Sediment type				Contaminant type				Contamination level		
Intervention option	**Clay**	**Silt**	**Sand + gravel**	**Mixed**	**Organics**	**Metals**	**Organo-metals**	**Mixed**	**Low**	**Medium**	**High**
Ex situ dewatering:											
• Natural	-	+ +	+ +	+ +	+ + +	+ + +	+ + +	+ + +	+ + +	+ + +	+ + +
• Mechanical	-	+ + +	+ + +	+ +	+ + +	+ + +	+ + +	+ + +	+ + +	+ + +	+ + +
• Geobag	-	+ +	+ +	+ +	+ + +	+ + +	+ + +	+ + +	+ + +	+ + +	+ + +
Ex situ soil washing											
• Particle separation	-	+	+	+ + +	+ + +	+ + +	+ + +	+ + +	+ +	+ + +	+ + +
• Scrubbing	+	+ +	+ + +	+ +	+ +	+ +	+	+	+ +	+ + +	+ +
Ex situ immobilisation:											
• Thermal	+ +	+ + +	+ +	+ +	+ + +	+ + +	+ + +	+ +	+ +	+ + +	+ +
• Chemical	-	+ + +	+ +	+ +	+ +	+ + +	+ +	+ +	+ +	+ + +	+ +
Ex situ land farming:											
• Passive	-	+ +	+ + +	+ +	+ +	-	-	+	+ + +	+ +	+
• Active	-	+ +	+ + +	+ +	+ +	+	+	+	+ + +	+ + +	+ +

6.3.4 Selection Outcome

The outcome of stage 2 should be the selection of a range the most suitable intervention chains (i.e. series of options) to be taken forward into decision-making.

Based on previous UK experience of managing contaminated sediment, the most likely intervention chains are likely to involve one or more of the following interventions:

- In situ removal by dredging (particularly for river, estuary and sea environments);
- In situ removal by excavation (particularly for river environments);
- Ex situ pre-treatment by dewatering (particularly mechanical dewatering due to lower land requirement of this equipment and due to the higher dewatering efficiencies that can be gained by using filter and belt presses);
- Ex situ pre-treatment by soil washing using particle separation (particularly for mixed sediment where the fine sediment content is below 40 per cent and expected to be contaminated, and the residual coarse sediment is expected to be uncontaminated);
- Ex situ treatment by soil washing using scrubbing (particularly if integrated with soil washing using particle separation due to equipment and/or process integration);
- Ex situ treatment by thermal immobilisation (particularly for fine sediment comprising a mix of contaminant types, with a focus on the remediation of organics, and assuming the availability of equipment);
- Ex situ treatment by chemical immobilisation (particularly for fine sediment comprising a mix of contaminant types, with a focus on the stabilisation of metals); and
- Ex situ disposal involving landfill (particularly for relatively small volumes of dewatered contaminated sediment).

However, it is important to note that the most suitable intervention chains are likely to include ex situ pre-treatment and/or treatment options that generate re-use, recycling and/or recovery options for the contaminated sediment in order to offset the need for disposal.

7 Conclusions

7.1 Short List of Intervention Options

WP2B has presented a stepped options assessment procedure that uses performance matrices to compare the various in situ and ex situ removal, pre-treatment, treatment and disposal interventions with a range of technical, financial and environmental, social and economic performance criteria.

The stepped options assessment procedure also uses a two-staged options selection tool to select suitable interventions for formulated contaminated sediment problems. The options selection tool takes into account the need (or choice) of certain removal and/or disposal interventions and the influence of the contaminated sediment characteristics and remediation objectives on pre-treatment and treatment interventions.

On the basis of the above, WP2B has identified a short-list of the (chains of) intervention options that are considered to be most likely to arise under real-world situations (see **Figure 7.1**). All options include the initial need for a removal intervention (i.e. dredging or excavation). The short-list of most likely intervention options comprises:

- Ex situ pre-treatment (dewatering) and landfill;
- Ex situ pre-treatment (dewatering and soil washing using particle separation), landfill and re-use, etc.;
- Ex situ pre-treatment (dewatering), full treatment (chemical immobilisation), disposal and re-use, etc.;
- Ex situ pre-treatment (dewatering and soil washing using particle separation), partial treatment (thermal immobilisation) and full re-use, etc.; and
- Ex situ pre-treatment (dewatering and soil washing using particle separation), partial treatment (soil washing using scrubbing) and full re-use, etc.

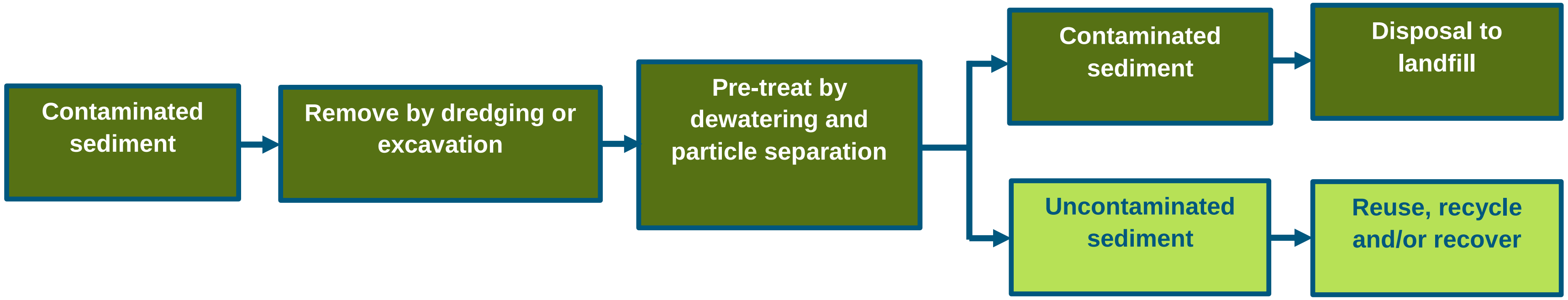
7.2 Next Steps

The outputs of WP2b will feed into the deliverables of Work Package 5a. This will present recommendations for further research and guidance to be developed. The short list of intervention options will feed into a high-level framework for actions at specified locations (as identified in Work Package 4a) to produce a high-level set of recommendations for further investigation (and potential treatment options following investigation).

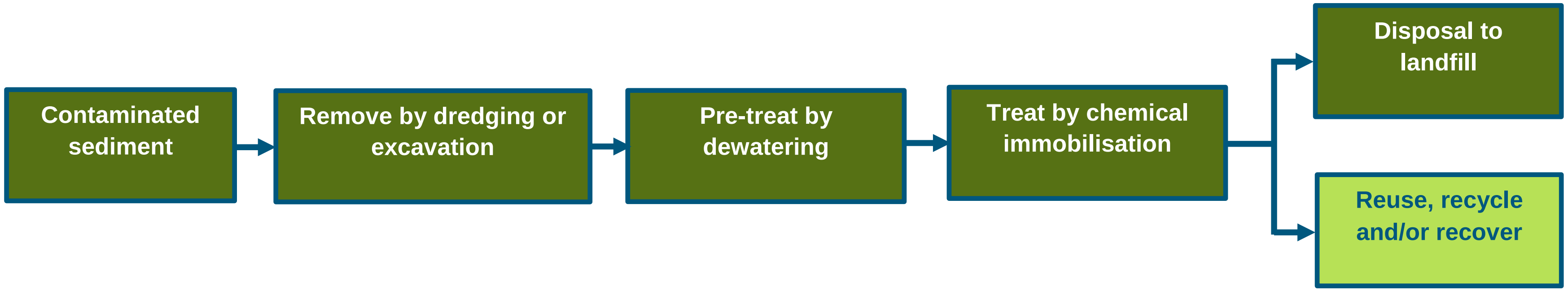
Figure 7.1 Stage 2 Short-List of Most Likely Suitable Options

Intervention Chain 1 – Ex situ pre-treatment and landfill

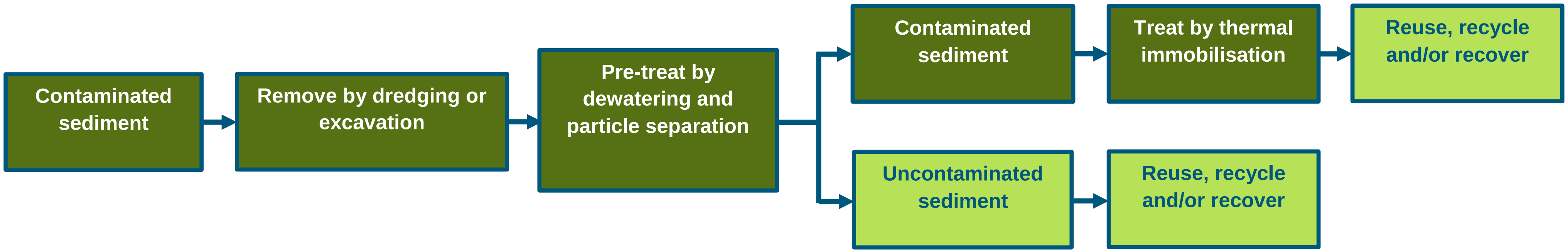
Intervention Chain 2 – Ex situ pre-treatment, landfill and re-use, etc.



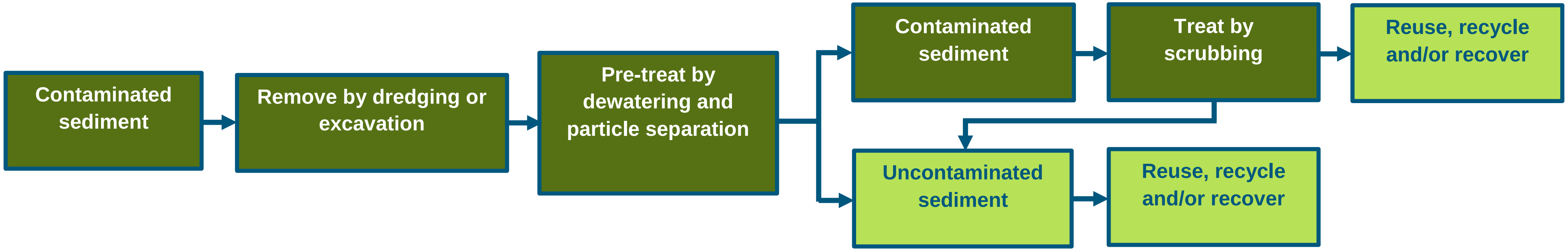
Intervention Chain 3 – Ex situ pre-treatment, full treatment, disposal and/or re-use, etc.



Intervention Chain 4 – Ex situ pre-treatment, partial treatment and full re-use, etc.



Intervention Chain 5 – Ex situ pre-treatment, partial treatment and full re-use, etc.



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