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A comparison of the technical sustainability of in situ stabilisation/solidification with disposal to landfill

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Abstract

Sustainability is becoming a very important issue in contaminated land remediation and should form one of the factors used in future selection of treatment technologies. In situ stabilisation/solidification (S/S) is a remediation technique that is increasingly being applied to the treatment of contaminated sites because of numerous advantages over other remediation techniques. This paper assesses and compares aspects of the technical sustainability of in situ S/S with landfilling. Criteria previously established for the assessment of the technical sustainability of the remediation of contaminated land are employed. The comparison is presented in the form of a case study based on a real remediation project in the UK. The analysis indicated that landfilling had a larger impact than S/S in the majority of areas investigated, such as waste production (1000 kg waste/t soil remediated for landfilling compared to none for S/S), transportation (12.9 km/t for landfilling, 0.4 km/t for S/S) and use of raw materials (1005.5 kg/t for landfilling, 88.9 kg/t for S/S), although S/S had high greenhouse gas emissions (12.6 kg/t for landfilling, 40.9 kg/t for S/S). In addition, a multi-criteria/cost-effectiveness analysis gave cost effectiveness scores of −34.2 to S/S and −138.1 to landfill (where more positive is better).

Keywords: Stabilisation/solidification; Landfilling; Sustainability; Multi-criteria analysis; Life cycle analysis

1. Introduction

The remediation of contaminated land is generally seen as a sustainable procedure. It recovers previously unavailable land for development, encouraging the recycling of land and regeneration of urban areas, as well as minimising greenfield development. Until recently, there was little consideration of the impact of the remediation process itself in the same light, but recent legislation is helping to change this. The European Union (EU) landfill directive [1], introduced in July 2004, is already having a profound effect on the waste disposal and land remediation industries in the UK. The co-disposal of hazardous and non-hazardous wastes is now banned, and hazardous waste has to be pre-treated prior to disposal in a landfill to minimise the amount of waste deposited. The use of excavation and disposal to landfill is therefore becoming less attractive as a method for contaminated land remediation. Coupled with both landfill tax and the UK government's target of 60% of new homes being built on brownfield sites this is leading to a great deal of interest in the use of process-based technologies and in situ techniques that minimise the amount of waste going to landfill.

Although these restrictions on waste disposal are one of the main driving forces behind the expansion of less common remediation methods, the amount of waste is not the only measure of sustainability. A large number of other factors must be taken into account if one is to properly assess the full impacts of a process. Although many technologies are perceived to be 'more sustainable' than landfill, it is not possible to be certain what is the most sustainable option for a given project without performing considerable investigation into the wider social, environmental and economic impacts of the scheme.

There is increasing support for the inclusion of sustainable development principles when selecting a remediation technology for use on a particular site, and research into methods of bringing this about. The EU research network CLARINET (Contaminated Land Rehabilitation Network for Environmental Technologies) produced a number of documents on the sustainability of remediation [2], promoting the use of 'risk based land management'. It was suggested that sustainable remediation should ensure that the site is fit for the designated future use, that

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the environment is protected and that long-term care is an important factor. In the US, there is a focus on the overall sustainability of brownfield sites development, particularly considering social and economic factors that make redevelopment successful [3,4]. There is less obvious focus on the remediation aspect, with concentration on ensuring that remediation is implemented quickly and cost-effectively which in turn will encourage redevelopment of such sites. The use of innovative technologies has particularly been encouraged where these might provide advantages in this respect [5]. The environmental impact of remediation is generally given most attention, and several studies have addressed ways to assess impact [6,7]. Suèr et al. [7] reviewed the use of life cycle analysis (LCA) as applied to contaminated land projects and their impacts, and found that the relative impacts of a particular technology can vary substantially from project to project although there are discernable underlying trends. Some studies, such as Bardos et al. [8], have considered other impacts (social and economic), in a qualitative rather than quantitative manner.

Stabilisation/solidification (S/S) is increasingly being used in the remediation of contaminated sites. It has a number of advantages, such as speed of implementation, facilitation of rapid redevelopment of the site, reduction of off-site disposal, reduced risk to site workers and use of well-established techniques and equipment. Landfilling, on the other hand, has been by far the most popular method employed in contaminated land remediation [9] due to its simplicity, reliability and relatively low cost. This paper presents a comparison between the environmental and technical sustainability of in situ S/S with that of off-site disposal to landfill. The purpose was to assess their relative sustainability and to identify the relevant criteria which affect the technical sustainability of these remediation techniques and which hence can be used to address potential improvements.

2. Method of assessment and presentation of data used

2.1. Sustainability criteria

A set of sustainability criteria were developed for use in the assessment and comparison of the technical sustainability of different remediation techniques and projects [10]. Technical sustainability is defined here as being concerned with physical impacts directly due to the implementation of remediation. Social and economic elements associated with the criteria, which are invariably caused by the basic physical impacts, are not considered here. Four criteria are used in this study and are given below. The reader is referred to Harbottle et al. [10] for further details:

- 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.
- Criterion 2: environmental impact of the implementation process is less than the impact of leaving the land untreated.
- Criterion 3: environmental impact of the remediation process itself is minimal and measurable.
- Criterion 4: the time-scale over which the environmental consequences occur, and hence inter-generational risk, is part of the decision making process.

Each criterion has been divided into a number of parameters. There is clearly some overlap between the different criteria and this is taken into account in the analysis. Each of these parameters is measured using one or more indicators (e.g. ‘air emissions’ is measured by the calculated emission of several pollutants, such as sulphur dioxide and carbon monoxide). A number of these parameters are used here to assess the performance of the two remediation technologies.

2.2. Method of assessment

The different types and use of decision support tools in the selection of remediation technologies has been described elsewhere for Europe [11] and the US [12]. Two methods are employed in this work, both of which utilise a life-cycle approach through the consideration of indirect as well as direct impacts (for example, in the excavation of raw materials). The first is a multi-criteria analysis (MCA), employed to give an indication of the overall impact complemented by an investigation and comparison of the individual impacts. This has been used to assess the overall benefits versus costs of the project, which satisfies Criterion 1 above. The second has been labelled as a life cycle analysis (LCA) method, and is used for the remainder of the Criteria 2–4, focussing on environmental impact and long-term effects.

The MCA method used here is based on that proposed by Postle et al. [13]. The method derives an overall score based on the performance of the technology under a number of categories (which have been expanded for this work). Scoring and weighting in the work presented here was performed in a semi-subjective manner, with data and available evidence used to justify values. Postle et al. [13] accept that subjectivity is possible in the method, but they suggest that clear records of decisions and reasons be kept. The analysis presented here includes brief justifications of the scores and weights used. Five categories of impact (human health and safety, local environment, third party/stakeholder concern, site use and global environment) have been assessed, using a total of eighteen subcategories. The following method has been used to calculate the overall impact of remediation:

- Development of four scores for each subcategory (during onsite, during offsite, after onsite and after offsite);
- Weights developed for each subcategory, for both onsite and offsite. The most important subcategory in each category is given a weighting of 1, and the others weighted relative to that;
- Scores and weightings are then multiplied to give category scores, which are divided by the total number of subcategory scores within them in order to ensure that any one category does not dominate;

- The category scores are then multiplied by category weightings, which represent the relative importance of each category, and then summed to give the overall score.

Because it is categories of information that are being compared (e.g. effect on groundwater quality or risks to public) rather than actual data, and they are all measured using the same scale, it is possible to aggregate the information into a single overall score. Sensitivity analysis was used to determine the sensitivity of the ranking order of the remediation techniques with investigation of the effect of variation in both the scores and weightings. Reasonable upper and lower bound scores were determined for each subcategory, largely on the basis of the accuracy of the data used for the original scores. Therefore, for scores directly determined 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). Four different sets of weightings were applied in the sensitivity analysis, each from a different point of view. These included overall weightings, expected view of a resident near the site, expected view of a resident near other involved sites and expected view of a developer.

The LCA method used for Criteria 2–4 takes into account a wide range of primary and secondary impacts of the remediation technology. This technique has been used previously for the assessment of remediation methods [7,14,15], although the data-intensive nature means that it is difficult to take into account every factor. Much of the data were also used in the MCA, but this analysis focusses on more specific areas and allows the impacts of individual parameters to be considered. Data from this analysis are not aggregated because it was considered important to display the relative importance of individual effects.

The functional unit employed in this study was the amount of soil remediated (i.e. data are presented and compared as ‘per tonne of soil remediated’), although in this particular case study a single site was used with the same amount of soil remediated in both cases. In addition, all foreseeable future impacts have been included as accurately as possible, with no time limit set.

2.3. Data used in this study

The actual remediation technique employed on the case study site was in situ S/S from which data was obtained for this analysis. The scenario of disposal to landfill was hence idealised under the same conditions in order to facilitate the comparison. Where site data was not available, predictions of the impacts were made. The analysis described here is based on that in Harbottle et al. [10], which has been revised and expanded. The case study site is a former industrial site adjacent to a river in a mixed industrial/commercial/residential area in England, and which has been developed for housing. The soil profile consisted of made ground over alluvium, gravels and an impermeable clay layer, contaminated (above the clay) with high concentrations of organic contaminants such as BTEX (benzene [to 1.2 mg/kg in soil and 0.61 mg/l in groundwater], toluene [to 400 mg/kg and 26 mg/l], ethylbenzene [to 1000 mg/kg and 2 mg/l] and xylenes [to 5000 mg/kg and 8 mg/l]) and total petroleum hydrocarbons (TPH; maximum of 8000 mg/kg and 4.3 mg/l). Remediation targets were based on Dutch Intervention Values [16]. On this particular site, S/S was favoured over landfilling mainly because of higher cost and disturbance associated with the latter method. The remediation involved the S/S treatment of hotspots and the creation of a barrier wall around the site.

Table 1
Data for the remediation by in situ stabilisation/solidification

Volume of soil remediated	4400 m^3/7040 t[a]
Stabilisation mix[b]	Cement:bentonite—2.5:1, water:dry grout—3.8:1, soil:grout—3.5:1
Distance from bentonite supply	88 km (80 km motorway, 6 km ‘A’ roads, 2 km local roads)
Distance from cement supply	24 km (19 km motorway, 3 km ‘A’ roads, 2 km local roads)
Site plant used	2 auger rigs + batching plant
Distance from plant hire	104 km (69 km motorway, 29 km ‘A’ roads, 6 km local roads)
Remediation outcome	Groundwater concentration reduced by 98%[c]

[a] Assumed bulk density of 1.6 t/m^3.

[b] Additives were used to increase the sorptive capacity of the mix, but these are not included here.

[c] Monitored as below target levels for 18 months. Leachate from S/S material satisfied objectives.

Details of the in situ S/S and landfilling remediation methods are given in Tables 1 and 2, respectively. A number of simplifications and assumptions have been made in order to develop the data presented. The distances to suppliers of resources or goods are included in the calculations, although any further transportation (such as transport of raw materials to manufacturers) is not included.

Other relevant information used is presented in Table 3. The rates of excavation (onsite and for raw materials) and other onsite work were calculated using data presented by Harris [17]. Allowance was made for the difficulty of extraction (e.g. clay compared to sand) as well as swell of excavated material and production loss. Data such as rate of fuel consumption used in this calculation are based on typical values from existing equipment (listed in Table 3).

The raw materials and energy used for cement production and electricity generation were also calculated and are presented in Table 4. Other materials used (e.g. bentonite,

Table 2
Estimated data for the remediation by off-site disposal in landfill

Soil disposal	4400 m^3/7040 t
Distance to landfill	96 km (80 km motorway, 14 km ‘A’ roads, 2 km local roads)
Resources used	7040 t clean fill (assumed similar properties to removed soil)
Distance to borrow pit	32 km (16 km motorway, 13 km ‘A’ roads, 3 km local roads)
Site plant used	Excavators, bulldozers, compactor
Distance from plant hire	As for S/S (Table 1)
Remediation outcome	Assumed all contaminants removed to landfill

Table 3
Other information (HGV: heavy goods vehicle)

HGV/tipper truck	Fuel consumption	2.8 km/l diesel
	Capacity	20 t
Excavator	Engine size	81 kW
	Fuel consumption	16 l/h
S/S auger rig	Engine size	160 kW
	Fuel consumption	32 l/h
Bulldozer	Engine size	108 kW
	Blade details	3.5 m length, 3 m^3 capacity
	Fuel consumption	49 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
Compactor	Details	Static weight roller, 3 m wide, performs six passes over 0.5 m lifts
	Speed	10 km/h
	Fuel consumption	23 l/h

Table 4
Production of consumables

Cement	Raw material (t/t cement) [18]	Limestone (1.095), shale (0.3375), sand (0.063), iron oxide (0.0045), coal (0.154)[a]
	Energy [18]	30 kWh/t cement (for grinding)
Electricity	Electricity production in UK [19]	Natural gas (37%), coal/lignite (34%), nuclear (23%), hydro/wind (2%), petroleum products (2%), biomass/geothermal (1%)
	Raw material (kg/kWh)	Coal (0.4), oil (0.29), natural gas (0.26), uranium ore (0.074)

[a] Assumed that clinker produced in coal-fired semi wet/dry rotary kiln. Approximately 1 Mcal/kg clinker (coal calorific value 6.5 Mcal/kg) [18].

coal) are assumed to have had no processing aside from extraction.

3. Results and discussion

3.1. Multi-criteria analysis (Criterion 1)

The scores and their justifications as used in the multi-criteria analysis for S/S and landfilling are presented in Tables 5 and 6, respectively. These are not derived in isolation, but are comparisons between the two techniques considered. Effects during and after remediation are considered, using a scoring system with a −100 to +100 range with −100 as the worst impact in a category, 0 as no impact and +100 as maximum benefit. Four scores are presented (during and after remediation, both onsite and offsite). ‘Onsite’ refers to the remediated site itself and ‘offsite’ to other sites that were involved, such as landfills, borrow pits or quarries. The methods used in determining impacts for a number of categories are described in more detail in Section 3.2. The weights used to aggregate the scores are presented in Table 7. Sub-category weights (both onsite and offsite) were developed with reference to the objectives of remediation (e.g. the safety of future site users and the cleanliness of the nearby river were deemed to be the most important factors in the remediation, and therefore risks to ‘site users/public’ and ‘surface water quality’ have maximum weights). The category weights were determined by assuming that the category of primary importance is human health and safety, and that local issues of site use, local environment and stakeholder concern are close behind. Global environmental effects, whilst still considered important, have been placed as less important than immediately local effects. This is again due to the known objectives of remediation (e.g. to protect human health and the nearby river). The overall score was then combined with overall financial costs (taking into account cost of remediation and estimated land costs/values) to give a final ‘cost effectiveness’ score.

The results presented in Tables 5–7 are a refined version of those presented in a previous comparison [10]. This is based on additional data that has become available since. Previously, the method identified the cost effectiveness by either dividing scores by costs (if any scores were positive) or multiplying by costs if all scores were negative. However, this could potentially lead to an erroneous ranking of negatively scored options in the former case (an option with a large negative score and large costs could rank better than an option with lower cost and less negative score). Therefore, in this work an amended method of cost-effectiveness analysis (CEA) has been used, treating the financial cost as an additional scoring category. The costs of each option were scored on the −100 to 0 scale (−100 for the most expensive, 0 for no cost), and weighted with subcategory and category weights of 1 (cost was assumed to be an important consideration). These additional scores were then added to the score from the MCA to give an overall result.

The weighted score for S/S was +18, with an estimated cost of remediation of approximately £ 28 t^{-1} of soil, which were combined to give the final ‘cost effectiveness’ of −34. For disposal to landfill, the weighted score was −38, the estimated cost approximately £ 55 t^{-1} of soil and so the final score −138. Therefore, S/S is ranked as having a lower impact (including cost) than landfilling. Sensitivity analyses showed that the overall ranking between S/S and landfill remained the same with reasonable variation in scores/weights. MCA scores and cost effectiveness are presented in Fig. 1 for each remediation option. Error bars on this plot indicate the range of potential scores/cost effectiveness as determined by the sensitivity analysis.

3.2. Life cycle analysis

3.2.1. Overall effects (Criterion 2)

The overall impact of remediation in the short term incorporates the effects of the contamination and the effect of the remediation process itself. The former are considered in this section, and the latter are discussed in Section 3.2.2 (Criterion 3).

Table 5
Scores and their justifications for MCA—stabilisation/solidification

Category	Criterion	Scores during		Scores after		Justification
		Onsite	Offsite	Onsite	Offsite	
Human health and safety	Risks to site users	−30	−5	90	0	Minimal contaminant emission and site work, little work or transportation offsite. Long-term reduction in risk due to contamination, no effects offsite
	Risks to public	−2	−6	10	0	Small amount of dust/odours, small number of HGV movements, transportation and dust relatively low offsite. Small improvement after due to contamination being stabilised (no offsite effects)
Local environment	Surface water quality	0	0	80	0	Improvement after through prevention of contamination reaching river onsite
	Surface water quantity	0	0	−100	0	Reduction in permeability of site due to solidified material
	Groundwater quality	0	0	95	0	Contamination reduced by factor of 50
	Groundwater quantity	0	0	−20	0	Reduction in site permeability
	Air quality (pollution)	−73	0	0	0	4.11 kg non-greenhouse emissions (all assumed onsite)
	Quality/structure of soil	−40	0	−40	0	Increase in pH, strength and reduction in permeability onsite. Stabilised mass remains for foreseeable future
	Habitat/ecology	−100	0	−40	0	Effective loss of soil and surface habitats during remediation. Continued loss of soil habitat although risk due to contamination is reduced
3rd party/stakeholder concern	3rd party/stakeholder confidence	0	0	0	0	No information
	3rd party/stakeholder acceptability	−1	−1	90	0	Relatively low noise, dust, odours, transportation on and offsite. Majority of risk from contamination removed
Site use	Duration of remediation	−100	0	0	0	2 months
	Impact on landscape	0	0	0	−5	Small impact from extraction of raw materials offsite
	Site use	0	0	83	−8	Potential future onsite use could be in any of five categories (residential, commercial, industrial, non-green and green public open space). Offsite, loss of 0.5 due to raw materials extraction
	Surrounding land use	−1	−1	100	0	Small impact due to congestion on and offsite. After: removal of blight, reuse of land
Global environment	Air quality (greenhouse gas)	−100	0	10	0	42.78 kg (all assumed onsite) After: −4.26 kg (absorption)
	Use of natural resources	−9	0	0	0	89.5 kg (during)
	Non-recyclable waste	0	0	0	0	None

Risks to human health were calculated for the long term using the Contaminated Land Exposure Assessment (CLEA) model [20], but only for contaminants currently in the CLEA database. For this assessment, the model used a female between the ages of 0 and 6 as the target receptor, sandy soil (pH 7), inhalation and oral exposures (all pathways), residential land use with ground-bearing slab and with pressure driven flow in winter. The options chosen are either based on known site information (e.g. soil) or are default options in the program for residential end use of the site, and are considered the most critical scenario. After remediation by S/S, the CLEA analysis was performed by assuming the soil type was now clay, with a pH of 11 and all contamination concentrations remaining the same (thereby modelling the high pH, low permeability nature of the cement-stabilised soil, although this most likely gives an overestimate of the exposure as the S/S mix was designed to have an increased sorptive capacity). The pathways were reduced to inhalation only due to the solidification process (the possibility of inhalation of dust was thought minimal, but was included as a worst case). The output is given as the ratio of the average daily exposure (ADE) to the index dose (ID) or tolerable daily intake (ADE/ID) (a measure of the level of minimal risk, or the no-effect concentration, depending on the contaminant). In this case, because of the presence of a number of contaminants, the maximum ADE/ID is taken and divided by the maximum prior to remediation to give an indication of the maximum worst risk afterwards compared to if remediation was not performed. Excavation and disposal was assumed to remove the contamination and so had a before/after

Table 6
Scores and their justifications for MCA—disposal to landfill

Category	Criterion	Scores during		Scores after		Justification
		Onsite	Offsite	Onsite	Offsite	
Human health and safety	Risks to site users	−100	−100	100	−5	Highest risk due to contaminant emission and site work (on and offsite). Reduction in contamination risk (small risk of escape of contaminants offsite)
	Risks to public	−100	−100	20	−5	Large effects of dust and transport on and offsite. After, improvement due to contamination removal onsite, small contaminant escape risk from landfill
Local environment	Surface water quality	0	0	100	−5	No effect during remediation. Onsite improvement due to source removal, small risk of escape from landfill
	Surface water quantity	0	0	0	0	No effect
	Groundwater quality	−5	0	100	−5	Small risk of contaminant escape during excavation. After, removal of all contamination, although small risk of escape from landfill
	Groundwater quantity	−100	0	0	−5	Disturbance/dewatering during groundworks. Possible small effect due to landfill cap/liner
	Air quality (pollution)	−100	0	0	0	3.88 kg non-greenhouse emissions
	Quality/structure of soil	−100	−40	10	−20	Loss of structure onsite due to excavation, contamination all transferred offsite
	Habitat/ecology	−100	−80	50	−20	Loss of surface/soil habitats onsite plus surface on landfill site. After, habitat restored onsite, although contamination remains in landfill
3rd party/stakeholder concern	3rd party/stakeholder confidence	0	0	0	0	No information
	3rd party/stakeholder acceptability	−40	−20	100	−50	Largest impact from noise, dust and transportation on and offsite. After, no risks remain onsite but landfill remains unpopular
Site use	Duration of remediation	−50	−50	0	0	1 month (includes work on landfill, borrow pit)
	Impact on landscape	0	0	0	−100	Long-term negative impact of landfill
	Site use	0	0	100	−67	Potential future onsite use could be in all six categories (residential, industrial, commercial, agricultural, non-green and green public open space). Offsite, loss of four due to raw material extraction and landfill
	Surrounding land use	−20	−20	100	−80	Largest impact due to congestion on and offsite. After, removal of blight and reuse of land onsite but blight associated with landfill
Global environment	Air quality (greenhouse gas)	−31	0	−1	0	12.85 kg during and 0.35 kg after
	Use of natural resources	−100	0	0	0	1005.6 kg used
	Non-recyclable waste	−100	0	0	0	1000 kg disposed of

ratio of 0, whereas S/S has a value of 0.07 (i.e. the maximum risk afterwards [due to ethylbenzene] is 7% of that initially [due to toluene]).

A number of contaminant concentration benchmarks exist for ecosystems (or parts of them), and those that have been used here were determined primarily from the Oak Ridge National Laboratory (ORNL) Risk Assessment Information System Ecological Benchmark Tool [21]. These include, for soil, Dutch guideline and target values [16], various US Environmental Protection Agency (EPA) measures including Ecological Soil Screening Levels (Eco-SSL) and ORNL soil screening benchmarks, which cover a variety of types of wildlife receptor. For groundwater, Dutch values are used, and surface water screening benchmarks include the following: Canadian water quality and various species-specific measures; various US EPA measures; lowest chronic values (LCV); National Ambient Water Quality Criteria and secondary chronic and acute values. The contaminant with the most onerous ratio of site concentration to benchmark level (for all available benchmarks) is considered to be the worst case and is used to represent the site. A ratio for soil was not determined for S/S, as the contamination remains at the same levels before and after remediation, whereas the bioavailability will be significantly affected. In groundwater, the risk ratio is 0.009 and in surface water it is 0.04 (assuming Dutch Intervention Values were just met). As with risk to humans, the process of excavation and disposal was assumed to remove risks due to contamination.

The number of categories of potential future use is a measure of the versatility of the sites involved following the remediation process (including both the site itself and any other areas

Table 7
Weights and justifications for MCA (on: onsite; off: offsite; cat: overall category weights)

Category	Criterion	Weights			Justification
		On	Off	Cat	
Human health and safety	Risks to site users	1	0.5	1	Onsite: future residential use. Offsite: few site users, for working hours only
	Risks to public	1	0.5		Onsite: high population in local area. Offsite: low population near landfill
Local environment	Surface water quality	1	0.7	0.9	Onsite: protection of the river is an objective of the project although groundwater flow and expected probability of significant impact are low. Offsite: nearby lakes for recreational use
	Surface water quantity	0.2	0.2		Onsite: water not used for abstraction, small site. Offsite: little effect on nearby lakes
	Groundwater quality	0.8	0.7		Onsite: shallow aquifer, not used for drinking but important for river quality. Offsite: some importance due to nearby lakes
	Groundwater quantity	0.2	0.2		Onsite: not used for abstraction, slight importance for river. Offsite: slight importance (nearby lakes)
	Air quality (pollution)	0.7	0.5		Onsite: high local population. Offsite: low local population
	Quality/structure of soil	0.2	0.1		Onsite: slight importance due to construction. Offsite: little importance as contained in landfill
	Habitat/ecology	0.1	0.3		Onsite: low importance. Offsite: landfill near to nature reserve
3rd party/stakeholder concern	3rd party/stakeholder confidence	0.8	0.6	0.8	Onsite: local/site population is high and so remediation affects more people. Offsite: lower population
	3rd party/stakeholder acceptability	1	0.7		
Site use	Duration of remediation	0.6	0.4	0.9	Onsite: important due to disturbance and need for development. Offsite: less important
	Impact on landscape	0.5	0.7		Onsite: some importance—high local population but is in urban area and to be redeveloped. Offsite: rural area so some importance
	Site use	1	0.6		More important in urban area due to pressure for land
	Surrounding land use	0.8	0.6		
Global environment	Air quality (greenhouse gas)	1	1	0.7	Global importance—equal weights
	Use of natural resources	1	1		
	Non-recyclable waste	1	1		

impeded by the presence of the contaminants, e.g. landfill). Here, it is a simple sum of the potential categories of use for the remediated site and other sites. The categories are: green space, agricultural, residential, commercial, industrial and non-green open space. An S/S-remediated site is expected to be useable for residential, industrial, commercial and green and non-green open space use (a score of +5), although this is reduced by the effect of raw material extraction offsite (dependent on the amount of material relative to the amount remediated). The overall site use score for S/S was 4.5. For landfill disposal, effects on the landfill are counted as positive, assuming that the landfill site was in a former quarry to begin with. For example, the ‘landfill’ remediation option has all 6 potential uses onsite after remediation, and has +2 on the landfill site (regains possible use for green and non-green open space). The loss of use of land for the borrow pit, however, is given a score of −6 (loss of all categories), giving a total of 2.

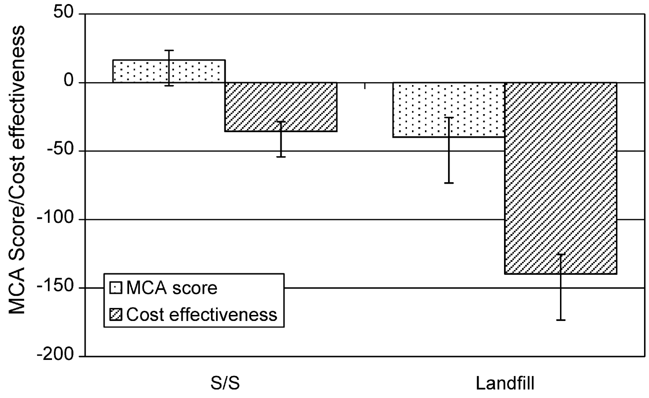

Fig. 1. Comparison of scores and cost effectiveness from the multi-criteria analysis. Error bars represent the upper and lower limits of these values as determined by sensitivity analysis.

Long-term effects on air pollution and soil properties are taken into account when considering the effects of the remediation process in Section 3.2.2.

3.2.2. *Process effects (Criterion 3)*

It is assumed for the purposes of this assessment that the material used to replace the soil disposed of in landfill would have similar properties before and after remediation. With S/S, although the site soil remains, its properties would change significantly—strength may increase typically by 300–800%,

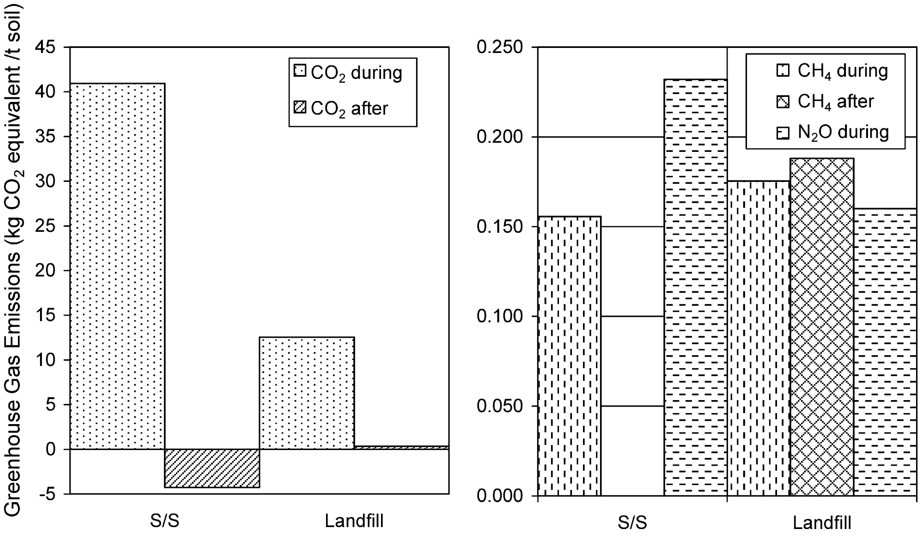

Fig. 2. Greenhouse gas emissions (during/after remediation) in terms of global warming potential.

whereas permeability may reduce by a factor of between 10^2 and 10^4. In addition, the pH would increase substantially, up to a maximum of approximately 12.

Emissions from sources such as road transportation (to landfill, during supply of resources, etc.), off-road work (excavation of contaminated soil, raw materials, etc.), electricity generation and cement production have been calculated using emissions tables presented by the UK National Atmospheric Emissions Inventory [22] for a range of pollutants. Gaseous emissions from landfill or from untreated soil are calculated using the Intergovernmental Panel on Climate Change (IPCC) Tier Two methodology (as described in Gregory et al. [23]), assuming the organic matter content of the soil is 2% (a typical value for a sandy surface soil, as the actual value was not available). Total emissions are presented in Fig. 2 (greenhouse gases during and after remediation) and Fig. 3 (other pollutants during remediation). The overall effects of greenhouse gases are indicated by their global warming potential (GWP). Methane, for example, has a GWP of 21 over 100 years [24], indicating that it has 21 times the effect of CO_2. Nitrous oxide (N_2O) has a GWP of 310 over 100 years. Cement production accounts for the largest proportions of CO_2 (91%), N_2O (88%) and general nitrogen oxides (90%), sulphur dioxide (93%), black smoke (91%), mercury (99%) and lead (90%) during S/S remediation, and is the main explanation for why these contaminants are all higher for this method (Figs. 2 and 3). The majority of the emissions of remaining contaminants are due to vehicle/plant emissions (between 95 and 100% for both S/S and landfilling). This explains why landfilling has higher emissions of these compounds, as this has greater use of such equipment. The negative emission of carbon dioxide after remediation in S/S (Fig. 2) is due to the assumption that the cement will absorb 0.1 kg of carbon dioxide per kg over time. Otherwise, emissions of CO_2 and CH_4 after remediation are due to degradation of organic matter in landfill. No biological production of either CO_2 or CH_4 was assumed in S/S due to the conditions within the solidified material being

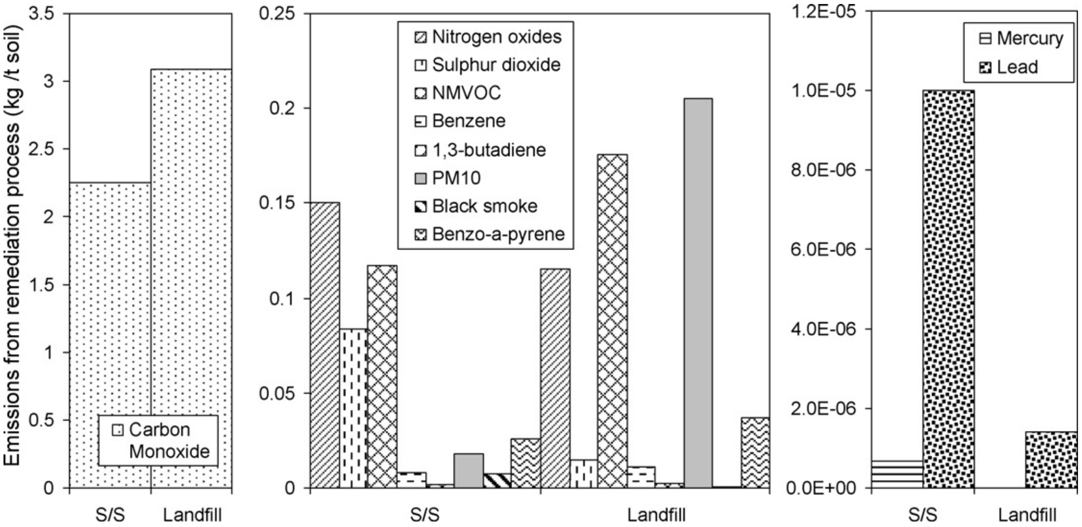

Fig. 3. Gaseous emissions during remediation [PM_{10}—particulate matter; NMVOC—non-methane volatile organic compounds].

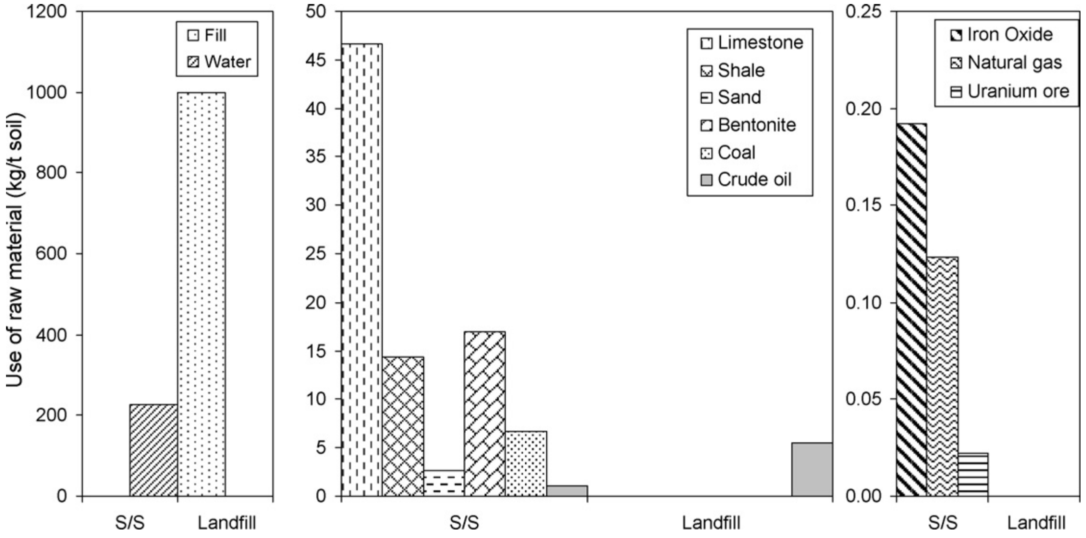

Fig. 4. Use of raw materials.

unsuitable for microbial growth. In reality, there may well be production of these gases over time as the S/S system breaks down, but prediction of the extent or rate of production was not attempted here. Also, the actual amount of gas produced will be small compared to other sources considered here (e.g. transport, cement production) and so this particular impact has not been considered further in this study.

Fig. 4 shows the use of raw materials (calculated from the information in Tables 1–5). All materials used in S/S remediation, other than crude oil and a small amount of coal, are due to the production of cement, whereas the use of fill is the major source of material for disposal to landfill.

The data from additional parameters considered are presented in Table 8. Parameters compared include: total road travel (by road type, as a measure of off-site disturbance); density of heavy goods vehicle (HGV) arrivals and departures per month; remediation location (in situ remediation as better than ex situ, onsite better than offsite); breakage in pollutant linkages; time-scale; energy used; waste produced. The total amount of material extracted or dumped offsite is included as a measure of the disturbance to areas other than the remediated site itself.

Table 8
Data for additional parameters

	S/S	Landfill
Total road travel (km/t soil)		
Motorway	0.30	9.70
‘A’ road	0.06	2.74
Local road	0.02	0.51
HGV movements per month[a]	25	1418
Noise[b]	61.5	65.5
Remediation situation	In situ onsite	Ex situ offsite
Break in pollutant linkage	Pathway	Source
Duration of site work	2 months	1 month
Energy (electricity)	1.28 kWh/t	0
Off-site waste disposal	0	1000 kg/t
Material excavated/dumped offsite[c]	89 kg/t	2004 kg/t

[a] A measure of disturbance in the site vicinity.

[b] Assessed using method of Wills and Churcher [25].

[c] A measure of the effect on other sites.

3.2.3. Long-term effects (Criterion 4)

The remediation of the site by disposal to landfill was assumed to leave no contamination above the target values on the site itself, and so there are assumed to be no long-term effects associated with the site in this case. Considering the contaminated soil in the landfill site, it might be expected that organic contaminants would eventually be degraded within the landfill. Monitoring and maintenance of the landfill itself was assumed to take place for up to 40 years after closure, with cap and liner condition, leachate monitoring and collection, and leakage, gas and groundwater monitoring [26]. These were expected to be required less frequently as time went on, however. The durability of a modern engineered landfill can be difficult to predict, although if post-closure maintenance is maintained then there is no reason it cannot last for many decades.

At the site used in this paper, groundwater was monitored for 2 years after S/S remediation to ensure that no significant leaching of contaminants was taking place. As the stabilised/solidified mass would be buried, no post-closure maintenance will be performed. There has been a limited number of investigations of the long-term effectiveness and durability of S/S contaminated soils which included case studies of sites with conditions similar to those used in this [27–29]. Those case studies investigated the long-term behaviour of S/S treated soils from contaminated sites after 3 to 5 years and noted no significant deterioration over this period. This offers some level of confidence in the medium-term behaviour of S/S treated soils. Clearly knowledge of the much longer-term behaviour is required and although this is being addressed in an extensive laboratory programme using accelerated ageing techniques [30–32], there is no substitute for real time data.

The fact that the contaminants remain in the ground following S/S treatment would clearly remain a major concern even if the long-term validation is being investigated. This is currently being addressed by investigations of the feasibility of incorporating some form of contaminant attenuation such as biodegradation, in order to reduce the contamination remaining on site.

In the long term, therefore, a landfill is more likely to be better maintained and may allow more effective isolation of the contaminants from the environment. It might also be more likely to allow long-term attenuation of the organic contaminants. However S/S is likely to facilitate more sustainable use of the soil as a resource because the soil is treated and immediately reused while attenuation of contaminants in a landfill takes too long for the soil to return to a usable form.

3.2.4. General discussion on the life cycle analysis

Because of the nature of the LCA analysis carried out no attempt will be made here to label one method as better than the other due to the difficulties of comparing disparate categories of information. However, it is possible to say that S/S performed better than landfilling in a number of areas, particularly in terms of materials used and waste produced. It is perhaps surprising to note that the predicted emissions are sometimes greater for S/S—this is primarily due to emissions from cement production. Several criteria indicate that S/S has a greater impact than off-site disposal on the site itself, which is perhaps true in the long term, due to the assumed complete removal of the contamination for the latter. However, several of these factors do not currently include a full measure of the effect on the landfill site, which must be included to fully assess all impacts.

This analysis of the impacts of remediation has highlighted several points that could be tackled to create a more sustainable solution. For example, with S/S, major impacts include the emissions from cement production. This might be offset by using modern cements designed to reduce energy requirements. The inclusion of some form of biodegradation in conjunction with S/S would be advantageous, as this would introduce a degree of attenuation with time, something which S/S is not currently designed for. A major impact of landfill is the transport of materials offsite, contributing to emissions, consumption of crude oil and disturbance. Where possible, onsite landfilling might be considered, as this would reduce all of these impacts, but might mean that construction was hampered. The recycling of uncontaminated material such as concrete as fill to replace excavated contaminated soil is now commonly used, and can have a significant positive impact on the amount of material transported offsite for disposal.

4. Conclusions

The technical sustainability of the treatment of a contaminated site using in situ stabilisation/solidification and off-site disposal to landfill were compared using previously developed criteria. Multi-criteria analysis was used to compare overall costs and benefits of the two techniques. For S/S it gave a weighted score of +18 and an estimated cost of remediation of approximately £ 28 t^{-1} of soil, giving a ‘cost effectiveness’ score of −34. For disposal to landfill the weighted score was −38, the estimated cost approximately £ 55 t^{-1} of soil giving a cost-effectiveness score of −138. Hence given the level of information used in the analyses, S/S is ranked as having a lower impact (including cost) than landfilling.

From the life cycle analyses performed to compare the environmental impact it was apparent that the further advantages of S/S are lower material usage, potential ground improvement for immediate reuse and a lesser impact on the local community during the process. However, the contaminants remain on the site, which entails a great deal of uncertainty for the future. In addition, the associated emissions are relatively large. Hence improvements to S/S must consider the incorporation of some form of contaminant attenuation such as biodegradation, in order to reduce the contamination remaining on site. Other potential improvements include the use of more environmentally sustainable cements. The technical sustainability assessment presented in this paper shows that S/S performs better than disposal to landfill in most, but not all, respects. It also highlighted areas that can be improved upon in terms of delivering a more sustainable S/S solution. It should be emphasised that the outcome of the analysis is governed by the amount of information available and the level of assessment of information required.

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