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A GIS raster technique to optimise contaminated soil removal

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Abstract

A geographic information system (GIS) raster technique has been developed and used interactively with remediation designers to evaluate the optimum extent of excavating soil contaminated by chlorinated solvents. The technique and the results of its application are presented. The site was a former chemical storage plant for acids and solvents. Two distinct solvent plumes were detected within the ground using a photo-ionisation detector. The solvents were found to be dissolved in the groundwater and migrating in the general direction of groundwater flow. A remediation strategy was proposed involving the localised excavation of contamination 'hot spots' followed by the implementation of a groundwater remediation system. A number of excavation options were discussed and the GIS raster technique was developed to evaluate these options in terms of contaminant removed and excavation cost.

The plumes were initially mapped using a triangular irregular network (TIN). These TIN models were rasterised to produce a regular grid of rectangular cells, each cell having a value relating to the concentration of contaminant at that spatial point. The proposed excavation zones were then overlaid on to the raster models as masks. The relationship between the value of contaminant concentration of cells within the mask (or excavation zone) and the total value of contaminant concentration of cells within the solvent plume was used to determine the efficiency of the excavation.

The excavation options were compared taking into account the percentage of the contaminant plume removed, the excavation area (soil volumes) and related costs. Once the GIS raster technique had been developed, it proved very quick to rerun the analysis for the other excavation zones. The optimum excavation zone, based upon cost and contaminant recovery, was found for the site. The technique helped by targeting the worst area of contamination and provided the client with a cost-benefit analysis of the different remediation options. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Remediation; Geographic information system; Contamination; Volatile organic compounds; Modelling

1. Introduction

A geographic information system (GIS) has been used extensively within WS Atkins Consultants Ltd. to assess and design remedial and reclamation work on former industrial sites. It has become a standard tool for such projects where large quantities of data need to be stored, linked and interrogated to produce visual maps of information (Hellawell et al., 2001). In addition to the standard functions of GIS, the spatial modelling facilities have also proved extremely useful for calculating the soil or waste volumes. This paper describes a technique that utilises these spatial modelling functions for mapping a contaminant plume and evaluating the excavation options to remove contaminated soil, in terms of efficiency and cost.

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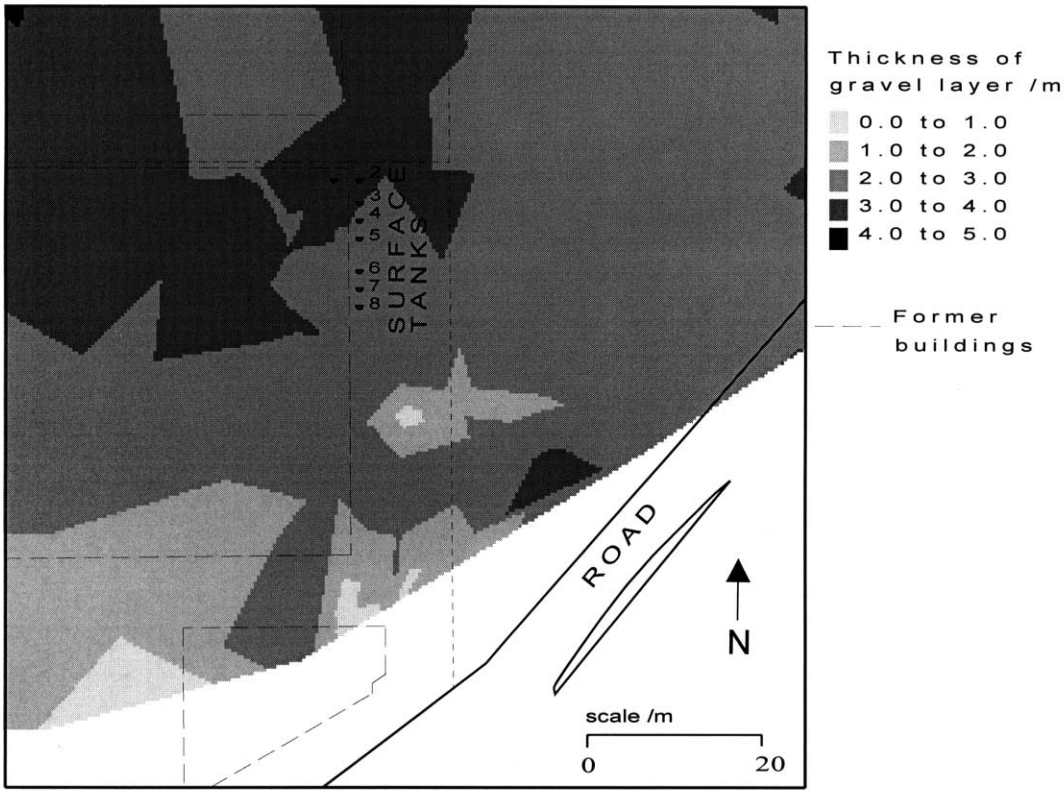

Fig. 1. Plan view of the thickness of the gravel layer.

2. Site

The site in Western Europe had been used for the storage, bottling and packaging of chemical liquids including solvents and acids. During the 1960s, eight above ground storage tanks were constructed that were used to store, pending bottling, a variety of acids (acetic, hydrochloric and sulphuric) and solvents (formaldehyde, trichloroethene, tetrachloroethene and chloroform). Occasional spillage or leakage of these solvents occurred. Acid spills were usually neutralised with soda ash and washed into the nearest foul sewer. It is believed that some parts of the drainage system were damaged as a result of the acidic conditions.

The tanks were removed in the 1970s and the eastern quarter of the site is currently occupied by a warehouse, offices and a car park. The remainder of the premises is currently non-operational and contains the floor slabs of the demolished former works buildings.

3. Site investigation and contaminant mapping

An extensive site investigation was carried out. This included a historical desk study, preliminary site investigations and assessment, the installation of boreholes and a detailed trial pit investigation, and a soil vapour and groundwater survey. Soils headspace testing combined with laboratory analyses were used to determine the lateral and vertical extents of solvent contamination. Sampling locations were selected following the interpretation of earlier preliminary investigations and groundwater monitoring.

The geology of the site is 0.5–1.5 m made ground overlying approximately 4 m thick gravels and a thick layer of clay. Solvent contamination was predominantly found within the gravels, with the clay acting as an impermeable barrier. The gravel layer comprised gravely coarse sand, very sandy gravels with occasional clayey lenses. GIS models of the geological strata were produced from the site investigation data and used to create maps showing the thickness of the gravels (Fig. 1) and the location of the clay barrier layer. Borehole water levels indicated that the groundwater was 1–2 m below ground level (BGL) and that the groundwater flow was in a south-easterly direction.

Soil samples were taken at 0.5 m intervals at each trail pit location until the clay layer was reached at about 4 m BGL. Fig. 2 shows the sampling locations. These were limited to the north by the location of the existing buildings and foundations. Each sample was split into two sample vessels. Two photo-ionisation detectors (PIDs) with different ionisation levels were then used to test the samples for volatile organic compounds (VOCs). Using two detectors enables a wider range of volatile species to be investigated. The VOC concentrations were determined from the headspace readings on the soil samples coupled with laboratory quantitative analysis.

The ground investigations did not identify the free-phase chlorinated solvents. These may, however, have occurred near the contaminant source, at the capillary fringe. The chemicals detected were dissolved in the groundwater and had migrated in the general direction of groundwater flow in the shallow gravels (towards the south-east). Despite the former uses of the site, there was little evidence either of contamination of the made ground or of a source of VOCs in the unsaturated zone.

To understand the extent of the contamination problem, a plan view of the plume at the different sampled depths was required. Horizontal slices through the plume at 0.5 m depth intervals were produced, giving a pseudo three-dimensional map. The PID readings from each depth were used to produce a triangular irregular network (TIN) contamination model. TIN is a standard facility that is available in many GIS packages in which data points are

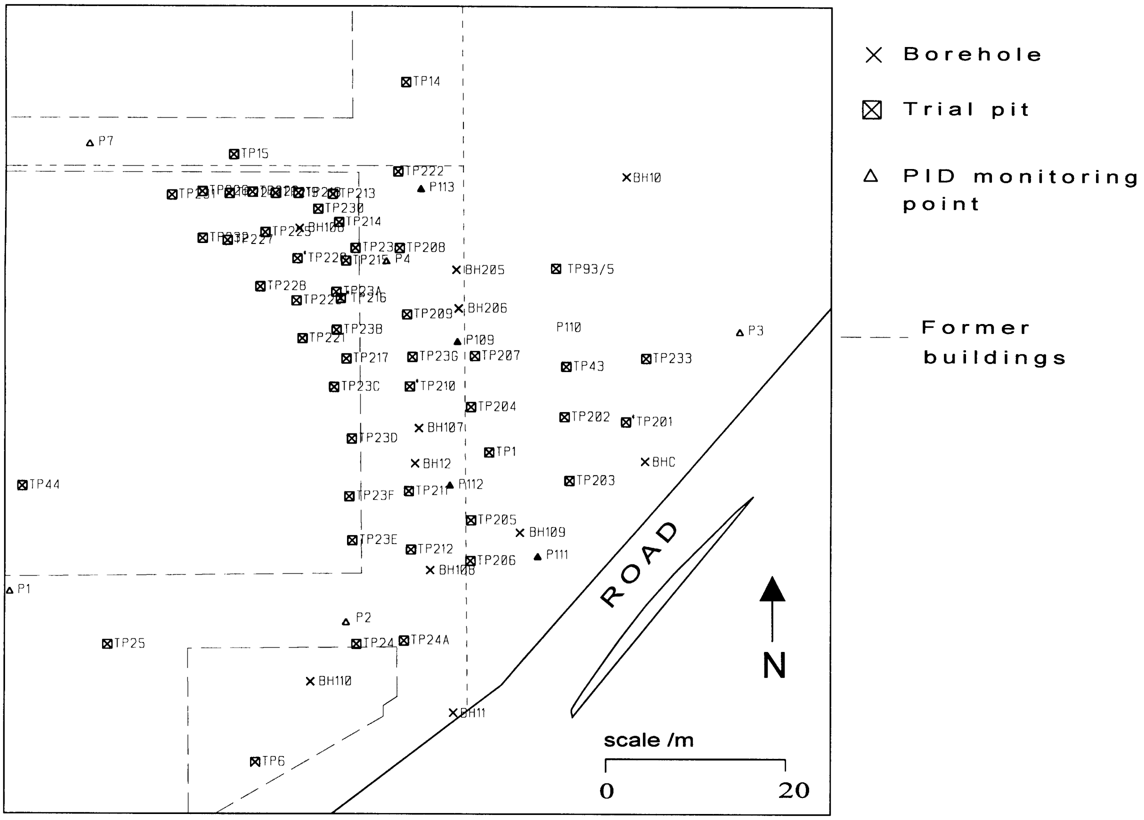

Fig. 2. PID sampling locations across the site.

connected to form a set of non-overlapping triangles (Fig. 3). These triangles form a surface between the three data points. The value of any point on the triangular surface is obtained by linear interpolation. (Further explanation of GIS terms and functions used in this paper are detailed in Chrisman (1997)). Contour maps of the plume at each depth were then produced from the TIN models (Fig. 4) and overlaid, within the GIS, on to the site maps.

These contaminant maps revealed two 'hot spots' of contamination with the plume. Although no direct

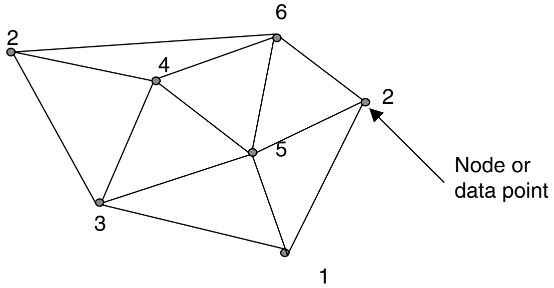

Fig. 3. Schematic of a triangular irregular network for six points.

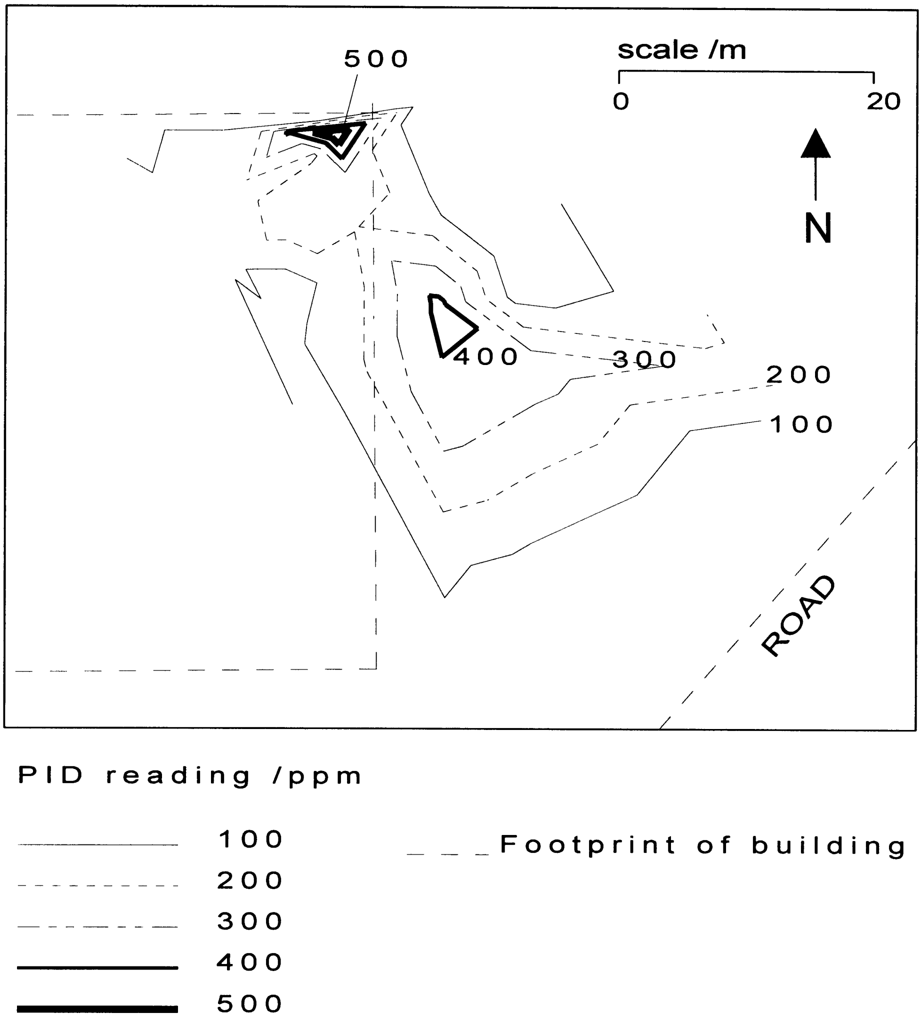

Fig. 4. Contoured concentrations of VOC at 3.0 m depth.

sources of VOCs were detected in the capillary fringe above these hot spots, their locations were linked to previous site activities:

- Hot spot 1 was centred near the north-western corner of the site and was probably caused by spillages on the 'wet floor' area of the works. Typical groundwater VOC concentrations within the plume were 130 mg/l.
- Hot spot 2 was located in the vicinity of former

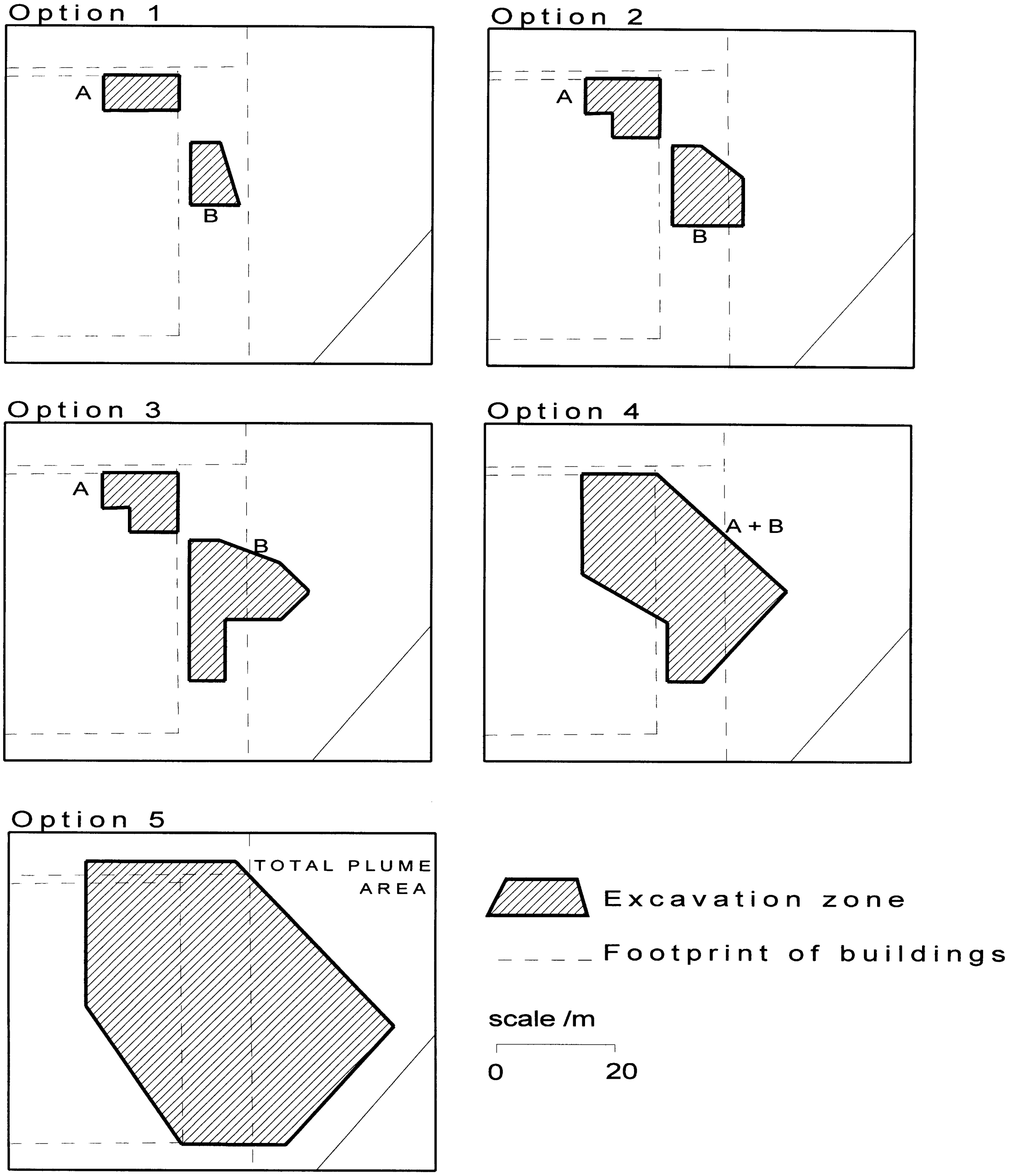

Fig. 5. The five excavation options considered.

tank filling operations and probably resulted from the overfilling of these tanks and/or the leakage of solvents from a damaged drain. Groundwater VOC concentrations were typically 70 mg/l.

Fig. 4 indicates that the contaminant plume may also extend to the north of the sampling area. The existing foundations, the identification of the contaminant source and the direction of groundwater flow, however, reduce this possibility. Diffusion is therefore the only transport mechanism causing the pollutant to migrate northwards.

4. Remediation design

The remediation strategy was developed based upon the results of site investigations, the groundwater monitoring and risk assessment studies. The specific objectives of the remediation works were to remove the majority of the solvent sources present and reduce groundwater contamination concentrations in the remaining soil using an active groundwater remediation system. In addition to significantly reducing the heaviest existing contamination, the remedial action was designed to minimise the potential for future mobilisation of any residual contaminants and, therefore, to reduce the risk of migration off-site.

The remediation was to be achieved by localised excavation of soil in the worst affected areas (with disposal of waste materials to the licensed landfill) followed by implementation of an active groundwater remediation system. The issue to be explored was the optimum level of excavation, taking into account the contaminant mass removal and associated cost.

Five excavation options were proposed (Fig. 5). These were defined using professional engineering judgement based upon the contour maps of the contamination plume. All the excavation zones were centred upon the identified hot spots. Options 1–3 comprised two discrete excavation zones. For Option 4 these excavation zones merged. Option 5 was the most expensive and involved the excavation of the maximum predicted extent of the contaminant plume.

A method was required to evaluate these remediation proposals in terms of the mass of the contaminant plume removed, and the excavation and disposal costs. The following technique was developed using the spatial analysis functions of GIS.

5. Optimising excavation efficiency

A raster model presents the spatial data as a matrix of cells or pixels (AGI, 1998; Chrisman, 1997). Each cell is a discrete unit of data (Fig. 6). In this problem, each cell represented the concentration of VOC at the cell's location. A spatial grid was therefore defined, made up of 150×100 rectangular cells of dimensions $0.4 \times 0.35\ \mathrm{m}^2$, covering the area of the contaminant plume. The pseudo, three-dimensional raster spatial model was created by re-sampling the TIN contamination models for each 0.5 m depth slice. This re-sampling changed the triangular model into a rectangular cell model. Using linear interpolation, a PID value was determined for each cell using the data from the discrete sampling points.

The sum of the PID values of the cells was evaluated for each raster model. A spatial mask was then created to delineate the boundary of the excavation zone. In the mask, the cells within the excavation were flagged with a code set to unity and the flags for all other cells were null. The mask was overlaid on to the raster model of the plume leaving just those cells within the excavation active (Fig. 7).

The efficiency of an excavation was determined by adding the PID values for the active cells and dividing this by the total PID values for all the cells in the surveyed area, for each 0.5 m model. Hence, the percentage of the plume removed by the excavation

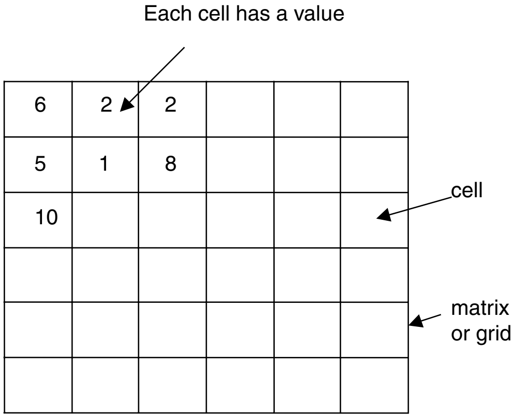

Fig. 6. Schematic of a GIS raster model.

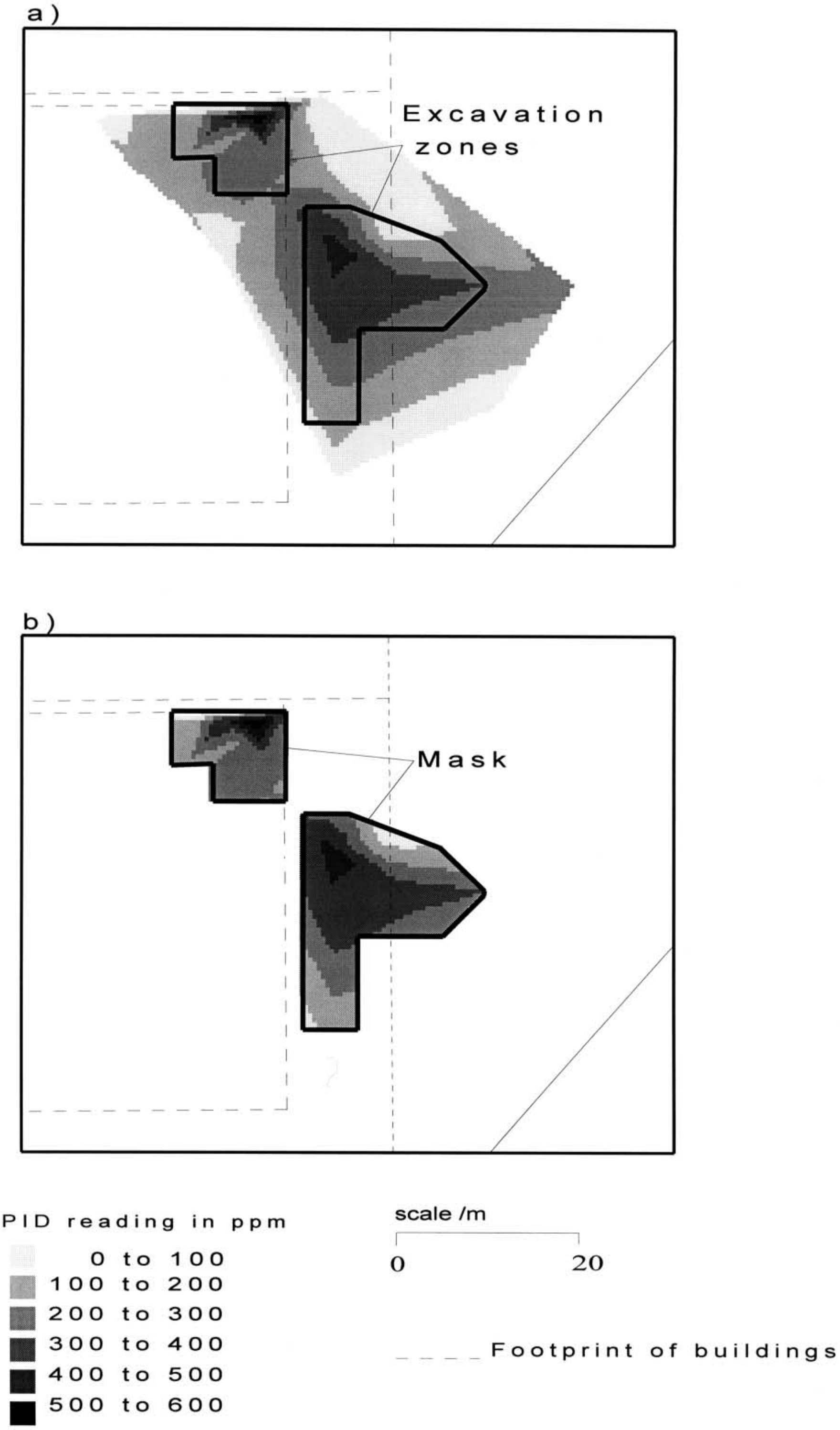

Fig. 7. Raster maps of the contaminant plume at 3 m depth showing the known extent of the plume (a), with the mask for excavation Option 3 overlaid (b).

was calculated from:

$$\% \text{ of plume removed} = \sum_{\text{depth}=0.5\text{ m}}^{\text{depth}=4\text{ m}} \left(\frac{\sum \text{PID values of nodes within the excavation boundary}}{\sum \text{PID values of total surveyed area}} \right) \times 100.$$

The cost of the excavation was then calculated based upon the volume of soil removed and its disposal cost. A simple estimate was initially used in which the disposal costs increased linearly with the contamination volumes.

6. Results

An example of the calculation and results for excavation Option 3 is shown in Table 1. This process was repeated for the five different excavation zones. The results for the five options are shown in Table 2 and plotted in Fig. 8. Options were compared, taking into account the percentage of VOC removed, the excavation volumes and the disposal costs to enable selection of the optimum excavation strategy.

With reference to Fig. 8, the rate of contaminant recovered is initially high and begins to fall when the excavation exceeds 30% of the calculated areal extent of the plume. Recovery is therefore more efficient, in terms of percentage of VOC removed and cost, below this 30% threshold. Above this threshold, recovery becomes increasingly less efficient and therefore less economic, with the contamination recovery rate steadily decreasing as the costs continue to rise in line with the excavation volume. The plot reflects the localised nature of the contamination with approximately 65% of the contamination being held within the two hot spot zones, which occupy about 30% of the total area of the plume.

For remediation, the GIS analysis demonstrated that excavation Options 1–3 lie below the threshold value and could therefore be considered efficient. Of these, Option 1 is the most efficient, in terms of maximising the ratio of percentage of VOC removed to cost; however, this option would leave high concentrations of contamination within the groundwater, increasing the timescale and costs of the in situ groundwater remediation phase. Option 2 would involve the removal of approximately 1000 m^3 or nearly 15% of the total area of the plume, and would recover almost 40% of the contamination at a cost of just over £50,000 ($80,000). Option 3 would recover a further 12–13% of the VOCs but the cost would escalate to over £80,000 (a 51% increase on Option 2). Hence, Option 2 was eventually chosen. The remaining contamination can be more economically recovered using the proposed in situ groundwater remediation system than by soil excavation.

Table 1
Calculation of excavation efficiency for Option 3

Depth of slice (m)	Total VOC concentration of plume (sum of all nodes) (ppm)	VOC concentration in excavated nodes (ppm)	% of plume excavated
0.5	54,764	29,078	53.1
1.0	324,278	180,727	55.7
1.5	132,086	85,141	64.5
2.0	348,725	213,435	61.2
2.5	559,744	310,388	55.5
3.0	824,219	395,101	47.9
3.5	689,958	321,898	46.7
4.0	574,794	271,186	47.2
Total	3,508,568	1,806,954	51.5

Table 2
Summary of results of the excavation analysis for the five options

Option	% of total area	% of VOCs removed	Cost (£)	Volume (m^3)
1	8.4	24	30,450	580
2	14.5	39	52,920	1008
3	22.1	52	80,325	1530
4	40.4	78	147,000	2800
5	100	99	364,014	6934

7. Discussion

This case study demonstrates the use of spatial analysis in remediation design. Once the process had been developed, it proved very quick to rerun the analysis for a modified excavation zone. The result is necessarily an estimate. There is some uncertainty in the analysis due to the spatial derivation and the two-dimensional assumptions for the plume. Increasing the number of PID sampling points and using more sophisticated interpolation techniques (e.g. Kriging) will reduce this uncertainty. However, the output must be considered a decision aid rather than a definitive answer.

This GIS raster optimisation technique does not constitute a full cost-benefit analysis of remediation as it only focuses on the excavation component. However, using the technique, the implications of different scenarios for excavation can be readily investigated. The output provides a rationale for deciding the extent of excavation that may be appropriate.

For this case study, the results obtained have not been compared with actual excavation values, as the remediation phase has yet to take place. Recent changes in landfill disposal costs and the emergence of improved in situ remediation technologies have led to air sparging and natural attenuation being considered to remediate the site. In this case, the excavation costs, derived from the GIS raster technique, should now be compared with the costs of these alternative remediation strategies. The next phase of this research is to develop the GIS raster technique to help optimise the design of these in situ remediation processes on the site.

8. Conclusions

Spatial analysis and GIS were shown to be useful aids in remediation design. The technology was used to map a contaminant plume and determine the most efficient locations and extent for excavation and contaminant removal. The GIS raster optimisation technique helped by targeting the worst areas of

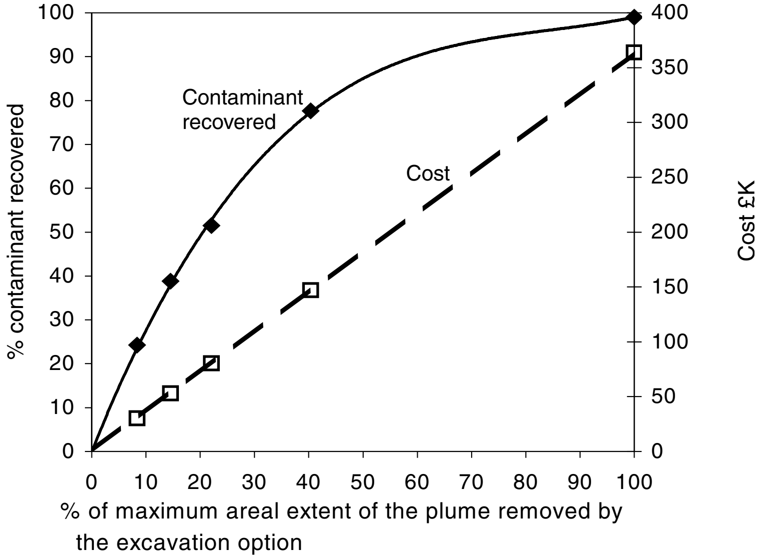

Fig. 8. Results of the excavation sensitivity analysis showing the percentage recovery of contaminant and the cost incurred.

contamination and provided the client with a cost-benefit analysis of the excavation phase of the remediation scheme.

The accuracy of the GIS technique is affected by the number and spatial distribution of the sampling points in relation to the contaminant plume. The technique is most appropriate for comparison of remediation schemes (excavation areas) rather than for predicting absolute contamination volumes.

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