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Sustainability of land remediation. Part 1: overall analysis

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A comparative assessment was carried out of the technical and environmental sustainability of five different contaminated land remediation projects completed in the UK between 1997 and 2002. The remediation technologies employed were in situ stabilisation/solidification, soil washing, ex situ bioremediation, cover system and excavation, and disposal to landfill. A further objective of the assessment was to highlight areas of sustainability concerns for the individual technologies and projects. The assessment is based around four principal criteria defined by the authors. Each project was assessed using both an overall multi-criteria analysis, detailed in this paper (Part 1), and a study of the detailed impacts on an individual project basis, detailed in Part 2.

1. INTRODUCTION

The remediation of contaminated land is often considered to be a sustainable practice as it allows the reuse and redevelopment of previously developed land. However, most remediation methods involve a wide range of activities that result in environmental, social and economic impacts. The largest, most obvious impacts (particularly cost and duration) will usually be taken into account when selecting an appropriate technology to be used. However, potentially significant impacts (such as emissions or use of raw materials) can often be overlooked. There is a general consensus on which remediation technologies are sustainable (process-based technologies) and which are not (dig and dump). However, there has been little work on the relative sustainability of remediation techniques based on the assessment of their wider impacts.

The UK construction industry is becoming increasingly aware of the concept of sustainability, with broad-based government strategies being incorporated into industry thinking both on a national scale, through the Institution of Civil Engineers, and through individual companies down to individual sites.[1] The UK government has produced objectives for sustainable development nationally,[2] which have been translated into 'themes for action' specifically for the construction industry.[3] The incorporation of sustainability into the design of remediation projects is increasingly being promoted through the above schemes and also through more focused systems. In Europe, for example, the Clarinet network has produced guidance on sustainable remediation, particularly the use of 'risk-based land management' and how

sustainable practices can be included in this through the consideration of fitness for use, protection of the environment and long-term care.[4,5]

Assessment of the overall sustainability of any remediation technologies is yet to be presented in the literature, although some studies have looked at environmental impact, mostly applying a life cycle analysis (LCA) approach, as summarised by Suèr et al.[6] Examples include Diamond et al.[7] and Page et al.,[8] who presented a method that assessed the true impacts of excavation and disposal to landfill in terms of factors such as emissions, energy use and waste as well as human and ecological toxicity on one case study. They concluded that, among other effects, offsite transportation was a major cause of material use and emissions, and considered to a limited extent the potential effects on areas other than the remediated site itself. More recently Bayer and Finkel[9] followed a similar approach in comparing a real funnel-and-gate project with a virtual pump-and-treat system for groundwater clean-up over time on the same site, concluding that the former method had long-term advantages whereas the latter had lower initial impacts. In both these cases considerable detail was available on the site considered, and hence the LCA was comprehensive, particularly in terms of human health effects, emissions, energy and materials used.

Blanc et al.[10] and Volkwein et al.[11] presented comparisons of the individual impacts of a number of techniques, both studies designed as selection tools on one particular site using projected data. In addition, Blanc et al.[10] applied a limited multi-criteria analysis to their data, and their overall analysis concluded that excavation and disposal to landfill would have significant impacts in many categories of assessment, whereas onsite containment, using an onsite landfill cell, performed the best. Volkwein et al.[11] highlighted how the required information for an LCA draws on many different sources and requires many assumptions to be made in a comparison of onsite landfilling, cover system (using asphalt) and decontamination (a combination of ex situ bioremediation, soil washing and thermal treatment). This study was an example of how such an analysis can be implemented, and deliberately does not draw definitive conclusions on the best technique for the site, but accepts that further non-technical issues would also have to be resolved prior to such a decision being made. Both Suèr et al.[6] and Andersson[12] assessed and compared a range of applications of similar techniques and found that the

use of different assumptions meant that two assessment methods applied to the same project could come up with different suggested technologies.

Many of the published case studies are employed on a single site to be remediated in order to select the most sustainable remediation technique for that site. Such analyses usually rely on projected rather than actual data. In addition, most of those studies, if not all, highlighted the difficulty in attempting to consider a wide range of potential impacts owing to the enormity of the task and also the common lack of information in a number of areas.

This two-part publication presents an assessment and comparison of the technical/environmental sustainability of five remediation projects, performed in the UK between 1997 and 2002. The remediation technologies employed in these projects are: in situ stabilisation/solidification; soil washing; ex situ bioremediation; cover system and excavation; and disposal to landfill. Back-analysis of completed projects allows a realistic comparison, taking into account actual rather than projected impacts. A method has been developed by the authors for the purpose of performing this comparison that takes a wider view of the whole project using an overall multi-criteria analysis, presented in this paper, as well as assessing individual impacts of remediation using detailed impact assessment, presented in Part 2 of this publication.[13]

The two methods of overall multi-criteria analysis and detailed impact assessment use an overlapping range of information, and complement each other. The multi-criteria analysis takes a broad overview of a remediation project, whereas the detailed impact assessment focuses on specific areas of impact. The multi-criteria analysis has the advantage that areas where little or no quantitative information is available can still be included. As a result, weightings and scores incorporate a degree of subjectivity, and hence including a sensitivity analysis allows a range of scores to be presented that take this subjectivity into account.

2. ASSESSMENT OF TECHNICAL/ENVIRONMENTAL SUSTAINABILITY

2.1. Assessment criteria
A method for performing sustainability assessment for the technical and environmental aspects of contaminated land remediation is presented here, based on Harbottle et al.[14] Technical sustainability is defined as being concerned with the physical impacts arising due to the implementation of remediation. Social and economic effects have not been addressed directly, although their physical causes are included. This assessment is based around four principal criteria, as follows.

(a) Criterion 1: Future benefits outweigh cost of remediation. This requires any benefits of the remediation to outweigh any costs over the lifetime of the project and beyond. Benefits and costs measured in non-financial terms include: risks to site users and the public; the quality and quantity of surface water, groundwater, air and soil; the use of non-renewable resources; non-recyclable waste; and the potential range of future uses of the land. Financial

benefits include the economic value of the land, the impact on surrounding areas, and incentives/tax breaks. Costs include capital, operation and maintenance, labour, site investigation, monitoring/post-closure maintenance, professional fees, insurance/legal and off-site disposal. This criterion is being addressed by the multi-criteria analyses presented in this paper.
(b) Criterion 2: The environmental impact of the remediation is less than the impact of leaving the land untreated.
(c) Criterion 3: The environmental impact of bringing about the remediation process is minimal and measurable.
(d) Criterion 4: The timescale over which the environmental consequences occur, and hence inter-generational risk, is part of the decision-making process.

Criteria 2, 3 and 4 are addressed by the detailed impact assessment presented in Part 2 of this publication.[13]

2.2. Assessment technique: multi-criteria analysis (MCA)
A number of decision support tools have previously been used or considered for use in selecting remediation technologies.[15] Such techniques can be used for sustainability assessment and comparison. Two such methods are used in the work presented here. The first is an overall multi-criteria analysis (MCA), described in this paper, which was used to investigate the overall effect of remediation—that is, addressing criterion 1 above. The second is a detailed assessment of individual impacts, described in Part 2 of this publication, to investigate specific impacts by addressing criteria 2–4.

The MCA method used here is based on that developed by Postle et al.[16] for the Environment Agency. The basic method was originally designed to assist with the selection of appropriate technologies for contaminated land remediation on a given site, and has here been adapted to allow the comparison of the technical sustainability of remediation projects on different sites. It gives scores and weightings to assess the performance of a technology in different categories (human health and safety, environment, stakeholder concern and land use) and related subcategories. A sensitivity analysis was then employed in order to determine the effects of uncertainty on the scores and weights. Because it takes into account all areas of impact, this method was suitable for addressing criterion 1 above.

Compared with the original method, a number of extra subcategories have been included here, taking into account effects such as the use of raw materials and the production of waste. The 'environment' category has been subdivided into 'local environment' and 'global environment'. Also, effects onsite (directly related to the remediated site itself and its surrounding area) and offsite (any ancillary sites used, such as landfills, and travel to/from those sites) have been quantified separately. Scores and weightings have been developed using the process described below.

(a) Scores were determined on a scale of −100 to +100, with 0 being no change from the original state, and −100 and +100 being the maximum negative and positive effects respectively. In each subcategory the project with the largest impact was selected and given the maximum score (positive or negative), and then scores for the other projects

in that subcategory were determined relative to that project. Methods for determining the impacts, and hence the scores, are given in Section 4 (Results and Discussion, with further information in the Appendix.

(b) The weighting system involves application of weights at two stages:

(i) The most important criterion within a category was given a weighting of 1·0, and all others in the category weighted relative to this. Separate weights were used for onsite and offsite scores (weighting of scores during and after remediation was employed in the original method of Postle et al.,[16] but this was not performed here).

(ii) Corresponding scores and weights were multiplied and summed to give the category score.

(iii) Each category score was then normalised. For example, the human health and safety category had a maximum score of 800 (two subcategories with onsite, offsite, during and after scores). The total was divided by 8 to give an overall category score out of 100.

(iv) The relative importance of categories for each site was determined by category weights, which were derived as described for subcategory weights. The total score for each site was then determined by combining category scores and weights and then summing.

Sensitivity analyses were performed in order to assess the effect of uncertainty on both the scores and the weights. The uncertainty in scoring was managed by investigating the outcome of a reasonable maximum and minimum set of scores for each site. Uncertainties in weightings were dealt with by preparing a number of different weighting sets based on the expected opinions of different stakeholders (in this case, nearby site residents, the developer, and residents near other sites used).

In order to allow direct comparison between the different projects and in different situations in a structured manner, a functional unit of 'per t of remediated soil' was used. The majority of studies in the literature used as a functional unit 'the treatment of a site', which is applicable only to the comparison or assessment of methods on a single site.

3. SITE AND REMEDIATION PROJECT DETAILS

The information used in this study was taken from remediation projects on different sites in the UK, which took place between 1997 and 2002. The data presented are therefore site-specific and not necessarily representative of the remediation technique in general. Summaries of the information used for each site are given below, with the data presented in Table 1. The identities of the projects and sites are confidential, and hence the projects were identified by the remediation technique used. It should be noted that although a large amount of information was available for each project, a significant amount had to be derived from other sources. Details of common parameters used in both assessment techniques are given in the Appendix.

3.1. Stabilisation/solidification (S/S)

The site was contaminated because of past industrial use, and was located in a mixed-use area. Remediation by S/S was implemented to allow residential reuse of the site. Contaminants were present in layers of made ground, alluvium

and gravels above an impermeable clay layer. A cement–bentonite binder mix was used for the treatment. The soil was stabilised in situ up to a depth of 4·5 m. The site was adjacent to a river, and a prime objective was to prevent its contamination. Distances to cement and bentonite suppliers were assumed based on distances to known production plants in the area. Leachate concentrations from S/S treated material were found to satisfy the remediation objectives set, and groundwater monitoring for a period of two years post-remediation indicated a 98% reduction in leached contaminant concentrations.

3.2. Soil washing

This site was a former gasworks with a nearby river. The future use of the site was expected to be commercial. The aims of this project were to prevent contamination of groundwater and the nearby river, and to minimise disturbance to surrounding residential areas over the duration of remediation. Hence soil washing was employed to remediate the site by removing fine-grained soil material and the contamination contained within it, and by minimising waste. The soil stratigraphy consisted of made ground overlying alluvial material and gravels down to bedrock, with a range of organic and inorganic contamination primarily near the surface. Soil washing was the main remediation technique used, although material not considered suitable for reuse onsite was disposed of in landfill (including fines from the washing process). Contaminated made ground to approximately 1·5 m, as well as deeper contaminated material, where practicable, was excavated and treated using an onsite soil washing plant. The actual landfill and borrow pit used in this project were not known, and so were assumed to be suitable local sites at the distances given in Table 1. Around 99% of the batches of washed soil were found to satisfy the set remediation objectives, and those not passing were rewashed. Dust monitoring was employed during remediation.

3.3. Ex situ bioremediation

The site in question was used historically for a range of industrial purposes including a gasworks. It is in an urban setting, surrounded by a variety of land uses, and is adjacent to a river. Site soil, consisting of made ground and alluvium, was excavated and 32% (with high concentrations of PCBs) was disposed of offsite by rail. The remainder was bioremediated onsite using windrows. The borrow pit used to supply fill material was not known: hence it was assumed to be a suitable local site. A range of residential and commercial uses was planned for the site. The majority of contamination was reduced to below the specified remediation targets, although occasional small areas at depth were left as they were not considered a risk. It was found that bioremediation was inexpensive but needed space, and was affected by the weather. During remediation, monitoring of dust, volatiles and odours was employed, and groundwater was monitored for two years following completion.

3.4. Cover system

This project consisted of hotspot excavation and tank removal on a former gasworks site followed by backfill (including reuse of clean excavated material) and then application of a cover. The amount of soil remediated by the cover system was considered to be that covered by the cap to a depth of 3 m (the maximum depth of hotspot excavation) and so was large

	Stabilisation/ solidification	Soil washing	Ex situ bioremediation	Cover system	Landfilling
Major contamination* (maximum in mg/kg)	BTEX (xylene to 5000); TPH (8000)	PAH (1300); TPH (7000); lead (3400)	TPH (37 000); PAH (7600); PCB (39); lead (1400)	PAH (120 000); lead (11 000); cyanide (44 000); mercury (200)	TPH (58 000); lead (61 000); arsenic (13 000)
Mass and fate of soil remediated:[†] t	Onsite reuse: 7040	Landfill: 108 000; offsite reuse: 11 100; onsite reuse: 158 000	Landfill: 25 700; bioremediation/onsite reuse: 56 700	Landfill: 190 000; onsite reuse: 882 000	Landfill: 4680
Fate of soil remediated: %	Onsite reuse: 100	Landfill: 39; offsite reuse: 4; onsite reuse: 57	Landfill: 32; bioremediation/onsite reuse: 68	Landfill: 13; onsite reuse: 87	Landfill: 100
Soil organic matter: %	2[¶]	2 (15·5 in waste fines)	2[¶]	2[¶]	17
Materials used in remediation: kg/t soil	Cement:[‡]43; bentonite: 17	Clean fill: 293	Nutrients Clean fill: 318	Geomembrane Recycled fill: 317	Recycled fill: 1000
Water use	227 kg/t soil remediated	112 kg/t soil remediated	Up to 10 m³ per day per windrow	N/A	1·9 kg/t soil remediated
Distance to material supply or disposal site: km	Bentonite: 88; cement: 24	Borrow pit: 24; landfill: 8	Borrow pit: 20; landfill: 312 (by rail)	Borrow pit: 1; landfill: several landfills used	Borrow pit: 0; (stockpiles on site); landfill: 12
Site plant used	2 auger rigs + batching plant	4 excavators, 4 bulldozers/ compactors, 2 loaders, crusher, 2 screens, soil washing unit[¶]	4 excavators, 4 bulldozers/ compactors, 4 loaders, windrow turner, 2 screens, crusher[¶]	5 excavators, 4 loaders, crusher, 3 screens, 5 bulldozers/ compactors	2 excavators, 2 bulldozers/ compactors[¶]
Distance from plant supply: km	104	91	34	332	332
Energy requirement (other than vehicle fuel)	0·154 kg coal/kg cement, electricity (clinker grinding) – 30 kWh/t[§]	1·29 kWh/t electricity (assumed 100 kW soil washing unit)	None considered	None considered	None considered
Duration of treatment: months	2	16	11	13	2

*BTEX: benzene, toluene, ethylbenzene, xylene; TPH: total petroleum hydrocarbons; PAH: polycyclic aromatic hydrocarbons; PCB: polychlorinated biphenyls.
[†]Where volume only was known, converted to mass using assumed density of 1·6 t/m³.
[‡]Per t cement: 1·10 t limestone, 0·34 t shale, 0·06 t sand, 5 kg iron oxide.[17]
[§]Coal-fired semi-wet/dry rotary kiln: approx. 1 Mcal per kg clinker formed, coal calorific value assumed to be 6·5 Mcal/kg (assumed all clinker ground to cement).[17]
[¶]Value assumed.

Table 1. Summary of relevant data for the five remediation projects considered

(~1·0 Mt). The cover consisted of approximately 1·0 m of clean granular material underlain by a geomembrane. The site has since been redeveloped for commercial use. Any impact on groundwater due to the treatment was to be minimised because of proximity to a major river: excavation below perched groundwater was avoided where possible. However, no clean-up of any contaminated groundwater was required, as the area surrounding the site was broadly contaminated and the source would not necessarily be on the site. All specified targets for contaminant reduction were reached. Monitoring consisted of dust and checks during remediation and groundwater for nine months afterwards.

3.5. Excavation and disposal to landfill
A variety of past industrial uses had left both organic and inorganic contamination on this relatively small site. The site was to be redeveloped for commercial/light industrial use. The soil stratigraphy comprised a layer of made ground overlying alluvium, gravel and sand layers. Hotspots of contamination in the made ground were excavated and disposed of to landfill. This was replaced by backfill using recycled material. The site was considered to have been successfully remediated. Groundwater and gas were monitored for a period of 18 months afterwards.

Flow diagrams highlighting the major stages of each remediation project are presented in Fig. 1 (details based on Diamond et al.[7]).

4. RESULTS AND DISCUSSION

4.1. Categories, subcategories and weightings
The categories, subcategories and related factors considered in each subcategory in the MCA analyses are shown in Table 2, and scores and weightings for the individual projects are presented in Tables 3–7 together with the results of the analysis. The weightings depended on the site, although there is a degree of consistency, particularly with category weightings. For example,
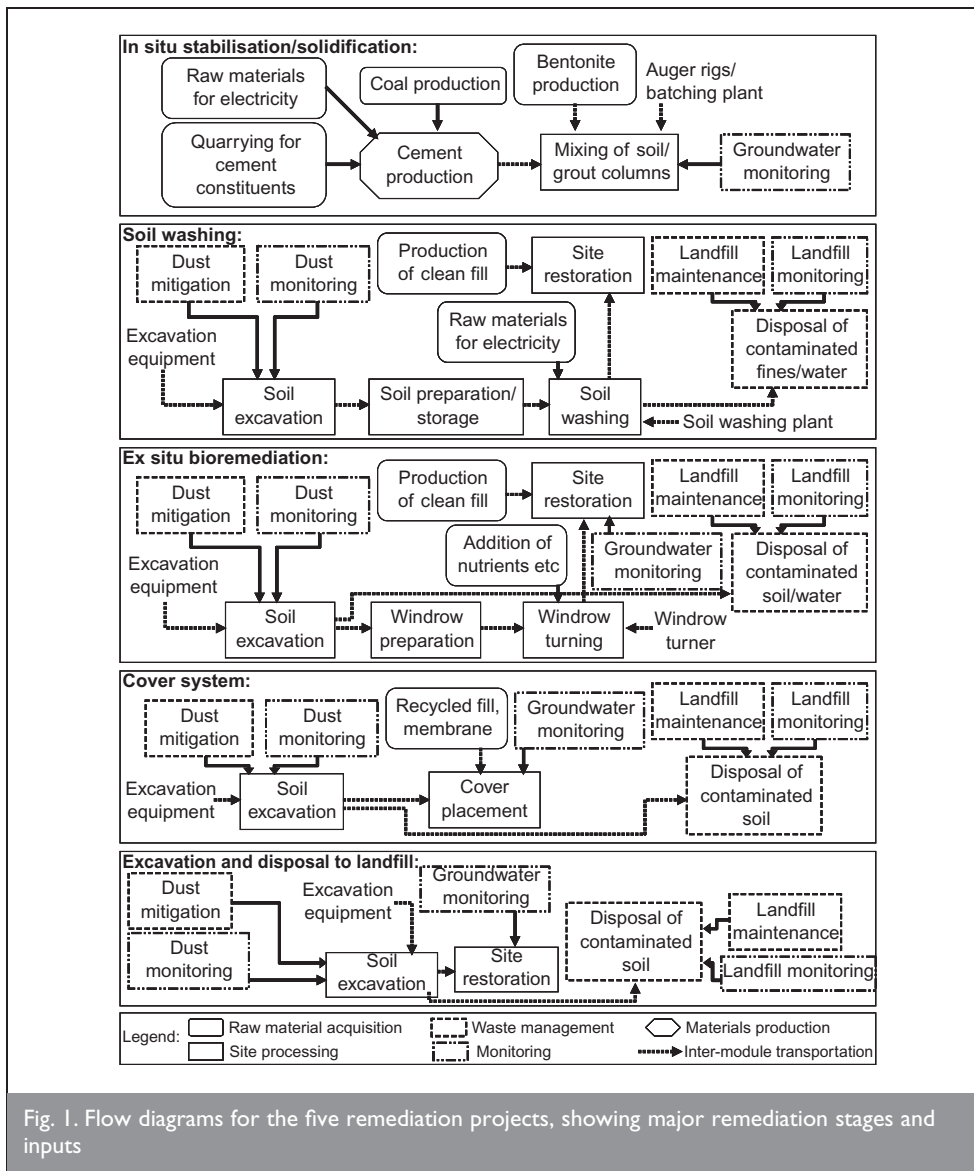
Fig. 1. Flow diagrams for the five remediation projects, showing major remediation stages and inputs

contamination, and much of the area is industrial and commercial in nature. For the bioremediation project this category was given an intermediate weighting, because the site is in an urban location, although the impact on nearby surface and groundwater sources was not prioritised.

General trends are also evident in the subcategory weightings. In 'human health and safety', 'risks to site users' was given a higher weighting than that of 'risks to the public'. This was particularly the case with offsite locations, which were expected to be relatively isolated from the public. In 'local environment', air, surface and groundwater pollution were usually considered the most important subcategories both on and offsite. With 'site use', the remediation duration was usually considered most important onsite, whereas impact on landscape took precedence offsite. The three subcategories within 'global environment' were given equal weighting in all projects, as they are all non-site-specific in their importance. In general, the offsite weightings were less onerous than those for onsite, because the controlled nature of landfill sites and borrow pits and their usually relatively isolated location meant that the potential for harm from such risks can be controlled and reduced.

'site use' was given priority in all projects, as this was the main driver behind the remediation. It is closely followed by 'human health and safety', as this was the main risk to be reduced. In each case 'global environment' was given the lowest weighting, because, although it is likely to be considered important, it does not have the same immediate local impact as the other categories. The 'stakeholder concern' category has been included to allow the inclusion of social aspects in the analysis, as in Postle *et al.*[16] However, while the 'acceptability' subcategory has been included, the 'confidence' subcategory has not owing to a lack of information. Indeed, the 'acceptability' subcategory has been considered only in a limited fashion in order to take into account the likely social impacts on the surrounding area, and therefore largely considered only stakeholders such as the public (including nearby residents) and developers. There would naturally be a large number of stakeholders from a wide variety of different backgrounds involved in each case, but information on this was largely unavailable. The 'local environment' category was the only category that was different for the various projects. It had the highest weighting for the S/S and soil washing projects because of nearby surface and groundwater receptors, and it had the lowest weighting for the cover and disposal to landfill projects because the area surrounding these sites is generally degraded, with widespread

4.2. Scores

For certain subcategories [air quality ('pollution' and 'global warming'), duration of remediation, site use, natural resource use and waste] scores were derived directly from values calculated as part of the detailed impact analysis.[13] Others were a combination of a range of effects measured both quantitatively and qualitatively, as described in Table 2. Certain subcategories (emissions and all those from the 'global environment' category) were taken to be onsite only, as this simplified the calculations. In addition, effects on ancillary sites were calculated by multiplying scores by the proportion of material involved on that site.

Scores arose from both quantitative and qualitative analysis, depending on the availability of data. Several of the subcategories were impossible to score exactly, and so some element of qualitative treatment was inevitable. A certain degree of subjectivity is therefore accepted as unavoidable,

Category	Subcategory	Factors
Human health and safety	Risks to site users	Intensity of site work (amount of soil excavated, placed, treated, compacted etc.) and risk of contamination during operations (qualitative). Contamination remaining (CLEA[18,19] analysis)
	Risks to public	Intensity of vehicle movements (no. HGVs/month), effect of transport (mileage), contaminant escape (qualitative).
Local environment	Surface water quality	Known or anticipated change to quality of surface water (qualitative)
	Surface water quantity	Known or anticipated change to quantity of surface water (qualitative)
	Groundwater quality	Known or anticipated change to quality of groundwater (qualitative)
	Groundwater quantity	Known or anticipated change to quantity of groundwater (qualitative)
	Air quality (pollution)	Emissions impacts due to remediation (total BEES[20] emissions impact, not including global warming), treated as all onsite
	Quality/structure of soil	Changes to properties and structure of soil (not including contamination effects: qualitative)
	Habitat/ecology	Loss of habitat (number of soil, surface or water habitats lost temporarily or permanently), effect of contamination on ecosystems (contamination compared with ecological indicator benchmarks)
Stakeholder concern	Confidence (not included)	Level of trust that stakeholders hold in those involved in bringing remediation about (e.g. regulators, contractors)
	Acceptability	Level of confidence of stakeholders in the remediation method (qualitative)
Site use	Duration of remediation	Length of remediation process
	Impact on landscape	Impact on landscape (qualitative)
	Site use	Loss of site use during remediation (qualitative), range of potential future uses of remediated and ancillary sites (from six categories: agriculture, residential, industrial, commercial, green and non-green open space)
	Surrounding land use	Impacts on surrounding land use due to inconvenience (likely during remediation) and also benefits due to redevelopment (qualitative)
Global environment	Air quality (global warming)	Global warming emissions impact (from BEES analysis), treated as all onsite
	Use of natural resources	Amount of natural resources used during remediation, treated as all onsite
	Waste	Amount of non-recycled waste disposed of, treated as all onsite

Table 2. Categories, subcategories and related factors considered in the MCA analyses (for details of factors used to derive scores in brackets see Appendix or Part 2)

although every effort was made to overcome this through the use of the sensitivity analysis and presentation of justifications for scores and weightings.

The total project score is calculated as follows:

$$\text{Subcategory score} = (\text{onsite during} + \text{onsite after}) \times \text{onsite weight} + (\text{offsite during} + \text{offsite after}) \times \text{offsite weight}$$

$$\text{Category score} = \text{category weight} \times \sum \frac{(\text{subcategory scores})}{\text{normalisation factor}}$$

$$(\text{normalisation factor} = \text{number of individual scores within category})$$

$$\text{Total project score} = \sum (\text{category scores})$$

The MCA results for each of the five remediation projects are presented in Tables 3–7, including all scores and weightings and their justifications.

4.3. MCA results for the S/S project

Scores and impacts for the S/S project are presented in Table 3 and summarised below for each category. The majority of impacts in this case were onsite.

(a) *Human health and safety.* Despite contaminants remaining onsite post-remediation, their availability was significantly reduced. Also, site operations and offsite movements were minimised. Long-term risks due to contamination were, however, uncertain. This is the only category that received a positive score for this project.

(b) *Local environment.* High emissions arose primarily from production of materials. The soil structure was disturbed, and would continue to be affected in the long term. A significant impact on any ecosystems on the site might be expected, owing to site operations, but the reduction of contamination risk was seen as positive in this respect. The highly negative onsite scores for those three subcategories led to this category having the second worst impacts for this project. On the other hand, groundwater contamination was found to be considerably reduced following remediation.

(c) *Stakeholder concern.* The continued presence of contaminants onsite was expected to have caused concern.

(d) *Site use.* Remediation was rapid, and the range of potential site uses was high. There was little impact on surrounding land use or landscape.

Category	Subcategory	Scores				Weights			Justification	Category score
		During		After		On site	Off site	Category		
		On site	Off site	On site	Off site					
Human health and safety	Risks to site users	−40	−5	90	0	1	1	0.9	*Score*: On site: least site operation; no excavation, hence little risk from contamination. Potential long-term contamination issue, so slightly reduced 'after' remediation score. Off site: owing to production of materials (89 kg/t), no impacts post-remediation. *Weight*: Most important as site users most affected.	4.43
	Risks to public	−15	−14	15	0	0.9	0.4		*Score*: On site: low vehicle movements (0.004/t per month). Reduced contaminant escape after. Off site: limited transport during remediation (0.5 km/t), no long-term effects. *Weight*: Similarly important to site user risk, ancillary sites expected to be isolated, with controlled access.	
Local environment	Surface water quality	0	0	0	0	1	0.8	0.9	*Score*: On site: no impacts—prevented by remediation. Off site: no impact. *Weight*: Highest subcategory weight onsite (river protection important).	−2.65
	Surface water quantity	0	0	0	0	0.8	0.6		*Score*: No impacts. *Weight*: Of some importance on the site owing to presence of river.	
	Groundwater quality	0	0	100	0	0.9	0.8		*Score*: On site: no change during but large decrease in contamination in 2 years after. Off site: no impacts. *Weight*: Important as potential effect on surface water.	
	Groundwater quantity	0	0	−5	0	0.5	0.6		*Score*: On site: no impact during. Local impacts on flow due to solidified mass in long term. Off site: no impacts. *Weight*: No abstraction nearby.	
	Air quality (pollution)	−80	0	0	0	0.8	0.8		*Score*: Moderate BEES impact. *Weight*: General importance not necessarily linked to location.	
	Quality/structure of soil	−100	0	−80	0	0.5	0.1		*Score*: On site: large change in soil structure and properties due to site work/solidification. Off site: no impact. *Weight*: Some value onsite for construction, future development etc.	
	Habitat/ecology	−90	0	50	0	0.4	0.4		*Score*: On site: loss of soil, surface habitats during, continued soil loss after (offset by reduced contamination). Off site: no impact. *Weight*: Relevance through proximity to river.	
Stakeholder concern	Stakeholder acceptability	−40	−9	50	−5	1	1	0.7	*Score*: On site: long remediation duration but little disturbance or noise. After remediation, contaminants remain. Off site: impacts from raw material source persist. *Weight*: Only subcategory considered.	−0.7
Site use	Duration of remediation	−67	0	0	0	1	0.3	1	*Score*: 2.8×10^{-4} months/t. *Weight*: Rapid development desirable onsite.	−2.02
	Impact on landscape	−10	−9	0	−9	0.4	0.8		*Score*: On site: limited effect during, no excavation. Off site: material extracted/dumped (89 kg/t). *Weight*: Ancillary sites usually in isolated areas, so effect is greater.	
	Site use	0	0	83	−9	0.6	0.3		*Score*: On site: suitable for 5 site use categories (all except agriculture). Off site: loss from raw material excavation (−0.5 uses). *Weight*: Some long-term effect.	
	Surrounding land use	0	0	10	0	0.6	0.3		*Score*: On site: benefit of redeveloped site. Off site: no impacts. *Weight*: Little integration with development of surrounding area.	
Global environment	Air quality (global warming)	−100	0	3	0	1	1	0.6	*Score*: Highest emissions (150 kg CO_2 equivalent/t during, 4 kg absorption after).	−6.25
	Use of natural resources	−28	0	0	0	1	1		*Score*: 89 kg/t raw material.	
	Non-recyclable waste	0	0	0	0	1	1		*Score*: 0 kg/t waste.	

Table 3. MCA for the S/S project

Category	Subcategory	Scores				Weights			Justification	Category score
		During		After						
		On site	Off site	On site	Off site	On site	Off site	Category		
Human health and safety	Risks to site users	−100	−50	93	−4	1	1	0·9	*Score*: On site: largest site operations, soil excavated. Low long-term contaminant risk. Off site: 695 kg/t extracted/dumped offsite (including contaminants). Small long-term contaminant exposure risk. *Weight*: Most important as site users most affected.	−8·42
	Risks to public	−16	−37	18	−2	0·9	0·4		*Score*: On site: during, low vehicle movement (0·005/t per month). After, contamination reduced. Off site: fairly low transportation during (1·1 km/t), small risk from landfilled material. *Weight*: Nearby residential areas. Ancillary sites isolated with controlled access.	
Local environment	Surface water quality	0	0	0	0	1	0·8	0·9	*Score*: No impacts. *Weight*: Particularly high weight onsite as river protection is important.	−5·41
	Surface water quantity	0	0	0	0	0·8	0·6		Score: No impacts. *Weight*: Of some importance on the site owing to presence of river.	
	Groundwater quality	−10	0	0	−5	1	0·8		*Score*: On site: contaminated groundwater produced onsite and disposed of during remediation. Off site: potential long-term low level effects on landfill. *Weight*: No nearby abstraction but important owing to potential effects on surface water.	
	Groundwater quantity	−20	0	0	0	0·5	0·6		*Score*: On site: dewatering of excavation. Off site: no impact. *Weight*: No abstraction nearby.	
	Air quality (pollution)	−96	0	0	0	0·8	0·8		*Score*: High BEES impact. *Weight*: General importance not necessarily linked to location.	
	Quality/structure of soil	−100	−4	−10	0	0·4	0·1		*Score*: On site: all soil excavated, fines removed. After, loss of fines. Off site: compaction on landfill. *Weight*: Some value onsite for future development.	
	Habitat/ecology	−100	−20	70	−8	0·4	0·4		*Score*: On site: loss of soil and surface habitats through excavation. Restored afterwards. Off site: loss of soil/surface habitat at borrow pit. Contained contaminants reduce long-term score. *Weight*: Some relevance through proximity to river.	
Stakeholder concern	Stakeholder acceptability	−20	−69	90	−20	1	1	0·7	*Score*: On site: low negative score as reduced vehicle movements. Good long-term score as contamination and potential blight removed. Off site: concerns over of borrow pit/landfill. Continued concerns in long term. *Weight*: Only subcategory considered.	−3·33
Site use	Duration of remediation	−13	0	0	0	0·6	0·3	1	*Score*: $5·8 \times 10^{-5}$ months/t. *Weight*: Duration not of importance for development, but still important for neighbourhood.	−2·39
	Impact on landscape	−20	−69	0	−69	0·4	0·8		*Score*: On site: limited effect during remediation. Off site: determined by material extracted/dumped (695 kg/t). *Weight*: Ancillary sites usually in isolated areas, so effect is greater.	
	Site use	0	0	50	−16	0·6	0·3		*Score*: On site: three potential site uses (commercial, industrial, non-green open space). Off site: effect of borrow pit/landfill (−1·0 uses total). *Weight*: Some long-term effect.	
	Surrounding land use	−1	−1	70	−20	1	0·3		*Score*: On site: long-term benefit from blight removal. Off site: long-term negative effects on landfill/borrow pit. *Weight*: Important onsite for removing blight.	
Global environment	Air quality (global warming)	−9	0	0	0	1	1	0·6	*Score*: 14 kg CO_2 equivalent/t.	−7·25
	Use of natural resources	−96	0	0	0	1	1		*Score*: 295 kg/t raw material (primarily fill).	
	Non-recyclable waste	−40	0	0	0	1	1		*Score*: 400 kg/t waste.	

Table 4. MCA for the soil washing project

Category	Subcategory	Scores				Weights			Justification	Category score
		During		After		On site	Off site	Category		
		On site	Off site	On site	Off site					
Human health and safety	Risks to site users	−100	−43	100	−3	1	1	0·9	*Score*: On site: as for soil washing. Off site: 625 kg/t material extracted/dumped offsite plus exposure to contaminants on landfill. Small risk of contaminant exposure in long term. *Weight*: Most important as site users are most affected.	−5·67
	Risks to public	−10	−25	18	−2	0·8	0·4		*Score*: On site: low vehicle movements (0·003/t per month). After, reduced risk of contaminant escape. Off site: low transportation (0·7 km/t), small long-term risk from contamination. *Weight*: Site isolated from residential areas but will be heavily used. Ancillary sites expected to be isolated and with controlled access.	
Local environment	Surface water quality	0	0	0	0	1	0·8	0·7	*Score*: No impacts. *Weight*: Highest weight onsite owing to river.	−3·33
	Surface water quantity	0	0	0	0	0·8	0·6		*Score*: No impacts. *Weight*: Of some importance on the site owing to presence of river.	
	Groundwater quality	−10	0	0	−5	0·8	0·8		*Score*: On site: slight increase in contamination during remediation, returned to background after. Off site: potential long-term low level effects on landfill. *Weight*: No nearby abstraction but important owing to potential effects on surface water.	
	Groundwater quantity	−20	0	0	0	0·5	0·6		*Score*: On site: dewatering and removal of contaminated groundwater during. Off site: no impact. *Weight*: No abstraction nearby.	
	Air quality (pollution)	−80	0	0	0	0·8	0·8		*Score*: Moderate BEES impact. *Weight*: Indicates general importance not necessarily linked to location.	
	Quality/structure of soil	−100	−3	5	0	0·4	0·1		*Score*: On site: all material excavated, soil improved in windrows. Off site: compaction on landfill. *Weight*: Of some value onsite for construction, future development.	
	Habitat/ecology	−100	−16	100	−6	0·4	0·4		*Score*: On site: as for soil washing. Off site: as for soil washing. *Weight*: Some relevance through proximity to river.	
Stakeholder concern	Stakeholder acceptability	−10	−63	90	−20	1	1	0·7	*Score*: On site: short project with transportation. After, most contaminants removed. Off site: as for soil washing. *Weight*: Only subcategory considered.	−0·53
Site use	Duration of remediation	−31	0	0	0	1	0·3	1	*Score*: 1·3 × 10^{-4} months/t soil. *Weight*: Rapid redevelopment important: central urban location.	−1·36
	Impact on landscape	−20	−64	0	−64	0·3	0·8		*Score*: On site: limited effect during remediation. Off site: determined by material extracted/dumped (625 kg/t). *Weight*: Ancillary sites usually in isolated areas, so effect is greater.	
	Site use	0	0	83	−22	0·6	0·3		*Score*: On site: five potential uses (all except agriculture). Off site: effect of excavation/landfill (−1·3 uses). *Weight*: Some effect in long term.	
	Surrounding land use	−1	−1	100	−15	0·8	0·3		*Score*: On site: part of redevelopment of surrounding area. Off site: long-term negative effects on landfill/borrow pit. *Weight*: Important onsite as major part of area redevelopment.	
Global environmentz	Air quality (global warming)	−11	0	0	0	1	1	0·6	*Score*: 16 kg CO_2 equivalent/t.	−7·15
	Use of natural resources	−100	0	0	0	1	1		*Score*: 313 kg/t raw material (primarily fill).	
	Non-recyclable waste	−32	0	0	0	1	1		*Score*: 312 kg/t waste.	

Table 5. MCA for the ex situ bioremediation project

Category	Subcategory	Scores				Weights			Justification	Category score
		During		After		On site	Off site	Category		
		On site	Off site	On site	Off site					
Human health and safety	Risks to site users	−85	−12	99	−1	1	1	0·9	*Score*: On site: fairly large site operations; small amount of excavation but is most contaminated. Off site: 126 kg/t material extracted/dumped offsite. Low contamination risks during and after (small proportion of material to landfill). *Weight*: Most important as site users most affected.	−1·19
	Risks to public	−10	−48	20	−1	0·8	0·4		*Score*: On site: lowest vehicle movements (0·003/t per month). Improvement through contamination reduction afterwards. Off site: moderate transportation distance (1·9 km/t). Very small risk from landfilled material afterwards. *Weight*: Site isolated from residential areas but will be heavily used. Ancillary sites expected to be isolated and with controlled access.	
Local environment	Surface water quality	0	0	0	0	0·8	0·8	0·6	*Score*: No impacts. *Weight*: Protection of river important but area is already generally degraded.	−1·27
	Surface water quantity	0	0	0	0	0·8	0·6		*Score*: No impacts. *Weight*: Of some importance on the site owing to presence of river.	
	Groundwater quality	0	0	0	−5	0·8	0·8		*Score*: On site: no impacts. Off site: potential long-term low level effects on landfill. *Weight*: No nearby abstraction but some importance owing to potential surface water effects.	
	Groundwater quantity	−20	0	0	0	0·5	0·6		*Score*: On site: excavation dewatering. Off site: no impacts. *Weight*: No abstraction nearby.	
	Air quality (pollution)	−45	0	0	0	1	0·8		*Score*: Low BEES impact. *Weight*: Indicates general importance not necessarily linked to location.	
	Quality/structure of soil	−13	−1	0	0	0·4	0·1		*Score*: On site: small proportion excavated. Off site: compaction on landfill. *Weight*: Of some value onsite for construction, future development.	
	Habitat/ecology	−50	−7	80	−3	0·3	0·4		*Score*: On site: some loss of soil habitat, surface habitat lost through cover (largely restored long term). Off site: loss of surface habitat on landfill (restored long term). *Weight*: Some relevance through proximity to river.	
Stakeholder concern	Stakeholder acceptability	−10	−13	85	−5	1	1	0·7	*Score*: On site: low negative impact as effect on local area is small, recycled materials are used. Off site: as for soil washing. *Weight*: Only subcategory considered.	9·98
Site use	Duration of remediation	−3	0	0	0	1	0·3	1	*Score*: 1·29 × 10^{-5} months/t. *Weight*: Rapid redevelopment most important.	0·33
	Impact on landscape	−20	−13	0	−13	0·3	0·8		*Score*: On site: limited effect during remediation. Off site: material extracted/dumped (126 kg/t). *Weight*: Ancillary sites usually in isolated areas, so effect is greater.	
	Site use	0	0	50	4	0·6	0·3		*Score*: On site: three potential site uses (commercial, industrial, non-green open space). Off site: effect of excavation/landfill (+0·2 uses). *Weight*: Will have some long-term effect.	
	Surrounding land use	−1	−1	10	−7	0·7	0·3		*Score*: On site: part of redevelopment of surrounding area. Off site: long-term negative effects on landfill /borrow pit. *Weight*: Site part of area redevelopment.	
Global environment	Air quality (global warming)	−6	0	0	0	1	1	0·6	*Score*: Lowest emissions (9 kg CO_2 equivalent/t).	−0·95
	Use of natural resources	0	0	0	0	1	1		*Score*: 1 kg/t raw material.	
	Non-recyclable waste	−13	0	0	0	1	1		*Score*: 125 kg/t waste.	

Table 6. MCA for the cover system project

Category	Subcategory	Scores				Weights			Justification	Category score
		During		After		On site	Off site	Category		
		On site	Off site	On site	Off site					
Human health and safety	Risks to site users	−90	−90	95	−10	1	1	0·9	*Score*: On site: all remediated material excavated, no processing onsite (so lower score than soil washing, bioremediation). Off site: 1002 kg/t material extracted/dumped. Off site risks similar to those onsite. *Weight*: Most important as site users are most affected.	−21·87
	Risks to public	−100	−100	18	−5	0·7	0·4		*Score*: On site: highest number of vehicle movements (0·052/t per month). Long-term improvement through contaminant removal. Off site: largest distance travelled (3·6 km/t). *Weight*: Industrial future use, isolated from residential areas. Ancillary sites expected to be isolated and with controlled access.	
Local environment	Surface water quality	0	0	0	0	0·7	0·8	0·6	*Score*: No impacts. *Weight*: Important to protect water courses but area was generally degraded, and site is some distance away from a river.	−4·40
	Surface water quantity	0	0	0	0	0·5	0·6		*Score*: No impacts. *Weight*: Moderate importance onsite; some distance from watercourse.	
	Groundwater quality	−10	0	−28	−5	0·7	0·8		*Score*: On site: contamination increase during remediation, further increase immediately after (potential long-term improvement). Off site: potential long-term low level effects on landfill. *Weight*: Of general importance but whole area degraded.	
	Groundwater quantity	−5	0	0	0	0·5	0·6		*Score*: On site: small amount of dewatering. Off site: no impacts. *Weight*: moderate; no abstraction nearby.	
	Air quality (pollution)	−100	0	0	0	1	0·8		*Score*: Highest BEES impact. *Weight*: General importance not necessarily linked to location.	
	Quality/structure of soil	−100	−10	0	0	0·4	0·1		*Score*: On site: all soil excavated. Off site: compaction on landfill. *Weight*: Of some value onsite for construction, future development.	
	Habitat/ecology	−100	−50	90	−20	0·3	0·4		*Score*: On site: loss of soil and surface habitat onsite, restored afterwards without contamination. Off site: loss of surface habitat on landfill, effects of contamination. *Weight*: Relatively unimportant.	
Stakeholder concern	Stakeholder acceptability	−100	−100	100	−30	1	1	0·7	*Score*: On site: highest negative impacts on local area. Off site: as for soil washing. *Weight*: Only subcategory considered.	−22·75
Site use	Duration of remediation	−100	0	0	0	1	0·3	1	*Score*: 4·3 × 10⁻⁴ months/t (slowest). *Weight*: Rapid redevelopment most important.	−15·16
	Impact on landscape	−20	−100	0	−100	0·3	0·8		*Score*: On site: limited effect during remediation. Off site: determined by material extracted/dumped (1002 kg/t). *Weight*: Ancillary sites usually in isolated areas, so effect is greater.	
	Site use	0	0	50	33	0·6	0·3		*Score*: On site: three potential site uses (commercial, industrial, non-green open space). Off site: effect of landfill (+2·0 uses). *Weight*: Will have some effect in long term.	
	Surrounding land use	−10	−5	10	−50	0·7	0·3		*Score*: On site: part of redevelopment of surrounding area. Off site: long-term negative effects on landfill /borrow pit. *Weight*: Site part of area redevelopment.	
Global environmentz	Air quality (global warming)	−12	0	−3	0	1	1	0·6	*Score*: 18 kg CO_2 equivalent/t.	−5·8
	Use of natural resources	−1	0	0	0	1	1		*Score*: 2 kg/t raw material.	
	Non-recyclable waste	−100	0	0	0	1	1		*Score*: 1000 kg/t waste.	

Table 7. MCA for the disposal to landfill project

(*e*) *Global environment.* Emissions from cement production contributed to a high global warming impact, which led to this category having the worst impact. Use of resources was relatively low, and waste was negligible.

4.4. MCA results for the soil washing project

The scores for the soil washing project are presented in Table 4, with the following key impacts, leading to negative scores for all the categories.

(*a*) *Human health and safety.* Other than risks due to contamination, risks to site users arose predominantly as a result of the operations on the site and attendant vehicle movements, which were significant, leading to high negative scores and the highest negative score of all categories.

(*b*) *Local environment.* Pollutant emissions to the atmosphere were high, owing to both transportation and site work. Excavation of the site soil led to the high negative scores owing to its effect on soil structure and ecological impact, although the latter was considered to be improved in the long term through the removal of contamination. Those three subcategories led to the highest negative scores for the onsite activities during the remediation stage. The impact on surface and groundwater was minimal.

(*c*) *Stakeholder concern.* The reduced vehicle movements, compared with the situation if all material were disposed of offsite, were likely to have reduced concern about disturbance, although there were still impacts on the local area. As the site was cleaned, future opinion was likely to be positive.

(*d*) *Site use.* The landfilling element of the project had a large influence on landscape post-remediation. The proposed land use on the site was commercial/industrial, and so clean-up targets were not as stringent as for residential projects. The site was an important part of the surrounding area, and its redevelopment could be important for local prosperity: hence the high score in this subcategory in the long term. The category weight was not high, however, as development was not imminent.

(*e*) *Global environment.* The assumed use of virgin fill in this work led to a highly negative material use score. Waste was still a problem despite the measures taken to reduce it. This resulted in the second highest negative category score.

4.5. MCA results for the ex situ bioremediation project

Table 5 contains scores for the ex situ bioremediation project, and highlights the following impacts in the various categories.

(*a*) *Human health and safety.* As with soil washing, excavation and movement of site soils led to a high site user risk during remediation, because of both contamination and operations. The reduction in contamination was sufficient to give the highest positive score for the post-remediation stage. Risks to the public were reduced through offsite transportation by rail. Because of the partly residential nature of the site development, risks to site users were considered most important. The remediation had the second highest negative impact on this category.

(*b*) *Local environment.* Air pollution was high, with site work and transportation being the main causes, and the excavation of the soil, as with soil washing, led to impacts

on the structure of the soil and habitat at the site. The final state was considered to be similar to that initially, albeit with contamination removed, leading to a high positive future habitat score. The weighting for soil structure and habitat was low, however, owing to the initially industrial setting and taking into account the future site use.

(*c*) *Stakeholder concern.* As most of the work took place onsite, this project had a relatively low level of concern during remediation and positive impact post-remediation, since most of the contaminants were removed, resulting in the least negative category score.

(*d*) *Site use.* A high site use score was due to remediation to residential standards, giving more flexibility in future. Additionally, this project was part of the redevelopment of the surrounding area: hence the high score. Use of a landfill gave a negative impact on landscape offsite.

(*e*) *Global environment.* The assumed use of virgin fill led to a high negative score for material use, and waste was also high, although global warming emissions were low. This resulted in the highest negative score being for this category.

4.6. MCA results for the cover system project

Table 6 contains the MCA scores for the cover system project, which are summarised below. Many of the impacts here were reduced through normalisation, as a large volume of soil was considered to have been remediated.

(*a*) *Human health and safety.* Only contaminant hotspots were excavated, but other earthworks were considerable. Therefore risks to site users were still appreciable during the project. Although some contamination still remained onsite, there was found to be little risk to human health once the cover was installed. Risks to the public were caused primarily by offsite transportation.

(*b*) *Local environment,* Impact scores in this category were generally relatively low, as they were reduced through normalisation with respect to the large volume of soil remediated. Remediation was considered to have a positive future effect on the site habitat. This category received the highest negative score, although this was relatively low.

(*c*) *Stakeholder concern.* The relatively small impacts for such a large site led to a relatively low level of concern. The remediation was scored as being acceptable, although tempered by the knowledge that a low level of contamination remained beneath the cover. The score for this category was the highest of two positive scores.

(*d*) *Site use.* Landscape impacts arose offsite. The proposed site use (commercial) meant that the standard of remediation would not be sufficiently flexible to allow unfettered future development on the site. The site was part of the redevelopment of a large former industrial area, and so surrounding land use was an important subcategory.

(*e*) *Global environment.* Because of normalisation by weight of soil remediated, the impacts here are reduced. The use of recycled fill and minimisation of waste to landfill also minimised impacts.

4.7. MCA results for the disposal to landfill project

Scores describing the impacts from the disposal to landfill project are given in Table 7, showing all the category scores to be negative, and are summarised below.

(a) *Human health and safety.* Risks to both public and site users were considered to be high in this case, as it had the largest proportion of soil disposed of offsite, and a large amount of soil excavation. Risks to the public were highest for all case studies because of the offsite disposal. This resulted in a relatively large negative score.

(b) *Local environment.* As in previous cases, excavation of the soil had impacts on soil structure and habitat. Groundwater was found to be impacted both during and immediately after remediation, although this was not considered particularly important owing to the degraded nature of the surrounding land. This had the smallest negative score.

(c) *Stakeholder concern.* The considerable amount of site work and disposal to landfill of all waste was expected to cause the most concern to other parties, resulting in a relatively large negative score.

(d) *Site use.* Per tonne of soil, this technique had the longest duration, although with this relatively small site, economies of scale might be less than in other cases.

(e) *Global environment.* Waste was highest of all case studies here, but use of material (owing to the use of recycled fill) and global warming emissions were relatively low.

4.8. Sensitivity analyses

Sensitivity analyses were carried out that took into account reasonable upper and lower bounds on the scores used in this study. This was determined primarily by how quantitative the data were for a particular category: scores derived from calculations were given little or no variability, whereas those with a qualitative background had more potential for subjectivity and so were given a higher potential variability. Therefore for scores determined directly from numerical data (e.g. air pollution) there was no variability, whereas with scores determined from qualitative information (e.g. impact on landscape) the variability might be ±10 or 20 (out of a total possible score of ±100). It is acknowledged that calculated data can also have uncertainty, depending on the quality of the data used, but this has not been considered here. The weights used in the sensitivity analyses took into account the likely views of nearby residents for both the remediated site and other involved sites, together with those of a developer. The values used in this part of the analysis are not presented here.

4.9. Overall scores and comparisons

The category scores and overall scores, developed from the results in Tables 3 to 7, are presented in Figs 2 and 3 respectively, together with the results from the sensitivity analyses represented by error bars. A comparison of the individual assessment categories between the five projects presented in Fig. 2 shows that

(a) in the 'human health/safety' category the in situ S/S project performed best and the landfilling project worst;

(b) in the 'local environment' and 'global environment' categories the cover system project performed best and the soil washing project worst;

(c) in the 'stakeholder concern' and 'site use' categories the cover system performed best and the landfilling project worst.

The variations in the outcome for each project from the sensitivity analyses shown in Figs 2 and 3 show that although
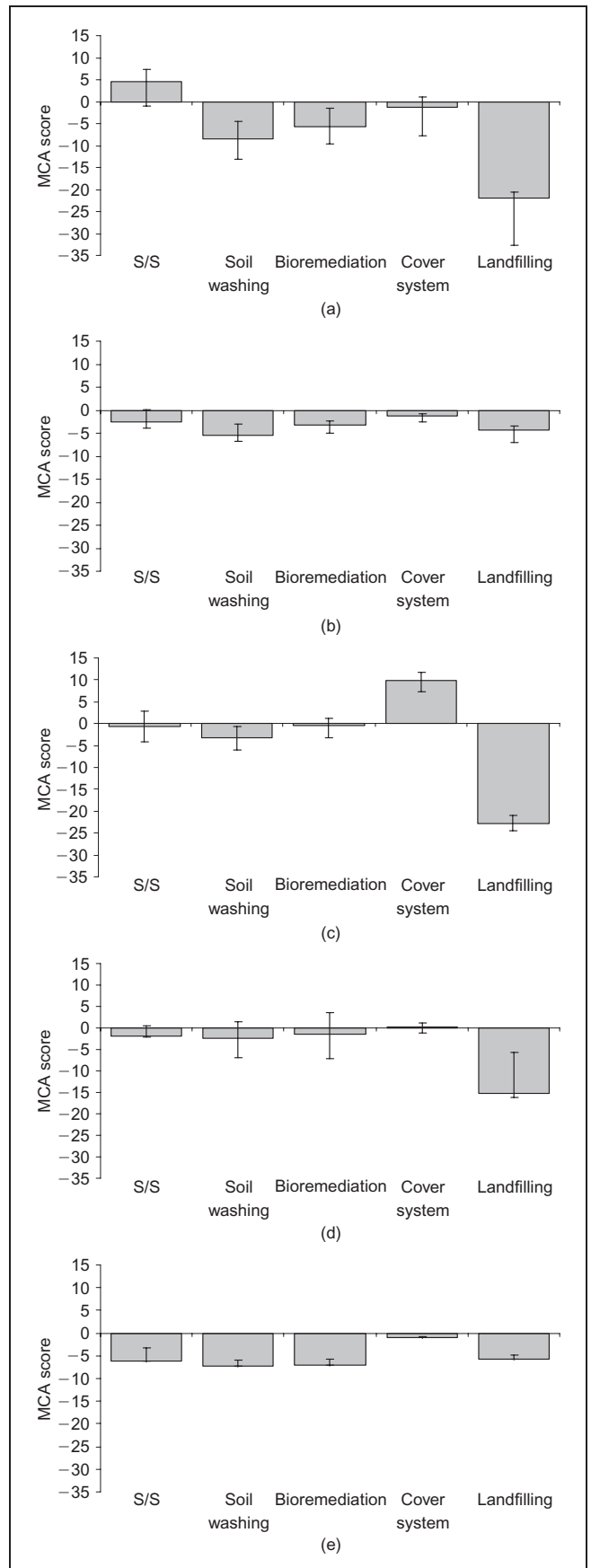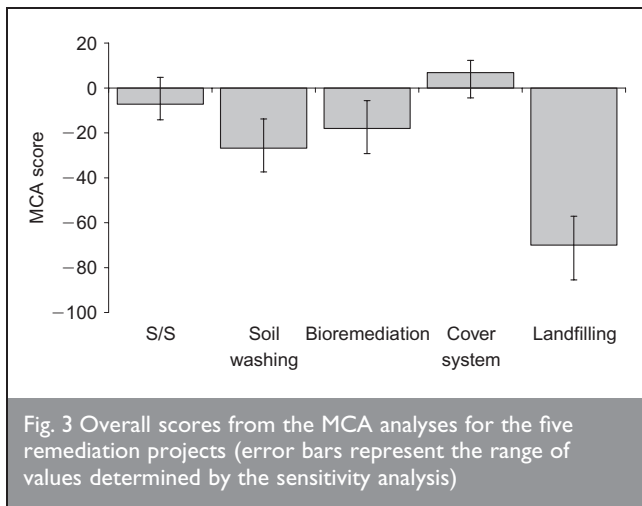

Fig. 2. Category scores from the MCA analyses for the five remediation projects (error bars represent the range of values determined by the sensitivity analysis): (a) human health and safety; (b) local environment; (c) stakeholder concern; (d) site use; (e) global environment

Fig. 3 Overall scores from the MCA analyses for the five remediation projects (error bars represent the range of values determined by the sensitivity analysis)

there is some overlap between the different technologies, this did not affect the overall conclusions of this study. 'Human health and safety' and 'site use' had the largest variability of the individual categories, while for the total scores the variability was consistent between the projects, although that for the cover system was slightly less. The level of variations is related to the level of information available for project and assessment category.

The MCA results show that the cover system project has the highest overall score and is hence considered the most sustainable from a technical/environmental viewpoint out of the five projects. The majority of impacts were not onerous, and the project had a high remediated volume of soil, which reduced impacts through use of the selected functional unit. On the other hand, the excavation and disposal to landfill project had the lowest overall score and is the least technically/ environmentally sustainable. The relatively good score for S/S was due primarily to the treatment being carried out in situ, minimising the impact on human health and the local environment, particularly with offsite effects. In all projects, apart from the S/S project, a certain proportion of the remediated soil was disposed of to landfill, and in the main it is this that led to the most onerous impacts. The main impacts of the soil washing and ex situ bioremediation projects were similar, and were particularly high in the categories of 'human health and safety', 'local environment' and 'global environment'.

It is also clear that the relative sustainability of a remediation project is dependent on the remediation criteria set. It is likely that the cover system project was ranked the most technically/ environmentally sustainable relative to the other projects because the issue of groundwater contamination was not important on that particular site, and hence a cover system solution was extremely effective in this case.

All the costs considered here are those in non-monetary terms. A final stage in the MCA would be to perform a cost-effectiveness analysis incorporating the actual costs of the remediation. Those costs were unfortunately not available for the five projects considered here. However, examples of how the cost-effectiveness calculations could be used to compare the costs and benefits of remediation techniques are given in an earlier study by the authors[14] and by Postle et al.[16] There is

also the potential for such an MCA method to be expanded to incorporate social effects, in order to provide a fuller assessment of the comparative sustainability of contaminated land remediation.

A general discussion combining the results from the MCA with those from the detailed impact analysis, presented in Part 2,[13] is presented in Part 2 of this publication, which highlights areas of sustainability concerns for the individual technologies and projects.

5. CONCLUSIONS

The multi-criteria analysis (MCA) performed on the five completed remediation projects highlighted the following.

(a) For the in situ S/S project there was an overall positive effect on human health and safety, whereas it had a negative impact on the local environment, stakeholder concern, site use and global environment, with the latter facing the worst impacts.

(b) For the soil washing project there was a negative impact on all five categories, with the impact on human health and safety being the worst and the impact on site use being the least onerous.

(c) For the ex situ bioremediation project there was a negative impact on all five categories, with the impacts on the global environment being the worst and the impacts on stakeholder concern being the least negative.

(d) For the cover system project there was a positive impact on stakeholder concern and—to a lesser degree—on site use. It had a slightly negative impact on the other three categories.

(e) For the excavation and disposal to landfill project there were negative impacts on all five categories, with the worst impacts on human health and safety and stakeholder concerns.

The conclusions are drawn only from the site-specific analyses used here, and not from the remediation technique in general. A comparison between the five remediation projects showed that the cover system project ranked the most technically/ environmentally sustainable. This was due primarily to the large volume of contaminated material that can be treated by this method. The in situ stabilisation/solidification project ranked second. This was due mainly to the process being performed in situ, with substantially reduced impacts in several areas. The ex situ bioremediation and soil washing projects ranked third and fourth respectively. Those two projects were found to provide benefits linked primarily to reducing the material taken to landfill, but had negative impacts linked to the risk to site users due to significant site operations, a range of impacts on the local environment and extensive use of raw materials. Not surprisingly the excavation and disposal to landfill project was ranked as the least technically/ environmentally sustainable. This was the case not only for the landfilling project but also where only a proportion of the soil was treated in this way, in combination with other remediation techniques. It was also clear from the analyses that the relative sustainability of a remediation project is dependent on the remediation objectives set. Comparative impacts highlighted in this study, together with those from the detailed impact assessment presented in Part 2, are discussed in Part 2 of this publication.

APPENDIX. GENERAL INFORMATION USED IN THE ANALYSES

The details of a number of parameters that were used in the analyses, in both Parts 1 and 2 of this publication, are given here. The information on these parameters was generally not sufficiently detailed or not available to allow accurate determination of site-specific factors. Also, information on methods used to calculate a number of impacts is presented.

A1. Soil properties and site equipment

A bulk density for the soil of 1600 kg/m^3 was assumed and the following information on ease of excavation for soils and raw materials was used to determine excavation rates and fuel consumption onsite.[20]

(a) 'easy dig' materials: virgin fill material (assume to be sand or gravel)
(b) 'medium dig' materials: site soil and bentonite
(c) 'hard dig' materials: limestone, shale, iron oxide, coal and uranium ore (for electricity production)

Site equipment data are presented in Table A1: they are either taken from or derived from Harris[20] or use representative values. Excavation volumes and rates are calculated using a swelling factor (excavated volume divided by in situ volume) of 1·25 and a production loss (a factor accounting for a variety of incremental delays that prevent full output) of 40%. The equipment used in each case was assumed based on information in the site reports (where specified) and the area of the site and volume of soil concerned. Noise was calculated using the method presented by Wills and Churcher.[21] For this purpose it was assumed that the noisiest operations (usually excavation, screening and crushing) were taking place close to the site boundary. It was assumed in this calculation that, for stationary plant, the source is fully screened and that the receiver was close enough to a wall for reflection to occur. Table A1 lists the basic plant noise levels used.

A2. Emissions

Emissions from both short-term and long-term processes were considered. Short-term air emissions for a number of processes (listed in Table A2) are calculated using information from the UK National Air Emissions Inventory.[22] In the long term, storage of materials containing organic matter in landfill can lead to methane generation due to anaerobic conditions. The amount of methane (CH_4) generated and emitted was calculated using the Intergovernmental Panel on Climate Change (IPCC) Tier Two methodology[23] using standard values for typical modern landfills. Carbon dioxide (CO_2) emission due to the breakdown of the organic matter or oxidation of methane is

HGV/tipper truck	Fuel consumption	2·8 km per litre diesel
	Capacity	20 t
	Basic noise level	106 dB
Excavator	Engine size	80 kW
	Fuel consumption	20 l/h
	Basic noise level	105 dB
S/S auger rig	Engine size	80 kW
	Fuel consumption	20 l/h
	Basic noise level	108 dB
Bulldozer	Engine size	108 kW
	Blade details	3·2 m length, 4 m^3 capacity
	Fuel consumption	23 l/h
	Speed	3 km/h dozing speed, 6 km/h return speed
	Distance travelled	Assumed equal to twice radius of site (there and back) per load
	Basic noise level	109 dB
Wheeled loader	Engine size	153 kW
	Fuel consumption	26 l/h (average)
	Shovel capacity	3·6 m^3
	Basic noise level	109 dB
Compactor	Details	Static weight roller, 3 m wide, performs 6 passes over 0·5 m lifts
	Speed	10 km/h
	Fuel consumption	23 l/h
	Basic noise level	109 dB (assumed towed by bulldozer)
Screen	Throughput	450 t/h (maximum)
	Fuel consumption	20 l/h
	Basic noise level	106 dB
Mobile crusher	Throughput	120 t/h (maximum)
	Fuel consumption	9 l/h
	Basic noise level	114 dB
Batching plant	Basic noise level	106 dB
Soil washing plant	Throughput	25 t/h
	Electrical power	100 kW

Table A1. Details of the equipment and plant used

Electricity generation*	Coal fired
	Fuel oil
	Natural gas
Road transport	Urban travel
	Motorway travel
Rail transport	Freight
Site works	Plant emissions
Raw materials	Raw material quarrying
	Cement production
	Plant emissions

*Assumed no net emissions from nuclear and renewable power generation.

Table A2. Processes included in the analysis for which air emissions have been quantified[22]

not considered, so there is an effective net loss of CO_2 through the creation of methane.

Raw emissions data were combined to assess a range of impacts based on the Building for Environmental and Economic Sustainability (BEES) analysis method[24]

(a) global warming potential: CO_2, CH_4 and N_2O
(b) acidification potential: NO_x and SO_2
(c) eutrophication potential: NO_x and N_2O
(d) criteria air pollutants: NO_x, SO_2 and particulates (PM10)
(e) human health: SO_2, benzene, 1,3-butadiene, mercury and lead
(f) smog: CH_4, CO, non-methane volatile organic compounds, benzene, PM10, benzo(a)pyrene, NO_x and 1,3-butadiene
(g) ecological impact potential: N_2O, NO_x, CO, non-methane volatile organic compounds, benzene, mercury, lead and benzo(a)pyrene.

Multiplication factors for substances in each group were used,[24] as well as normalisation factors (US-specific) for each group, allowing comparison between different areas. In addition, the seven impact areas were weighted using factors used in the BEES methodology, as derived by the US Environmental Protection Agency Science Advisory Board. For example, the normalised and weighted global warming potential was calculated as follows.

$$\text{Normalised and weighted global warming potential} = \left[\frac{\sum (\text{substance mass} \times \text{specific global warming index})}{\text{Normalising factor}} \right] \times \text{weight}$$

Calculated for carbon dioxide, methane and nitrous oxide

Normalisation and weightings used were as listed in Table A3.

For the MCA scores the global warming impact was addressed separately from the other pollutant impacts, as the latter are more localised. In scoring the localised air emissions impact the remaining normalised and weighted impact scores were all summed. Therefore this particular score is weighted twice: once to determine the relative impacts of each component (as part of the BEES analysis), and once as part of the overall MCA.

A3. Electricity use

Electricity use was considered when it formed a major part of energy supply: hence this was the case only in the S/S project, for cement clinker grinding, and in the soil washing project. Raw material use in the generation of electricity was calculated based on the proportion of electricity generation by different methods. According to UK electricity production statistics,[25] production of electricity was in the following proportions: 37% natural gas; 34% coal; 23% nuclear; 2% petroleum products; 2% hydro/wind; and 1% biomass/geothermal. Consumption of raw materials in electricity production was calculated in kg/kWh: 0·40 coal; 0·29 oil; 0·26 natural gas; and 0·08 uranium ore.

A4. Future usability of the site

The effect on future usability of all the project sites was determined based on six different categories of potential future use: green space, agricultural, residential, commercial, industrial, and non-green open space. The change in the number of potential future uses due to remediation was determined for the remediated site, the landfill and quarry or borrow pit and then summed, after normalisation by the amount of soil/excavated material involved for each site. The site was initially assumed to have no potential future uses because of the contamination. Waste was assumed to be disposed of in a landfill (such as a former quarry) which would otherwise not be usable in any of the six categories. Following remediation, possible uses included green and non-green open space. A borrow pit would initially be assumed to be pristine (all six categories possible), but following the remediation process (i.e. the extraction of material) this would be reduced to zero.

A5. Risk to humans and ecosystems from contamination

The change in risk to humans due to soil contamination was assessed using the UK's Contaminated Land Exposure Assessment (CLEA).[18,19] It determines the expected impact of contaminants on humans based on inhalation, oral and dermal contact pathways. The risk is presented as a ratio of average daily exposure (ADE) to index dose (ID) or tolerable daily exposure (TDI) (the level below which either minimal or no adverse effects are expected). Here, the ADE/ID ratio was calculated before and after remediation, and for each contaminant present. The maximum value afterwards was then divided by the maximum value beforehand to give an indication of the reduction in maximum risk. In most cases the soil conditions could be adequately modelled with the standard soil types in the program. However, an additional soil type was added to represent a stabilised/solidified soil, based on a clayey soil with low permeability and high pH. Impact on ecosystems was measured relative to ecological indicator benchmarks.[26]

A6. Transportation

Transportation mileage and number of arrivals and departures onsite were used as a measure of disturbance, and the impact on other sites was quantified for comparison using the total amount of material either extracted or dumped offsite. All the projects, except for the S/S project and excavation and disposal to landfill, involved two remediation techniques, one of which was landfilling, and so the overall score for this measure was determined by adding the scores for the proportions of soil treated in different places.

Area	Normalisation factor	Weighting factor
Global warming potential	25 582·64 kg CO_2 equivalents/year per capita	0·11
Acidification potential	7 800 200 moles H^+ equivalents/year per capita	0·05
Eutrophication potential	19·21 kg N equivalents/year per capita	0·05
Criteria air pollutants	19 200 microDALYs/year per capita	0·06
Human health	128 768·68 kg toluene equivalents/year per capita	0·11
Smog	151·5 kg NO_x equivalents/year per capita	0·06
Ecological impact potential	81·65 kg 2,4-dichlorophenoxyacetic acid equivalents/year per capita	0·11

Table A3. Normalisation and weighting factors for emissions impacts[24]

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