Project Siren:- Phase 2a
Benchmarking of Monitored Natural Attenuation Procedures

R&D Technical Report P2-208/TR/1

AEA Technology Environment,
Shell Global Solutions

Further copies of this report are available from:
Environment Agency R&D Dissemination Centre,
c/o WRc, Frankland Road, Swindon, Wilts SN5 8YF

tel: 01793-511711 fax: 01793-514562 e-mail: publications@wrcplc.co.uk

Further copies of this report are available from:
Environment Agency R&D Dissemination Centre,
c/o WRc, Frankland Road, Swindon, Wilts SN5 8YF

tel: 01793-511711 fax: 01793-514562 e-mail: publications@wrcplc.co.uk

Project Siren: Phase 2a
Benchmarking of Monitored Natural Attenuation Procedures

R&D Technical Report -P2-208/TR/1

T. Cutter[1], D. Jones[2], P. McCarthy[2], S. Macnaughton[1], G. Lethbridge[2], R.P.J Swannell[1]

Research Contractors:

AEA Technology Environment[1] and
Shell Global Solutions[2]

Environment Agency
Rivers House
Waterside Drive
Aztec West
Bristol
BS12 4UD

R&D Technical Report P***

Publishing Organisation:
Environment Agency
Rio House
Waterside Drive
Aztec West, Almondsbury
Bristol BS12 4UD
Tel: 01454 624400   Fax: 01454 624409

ISBN: 1857055330

This report is the result of work jointly funded by the Environment Agency, Shell Global Solutions and AEA Technology Plc.

Dissemination status
Internal: Released to Regions
External: Released to Public

Statement of use
This report summarises the findings of research carried out to compare and contrast three national Monitored Natural Attenuation ~~by~~protocols~~ the contractors for project P2-177~~?. -The information within this document is for use by Environment Agency staff and others involved in evaluating the use of natural attenuation.

Research contractor
This document was produced under R&D Project ~~P2-177~~ P2-208 (Umbrella Project P2-169)~~?~~ by:
AEA Technology Environment
National Environmental Technology Centre
Culham
Abingdon, Oxfordshire
OX14 3ED
Telephone 01235 463391
Facsimile 01235 463010

AEA Technology is the trading name of AEA Technology plc
AEA Technology is certificated to BS EN ISO9001(1994)

Environment Agency's Project Manager
The Environment Agency's Project Manager for this R&D Project P2-208 was: Alwyn Hart
National Groundwater and Contaminated Land Centre, Midlands Region

~~, Midlands~~

CONTENTS

APPENDICES

EXECUTIVE SUMMARY

There are now a number of protocols for the application of Monitored Natural Attenuation (MNA). The aim of this project was to benchmark three methods of assessing MNA using data from an existing site at which MNA had been shown to be an effective remedial strategy.

The three MNA assessment methods chosen for inclusion in this exercise were:

- the recently published Agency MNA guidelines (Agency R & D Publication 95).
- the American Society for Testing and Materials (ASTM) guidelines (Standard Guide for Remediation of Groundwater by natural Attenuation at Petroleum Release Sites, ASTM Standard Guide E1943-98).
- the Network for Industrial Contaminated Land in Europe (NICOLE) – TNO (Netherlands Organisation for Applied Scientific Research) draft MNA Protocol.

Each of these three decision support systems (DSS) was applied to data obtained from a site at which MNA had been previously shown to be an effective remedial strategy. Each of the DSSs was then compared and subjectively ranked using variables based on the following evaluation criteria chosen after discussion between the project team and the Agency.

- Ease of Use
- Transparency of decision making
- Robustness of conclusions

An accurate comparison between the Agency and ASTM DSS and the Dutch system was compromised by the lack of a complete translation of the Dutch into English. Integral to each of the DSSs was the establishment of clear lines of evidence indicating natural attenuation was occurring. Of the three DSS, only the ASTM allowed a remediation based upon MNA to proceed based solely on plume dynamics. Both the Agency and Dutch guidelines required further site investigation and assessment of geochemical and redox data before deciding whether to proceed with MNA. Moreover, both also required regulatory guidance as to whether or not MNA was the appropriate remedial strategy. The ASTM procedure required little consultation with the regulator. For large and complex sites, using plume dynamics alone as an indicator of the applicability of MNA, without recourse to regulatory guidance, may prove to be unsuccessful and may lead to mistakes in decision making. As such, the reliance on plume stability data was seen as a disadvantage of the ASTM DSS.

Of the three DSSs, only the Dutch DSS **required** the use of a solute fate and transport model prior to making a decision. However, using a recommended model, plume collapse was predicted to be more rapid than that observed from the field data. Given both the time taken to apply the model and the subsequent uncertainty that use of the model introduced, the necessity of applying the model was seen as a disadvantage of the Dutch guidelines.

Overall the Agency DSS compared favourably with the ASTM and Dutch systems, proving itself superior to both on some criteria. In part because of the tiered system of lines of evidence, the ASTM guidelines proved to be the easiest to apply and were the most

transparent. However the Agency DSS also provided for transparent decision making, did not require application of a model if evidence of MNA was considered decisive, and was more defensible than the ASTM system. Moreover, because of the requirement for regular regulatory monitoring, the Agency DSS had the least potential for accidental delay and could therefore prove to be more cost effective than the ASTM system. It should be noted, however, that the potential for bottlenecks does exist when applying the Agency DSS. In particular, the requirement for regular regulatory involvement in decision making may potentially result in resource implications for the regulatory bodies. To offset this, clear procedures should be established for the submission of MNA 'case' information with clear systems also set up for data review once utilisation of MNA has been agreed.

KEY WORDS: **To be completed**

KEY WORDS: Monitored Natural Attenuation……………………; Decision Support Systems; Benchmarking

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AOD	Above Ordnance Datum
ASTM	American Society for Testing and Materials
BGL	Below Ground Level
BOD	Biological Oxygen Demand~~BTEX Benzene, Toluene, Ethylbenzene and Xylenes (Components of Petrol)~~
BTEX	Benzene, Toluene, Ethylbenzene and Xylenes (Components of Petrol)
COD	Chemical Oxygen Demand~~BGL Below Ground Level~~
CSM	Conceptual Site Model
DCE	1,2 dichloroethane
DNAPL	Dense Non-Aqueous Phase Liquids
DO	Dissolved Oxygen
DSS	Decision Support System
~~EA~~	~~Environment Agency~~
GRO	Gasoline Range Organics
GPR	Ground Penetrating Radar
HVOCs	Halogenated Volatile Organic Compounds~~arbons~~
ICRCL	Interdepartmental Committee on the Re~~clamation~~development ~~(check with Theresa)a~~ of Contaminated Land
IWACO	Dutch~~UTCH~~ Consultancy
LNAPL	Light Non-Aqueous Phase Liquids
MNA	Monitored Natural Attenuation
NA	Natural Attenuation
NGWCLC	National Groundwater and Contaminated Land Centre (Agency)
NOBIS	Dutch Research Programme on in situ remediation of contaminated land
PAH	Polycyclic Aromatic Hydrocarbons
RNA	Remediation by Natural Attenuation
SIREN	Site for Innovative Research on Natural Attenuation
SKB	Centre for Soil Quality Management and Knowledge Transfer
SVOC	Semi Volatile Organic Compounds
TNO	Netherlands Organisation for Applied Scientific Research~~Dutch Research Council~~
TPH	Total Petroleum Hydrocarbons
VOC	Volatile Organic Compounds

1 INTRODUCTION

Natural attenuation has been defined as ~~the process by which naturally occurring processes in soil and groundwater environments lead to the reduction of the mass, toxicity, mobility, volume or concentration of contaminants in those media. These *in situ* processes include biodegradation, dispersion, dilution, adsorption, volatilisation and chemical or biological stabilisation or destruction of contaminants.~~"the effect of naturally occurring physical, chemical and biological processes, or any combination of those parameters to reduces the load, concentration, flux or toxicity of polluting substances in water" (Agency R&D Publication, No. 95). These processes~~These processes~~ occur naturally on many contaminated sites and can be harnessed to mitigate risks to human health and the environment associated with the contamination. Monitoring such transformations, and modelling their long -term performance can be a cost-effective alternative remedial tool especially when compared with more traditional engineered solutions. This approach has been termed "monitored natural attenuation" (MNA) and has been effective for a range of sites particularly in North America.

~~The SIREN (Site for Innovative Research into Monitored Natural Attenuation) Project is a joint innitiative by the Environment Agency, Shell Global Solutions and AEA Technology set up with the aim of identifying a site at which MNA could be demonstrated and investigated under UK conditions. A site has since been identified and characterised towards this end, the conceptual site model (CSM) for which will shortly be available (Environment Agency Technical Report …).~~

In this report we compare the performance of the Agency's new guidelines for MNA (The Agency R &D publication 95 (1)) with other existing MNA assessment procedures, namely the United States ASTM guidelines (2) and the Dutch guidelines recently published by NOBIS/SKB (3). This activity has been conducted ~~by the SIREN team~~ in order to help promote a wider understanding of MNA in the UK,- and to set the Agency's guidance in the context of ~~interantional~~international norms. ~~With the recent publication of MNA guidelines for the UK (Environment agency R&D Publication 95, **REFERNCE 1**), it was decided to compare the efficacy of three different MNA assessment procedures, namely a) the new UK guidelines, b) the United States ASTM guidelines **(2)**, and c) the Dutch guidelines recently published by NOBIS/SKB **(3)**.~~ The ~~UK~~ Agency's guidelines ~~have been~~were developed in response to the government's drive to redevelop contaminated sites and are~~is~~ consistent~~inline~~ with the principles of risk assessment and risk management ~~adopted under Part IIa of the Environmental Protection Act 1990, that took affect in April 2000~~ (4). ~~The American and Dutch assessment systems were chosen for comparison with the new UK guidelines for different reasons.~~ The ASTM Decision Support System (DSS) was first established in 1994 as the producti~~on~~ of ~~a~~ collaboration between regulators, industry and environmental groups. It has been used as a template for individual ~~American~~ S~~s~~tates to ~~create regulations and to~~ screen sites that potentially may be suitable for remediation by ~~using monitored~~ ~~for natural attenuation~~ MNA~~option feasibility~~. ~~Moreover,~~In addition, the ASTM guidelines have been used widely abroad by ~~American multinationals~~US companies in the absence of formal guidance, and as such were chosen for this comparison exercise. The NOBIS/SKB DSS was prepared ~~more recently~~in 1998 under the NOBIS framework by a consortium of consultants (TNO, IWACO and TAUW) and was one of the first published decision tools in Europe ~~(1998).~~ . It is not a regulatory prescribed guideline but a tool for making sound decisions on natural attenuation. The NOBIS/SKB guidelines were seen by the SIREN project team and the Agency to be sufficiently well developed as to ~~be~~ provide a useful European benchmark for comparison with the other ~~two~~ procedures. It should be noted that this DSS has thus far only been developed for application to chlorinated solvent contamination. H~~, h~~owever, a methodology for its application to BTEX contamination is under ~~evaluation~~development and a summary of this methodology was available to the project team.

During phase 1 of the SIREN project (Environment Agency Technical Report No. P358), a site in the UK was identified where monitored natural attenuation had already been successfully demonstrated by the site owner. Following discussions with the owners, the monitoring data collated in a consultants report was made available to the . This case study contained groundwater monitoring data from 1992 to 1998. Data taken from the report and used herein is provided in Appendix 1.

Using the consistent monitoring data from the latter 4 years (1994 – 1998) of the study, three different decision support systems for assessing the efficacy of monitored natural attenuation were compared:

1.1 Framework FOR For Benchmarking MNA Protocols

During Phase 1 of the SIREN project (Environment Agency Technical Report No. P358), a site in the UK was identified where MNA had already been successfully demonstrated by the site owner. Following discussions with the owners, the monitoring data collated in a consultants report was made available to the project. This case study contained groundwater monitoring data from 1992 to 1998, (Appendix 1), however only data from the latter four years of the analysis (1994-1998) proved consistent enough for this analysis.

To provide insight into how straightforward and easy to use the different Decision Support Systems (DSSs) DSS are for the non-expert, sSuitable Staff were selected from Shell Global Solutions and AEA Technology taken from the companies and organisations contributing to this research who had some contaminated land experience but limited knowledge of MNA. Moreover, they had no prior knowledge of the site we nominated that was chosen for the benchmarking exercise nor did they know what remedial treatment was actually selected at the study site.to use these three procedures independently on the data set provided. The staff were selected on the basis that they had some contaminated land experience but limited knowledge of monitored natural attenuation. In this way we hope to gain insight into how straightforward and easy to use the different assessment systems are for the non-expert. Moreover the eventual fate of the contamination at this site was not known to the assessors concerned, avoiding any preconceived ideas regarding the eventual outcome.

Herein is presented a benchmarking exercise comparing the performance of the three different DSSs using the data from the consultants report for this site.The companies involved in this project have amassed extensive experience in the contaminated land field, bringing specific, complimentary skills together for the purpose of this report. Shell Global Solutions supports staff with expert knowledge of the fate and behaviour of organic and inorganic contaminants in soil and groundwaters gained as part of shells global operations. Other skills include a thorough working knowledge of contaminated site investigation techniques, risk assessment

~~(frameworks, modelling). A particular area of expertise relevant to this project is the application of biotechnology to insitu and ex situ remediation technologies (such as monitored natural attenuation and engineered bioremediation).~~

~~AEA Technology Environment Ltd………~~

~~This report summarises t~~The site history, hydrology, geology, monitoring and investigation history are summarised (Section 2) and used~~s this information~~ to explore the application of the three MNA DSS protocols ~~to a site MNA~~ in ~~generic ways (~~Section 3~~)~~.

The performance of the DSSs were assessed against general category headings as follows:

- **Ease of Use**: how easy it would be for a recently qualified graduate to complete the process;
- **Transparency of Decision Making**: how clear the process would be to an external auditor and/or other stakeholder (*e.g.* general public); and
- **Robustness of Conclusions**: how the procedure helps to minimise the risks associated with the decision making process through, *e.g.*, the provision of contingency plans.

~~The Decision Support Systems were then compared using the criteria required by the Environment Agency, which are as follows (Section 4)~~
In order to assess the performance of each of the DSS against each category, the project team prepared a series of specific questions which are shown in Table 4.1 (a-c). The project team then ranked each DSS against these questions (1 for the best DSS, 3 for the worst). These rankings were used to give an indication of overall performance in each of the categories. On completion of the review, the project team used the rankings to assess each DSS for the time taken and the relative cost effectiveness, *i.e.* the time taken and likely relative cost for each DSS to be completed.

~~i)~~ ~~:~~

~~Ease of Use~~

~~Transparency of Decision Making~~

~~Robustness of Conclusions~~

~~Time Taken~~

~~Cost Effectiveness~~

~~Details as to exactly what each of these criteria headings mean can be found in section 4.~~

~~-~~Finally conclusions are presented~~were drawn~~ as to the performance of each of the three systems (Section 5).

2 2 SUMMARY OF SITE INFORMATION

2.1 Introduction

The Ssite report data was obtained for a which provided the information for this exercise concerns a petroleum distribution depot located in central England. The site covered rs anan area of approximately 4.5 hectares and consistsed of 24 above ground petroleum storage tanks of varying sizes separated into two distinct areas.

To the north the site wais bound by a redundant railway line, to the east by a road, to the south by a small industrial estate and to the west and southwest by open farmland. The site wasis located 72 – 76 m Above Ordnance Datum (AOD) with the closest surface water feature being a local stream 500 m to the south.

Prior to its purchase and development as an oil depot in 1959, the site was greenfield. Operations continued until 1991, over which time the site was developed a further three times (1964,1969 and 1972). Operations undertaken at the site included the storage and distribution of petroleum products. Product was bought in by train, off-loaded, stored, and then pumped to road tanker. Annual throughput was approximately 100 million litres.

The site layout is presented in Figure 2.11 with benzene, toluene, ethylbenzene, and xylene (BTEX) contamination concentrations in the soil shown in Table 2.1as they were in November 1994. The eastern tank farm containeds lighter distillates and it is from tthis area that may be the source of the groundwater contamination appearsed to be originating.

2.1 2.3 LocalOCAL Geology and& Hydrogeology

The site was lies to the south of an area of fluvial sands (*i.e.* the WhitechurchWhitchurch Sands) and gravels (River Terrace Deposits) with Portland and Purbeck Beds and Corallian limestone also present. The site is not located above Lower Greensand which in Buckinghamshire is considered to be a minor aquifer. The Whitechurch sand formation is deemed to be less vertically persistent and thus of less importance than the Lower Greensand. There wer are no potable water supplies in the area (within 3 km), although the three private agricultural water abstractions were located at considerable distancee to the east and south of the site take ground water from the Lower Greensand (no distance or volume provided in original documentation). Two potential receptors, namely surface water and a local brook, were located They are unlikely to be at risk of significant impact from groundwater contamination from the site. The nearest surface water is 500 m to the south of the site (downstream), and and a local brook is 1.5 km away from the site to the north west (upstream), respectively.

The site geology consisted ofwais primarily man-made fill with occasional concreted areas overlying predominantly sand and gravel with brick and concrete fragments. A clay layer was encountered beneath the made ground, extending typically 1-2 m below ground level, across the site but this was penetrated by foundation structures.

Figure 2.1: Base map compiled from plans provided by the owner (1971-1991) dated 1971-1991.

2.2 ~~2.5~~ Site Hydrogeology

The site investigation detected water in all the deep wells across the site (2.7 m – 5.2 m) indicating the presence of groundwater in the ~~Whitechurch~~Whitchurch Sand Formation. The groundwater levels~~contours~~ indicated a northeast to southwest flow across the site with no perched groundwater. Vertical infiltration flow may have been impeded by the presence of the clay layer but this had not been quantified. The hydraulic properties of the fine and silty ~~Whitechurch~~Whitchurch Sand combined to allow an estimated flow velocity of 20 to 40 m per year. The nearest potential receptor was the surface water located 500 m south of ~~from~~ the site.

2.3 ~~2.6~~ Monitoring History

~~To date~~T~~t~~he investigation of the sit~~e has~~ involved soil gas, soil and groundwater monitoring. Information regarding the groundwater chemistry and environmental conditions was derived~~s~~ from a total of 13 sampling visits between December 1992 to October 1998. A ~~sum~~ total of 30 boreholes ~~exist~~were present across the site (deep, shallow or both). Data from 17 boreholes were~~as~~ available for the period prior to November 1994. After November 1994 data ~~was~~ were collected from a different set of monitoring wells and includ~~ed~~ing 5 new wells placed in the area of the contaminant plume.

The concentrations of ~~Groundwater was analysed for~~ BTEX, volatile organic compounds (VOC), polycyclic aromatic hydrocarbons (PAH), total petroleum hydrocarbons (TPH), gasoline range organics (GRO), ~~hydrocarbon fingerprints,~~ ICRCL metals and methane in the groundwater were quantified. Indicators of ~~soil~~ environmental conditions provided in the report include hydraulic conductivity, alkalinity, biological oxygen demand (BOD), chemical oxygen demand (COD), pH, sulphur, sulphide, total nitrogen, nitrate, nitrite, ammoniacal nitrogen, iron, calcium, manganese, phosphate and sulphate. Field analysi~~i~~s results ~~given~~ included dissolved oxygen, temperature, redox potential and conductivity.

~~2.7 Site investigation history~~

To determine whether natural attenuation was a significant process at this site, changes in the contaminant concentrat~~i~~ion,~~ons and~~ and changes in plume size and plume migration/~~movement over time~~ were monitored over time. The major contaminants of concern within the site were identified as BTEX, of which benzene was found in the highest concentrations. Other contaminants detected included TPH, low concentrations of 1,2 dichloroethane (DCE) and various Semi Volatile Organic -Carbon ~~Compounds~~ (SVOCs). Table 2.1 shows a list of the major contaminants in the groundwater in 1994. Appendix 1 details the full list of contaminants.

It was decided that to ~~The~~ use ~~of~~ every contaminant of concern in ~~modelling~~ determining plume changes over time would be unnecessarily~~overly~~ complex. Consequently a contaminant indicator, benzene, was chosen to gain an appreciation of the plume's movement, contaminant concentrations and interactions with several- environmental variables (*e.g.* pH, dissolved oxygen, electron acceptors etc). Benzene was chosen because it was the contaminant that~~which~~ posed the greatest risk to human health and the wider environment ~~the~~

~~prime contaminant of concern~~ due to its carcinogenicity and mobility relative to the other chemical species present. It was also present at higher ~~concentrations~~concentrations than the other contaminants.

Table 2.1: Selection of Boreholes and Contaminant Concentrations from~~or at~~ November 1994 ~~(Appendix 1 holds the full results list)~~

Borehole	Benzene (µg ~~/~~L~~l~~$^{-1}$)	Toluene (µg ~~/~~L~~l~~$^{-1}$)	Ethylbenzene (µg ~~/~~L~~l~~$^{-1}$)	Xylene (µg ~~/~~L~~l~~$^{-1}$)
BH – A (S)	0.01	< 0.01	< 0.01	< 0.01
BH – A (D)	< 0.01	< 0.01	< 0.01	0.03
BH – B	< 0.01	0.0547	0.014	0.0656
BH – C	0.133	0.0655	0.051	0.07
BH – E	< 0.01	0.0216	< 0.01	0.0215
BH – F (S)	< 0.01	0.0329	0.0328	0.0548
BH – F (D)	0.041	0.044	0.032	0.1099
BH – G	< 0.01	< 0.01	0.0111	< 0.01
BH – H	< 0.01	< 0.01	< 0.01	0.0219
BH – I	< 0.01	< 0.01	< 0.01	< 0.01
BH – J	< 0.01	< 0.01	0.0216	0.034
BH – K	11.6599	0.012	0.02	0.053
BH – L (S)	0.0325	0.011	< 0.005	0.0327
BH – L (D)	0.011	< 0.01	< 0.01	< 0.01
BH – M	< 0.01	0.0327	0.0215	0.032
BH – N (S)	< 0.01	< 0.01	< 0.01	0.0111
BH – N (D)	< 0.01	< 0.01	Not Found	< 0.01
BH – O	0.0325	0.092	0.043	0.0877
BH – P	< 0.01	< 0.01	< 0.01	0.013
BH – Q (S)	0.113	0.0655	0.0219	0.031
BH – Q (D)	0.0216	0.0219	0.011	0.0325
BH – R (S)	0.2106	0.879	0.82	0.319
BH – R (D)	0.022	0.022	0.0325	0.0437
BH – S (S)	0.1328	0.1438	0.051	1.5494

Note 1: BH= borehole, S= shallow, D = deep.

~~From interpretation of the~~Data from November 1994 suggested that~~data~~ the plume ~~was observed to be~~ originat~~ing~~ed from the eastern tank farm. The ~~small area of high~~ BTEX concentration was greatest in this area (≥10,000~~,000 +~~ ~~µg~~ µL~~l~~$^{-1}$)~~., taken to represent worst case benzene contamination) must be close to the source of the contamination, because the maximum solubility of benzene in groundwater in contact with free phase gasoline is approximately 20 mg l^{-1} (Raoult's law).~~ The only observed free phase was in shallow well R~~,~~ although there may have been more floating undetected because of a rising water level, and because the slotted sections of boreholes may have been ~~being~~ below the water table. Benzene concentration decreased within 10 – 20 m of the suspected ~~is~~ source area to ~~below~~ ≤ 100 μ~~μ~~g ~~l~~L^{-1} to the east north and west, upstream of the source. Following the groundwater flow direction to the south and south west, a plume containing between 100 - 1000 μ~~μ~~g L~~l~~$^{-1}$ BTEX extended approximately 250 m, almost to the site boundary.

~~**See Figure 2: Isolinear diagram of contaminant plume change between 1994 and 1998.**~~

Monitoring results from April 1997 indicated that the highest benzene levels had ~~a slight~~ shifted south (downstream) and migrated laterally. This ~~of the centre of the high benzene concentration area as well as a lateral migration of contaminants~~ resulted~~ing~~ in benzene levels~~concentrations~~ of ≥10,000 μ~~μ~~g L~~l~~$^{-1}$ expanding to the east and west ~~(~~10 – 20 m from the new centre point~~)~~ (Figure 2.2). The area of benzene concentration between 1000 - 10,000 μ~~μ~~g L~~l~~$^{-1}$ had~~s~~ also spread ~~out, again~~ predominantly to the south~~, although t~~. The ~~. The~~ region containing between 100 - 1000 μ~~μ~~g L~~l~~$^{-1}$ benzene ~~appeared to have~~ receded somewhat within the site boundary.

Figure 2.2: Contour (isolinear) diagram of contaminant plume change between 1994 and 1997.

Figure 3: Isolinear diagram of contaminant plume change between 1998 and 1999.

Compared to the April 1997 survey, results from October 1998 indicated a substantial change in plume location and benzene concentration (Figure 2.3). The surface area of -groundwater containing ≥~10,000 µµg Ll^{-1} benzene was reducedsmaller. Such concentrations were only found in It only , a covereding an 5-10 m^2 areaarea to the south of the Eeast Ttank Ffarm of only 5 – 10 m^2. The area of the plume containing benzene at between 1000 - 10,000 µµg lL^{-1} had also shrunk with the change occurring in the southern perimeter and had , as if the plume shifted south slightly. Moreover,In this area the decreasereduction in benzene concentration to below 100 µµg lL^{-1} occurred within 3 – 5 m of the
-100,000 µµg Ll^{-1} isobar. These data indicated that the plume was no longer expanding, and in fact was collapsing.

In summary, following the first characterisation in 1994 the plume appeared to have spread out by 1996initially andbut had then reduced decreased in area by 1998.

Figure 2: Isolinear diagram of contaminant plume change between 1994 and 1998.

Figure 2.3: Contour (isolinear) diagram of contaminant plume change between 1997 and 1998 ~~Isolinear diagram of contaminant plume change between 1998 and 1999.~~

3 EVALUATION OF SITE DATA WITH EACH PROCEDURE

~~EVALUATION OF SITE DATA WITH EACH PROCEDURE~~

~~To avoid any unintentional bias entering the use of a DSS by the subjects chosen, the data was extracted from the site report with any interpretation or clue as to the site location removed. This allowed any subjective conclusions concerning a particular DSS to be wholly a result of the assessors interpretation of the data without influence of interpretation from the site reports original author.~~

The following section introduces and describes each of the three ~~Monitored Natural Attenuation Decision~~ MNA ~~Support Systems (D~~Decision Support Systems (DSS) in more detail. Following ~~the~~ each description, the DSS is then ~~) and~~ applie~~d~~ds ~~them t~~to the site outlined in Section 2 and Appendix 1~~using the data provided~~.
~~The case study contained data for analyses carried out between 1992 and 1998.~~

3.1 ~~3.1~~ The Agency's MNA Decision Support System~~environment agency~~

~~Aims, Intent and Background to the procedure~~

The recently published ~~Environment Agency's Natural Attenuation~~ Agency ~~Decision Support System~~ ~~p~~Procedure (1) is~~is~~ ~~based upon~~ a multi-stage process involving structured decision making, iterative data collection and analysis. The DSS comprises~~has~~ four~~three~~ stages; s~~S~~creening, d~~D~~emonstration of current attenuation, a~~/ A~~ssessment of longer term attenuation capability and i~~I~~mplementation (performance monitoring). Given the detail provided in the Agency's DSS (1), only brief summaries of the four stages will be included herein. However, the flow chart from the DSS is included (F~~f~~igure 3.1).
~~The section summary in the guidance documentation describes effectively the role of each stage in the DSS, as follows:~~

~~The screening stage considers the viability of natural attenuation based upon preliminary assessment of technical, practical, legal and economic constraints. The process is designed for use with limited data where only an indication of the potential for natural attenuation is sought. Typically this will be at the feasibility stage where alternative remedial options are also under consideration.~~

3.1.1 Screening

The screening stage considered the viability of natural attenuation based upon a preliminary assessment of technical, practical, legal and economic constraints. The process wa~~i~~s designed for use with limited data in order to obtain ~~where only~~ an initial indication of the potential for natural attenuation at the site~~is sought~~. Utilised correctly, the process should highlight the practical, technical, legal or economic constraints that may preclude application of MNA as a remedial strategy. By including a screening stage, unnecessary detailed characterisation should be avoided where MNA wais not a viable option. The screening stage assumedds that a site investigation and risk assessment have been completed.

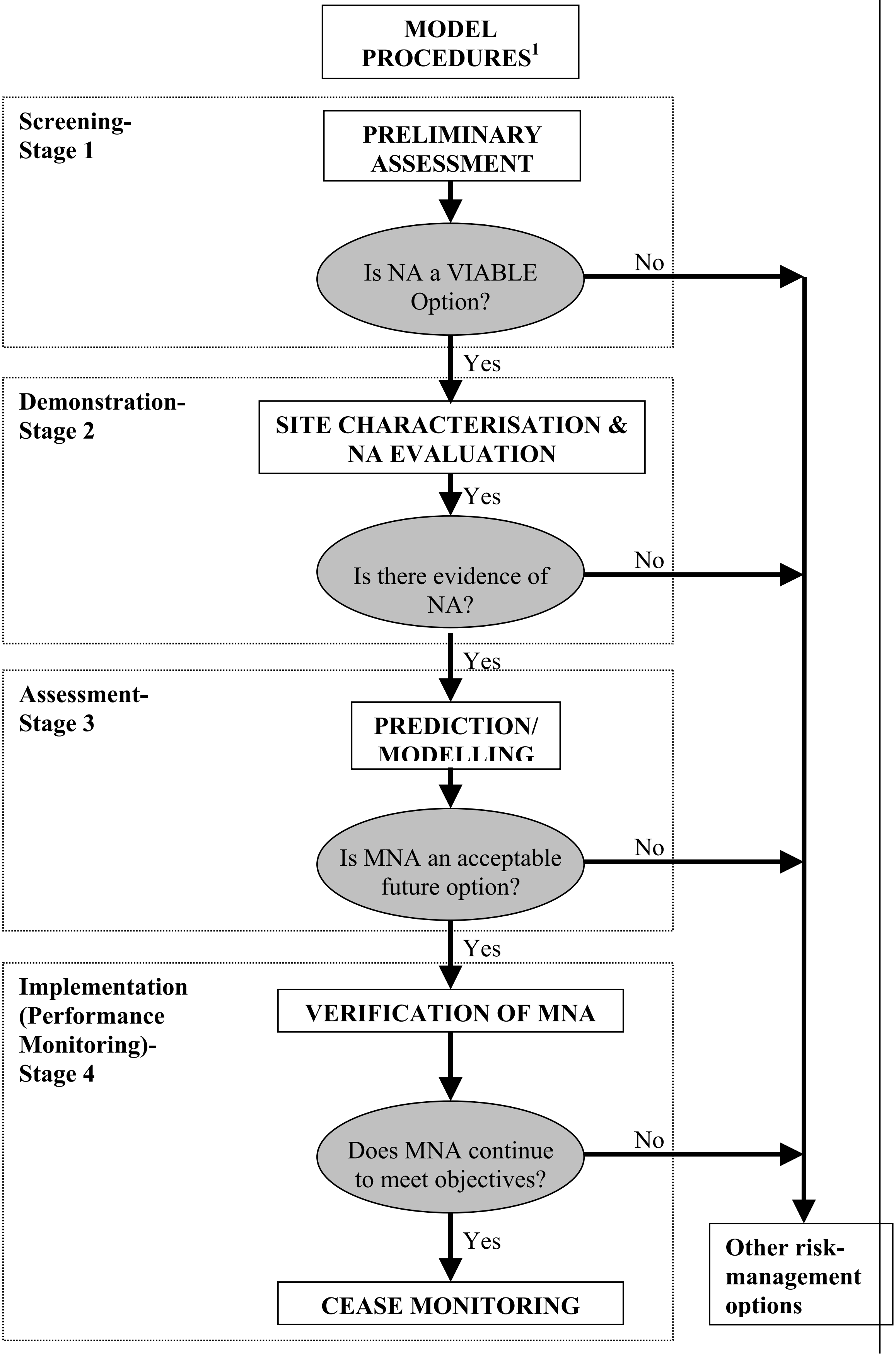
The methodology required throughout the screening stage includedds:

1. a review of site information for the purpose of MNA assessment including a risk assessment and refinement of a conceptual site model (CSM);
2. the identification of technical, regulatory and practicability constraints to NA including further refinement of the CSM;
3. the evaluation of constraints to determine viability of MNA including initial quantitative risk assessment for MNA and constraints analysis.

Minimum data requirements at this stage included contaminant properties (*e.g.* concentration, delineation of plume, nature of contaminant including phase (*i.e.* is the contaminant adsorbed, gaseous, liquid etc, and identification of source). Data regarding aquifer characteristics wereis also required (*e.g.* aquifer status, source protection zone, direction of groundwater flow and velocity), as were data onis the identification and location of possible receptors. During this review priority wais given to determining any imminent risks that would warrant urgent action or pre-empt MNA.

The next stage of the screening procedure requiredds consideration of the technical reliability of MNA, practicability, economic viability and regulatory acceptability and /institutional controls. Technical screening factors weare divided into contaminant properties and environmental characteristics and, taken together, determined the fate and behaviour of contaminants in d

Figure 3.1: The Agency's MNA Decision Support System Flowchart (1).



[1] CLR 11: *Model procedures for the management of contaminated land*

aquifer systems. Practicability screening factors included, for example, migration of contaminants off site, and suitability of the time frame for NA to occur. Economic considerations included the finance of long term monitoring, the requirement for a detailed site characterisation, and the cost of any contingency plans. Finally, regulatory and institutional pressures were also may be important in determining whether MNA is an appropriate strategy.

3.1.2 Demonstration

The demonstration stage and assessment stages addresseds attenuation in greater detail with the aim of establishing demonstrating quantitatively that NA wais occurring at a rate that couldwill achieve the remediation objectives in a reasonable time frame. To achieve this end, the DSS proposed that sufficient of providing scientifically defensible evidence to support its subsequent implementation as part of a remediation strategy. The assessment relies upon a combination of comprehensive site characterisation and evaluation of natural attenuation to confirm its current effectiveness, followed by predictive modelling to estimate future contaminant fate and transport in groundwater.

The implementation stage covers the long term monitoring requirements to demonstrate that the remedial objectives are achieved, in line with the predictions made during the assessment. This process entails increased cost as the levels of uncertainty and conservatism in the assessment are reduced. Throughout the whole process and especially at key decision points, the regulator (Environment Agency or local authority) requires continual consultation.

The criteria used by the UK DSS to determine the viability of MNA as a remedial option was primarily the use of historical contaminant data to demonstrate a trend of reduced concentration downgradient along the groundwater flow path. Secondary criteria for assessment was the measurement of changes in chemical and geochemical data to prove a loss of contaminant mass. The tertiary level of criteria involves laboratory microbiological testing to show that indigenous bacteria are capable of degrading site contaminants. **The UK DSS approach is that of the more information collected the better.**

The UK DSS applied to site data was based on the draft R&D Publication 95, dated June 2000. This guidance document sets out a process with three main stages; Screening, Assessment and Implementation. Particular emphasis is placed on the fact that during, and at the end of each stage, the findings have to be discussed and agreed with the regulator before proceeding.

See Figure 4: UK Environment Agency Decision Support System Flowchart.

3.1.1 Screening

Only the data for the period 1992 to 1995 were used for the site screening process.

The initial site investigation data were reviewed and the following information drawn out under the headings used in the guidance:

3.1.1.1 Initial review of site data (development of a Site Conceptual Model)

The data collected in this stage of the DSS application to site data allows the construction of an initial conceptual site model which is used to "visualise and assess the plausibility of contaminant pathway receptor linkages and, thereby, potential risks, including:

Impact to discrete off site receptors;

Expansion of the plume into uncontaminated groundwater".

In line with the approach to the Conceptual Site Model given in the guidance documentation, a brief summary of the salient points from the site data that contribute the construction of a conceptual site model are listed as follows:

Contamination

The site is no longer operational, activity ceased in 1991.

No major spill incidents have been reported at the site. The most likely cause of contamination is minor spills and leaks during transfer operations.

The principle contaminant identified at the site is BTEX (from light-end fuel oils).

A contour plot of the plume has been produced using data collected in November 1994 and was supplied as part of the case study information.

Soil vapour data show low levels of VOCs, which can indicate aged contamination or contamination with semi- or non-volatile hydrocarbons.

Free product has been observed in test pit T-17, but none of the monitoring well records indicate the presence of free product, this may have been because of a high water table relative to the depth of monitoring borehole slotted sections.

Receptors

Lower Greensand is considered to be a minor aquifer in the study site area, due to its thin vertical extent and lateral impersistence. It can **take on local importance, but not at the study site, due to the lack of abstractions in the vicinity.**

There are no potable supplies within 3 km of the site, which equates to approximately a 30 year travel time protection zone.

Three private abstractions, for agricultural purposes, exist to the east and south of the site. It is considered unlikely that these would be impacted by flow from the site (which is in a south-westerly direction).

The nearest surface water lies some 1.5 km from the site, but to the north-west.

Pathways

Groundwater flow velocity has been estimated to be in the range of 20 to 40 m year^{-1}, based on soil hydraulic conductivity and the hydraulic gradient.

Groundwater contours suggest flow in a south-westerly direction.

Probable flow mechanism in Lower Greensand and Whitechurch Sand is intergranular.

The conceptual site model is not a static concept, it is intended to be refined through an interative process as more information becomes available from the general investigation of the site.

Following the initial review of data and formulation of an initial conceptual site model was a decision point when a judgement had to be made as to whether urgent action was required. Based on the nature of the contaminant and the distance to receptors, no urgent action was required and it is therefore was appropriate to proceed to the next stage of the DSS. [This decision would have been taken in consultation with the regulator (either the EA (in the case of a special site) or the Local Environmental Health Officer)].

3.1.1.2 Screening Process

Contaminant screening factors

Low density (LNAPL) - (form plumes that follow the groundwater flow).

High volatility.

High solubility (guidelines clearly indicate that BTEX is highly soluble).

Sorption - BTEX is known to be moderately sorbed (Degree of sorption is dependant on the organic carbon content of the aquifer, which is unknown).

Dissolved Oxygen (DO) and Sulphate were found to be the principal electron acceptors at the site. Dissolved Oxygen concentrations ranged between < 0.15 to 1.75 mg/l. Sulphate was present in higher concentrations than DO, between 7 to 600 mg/l.

Will degrade aerobically or anaerobically.

Of all the screening wells on site only a few were used to screen the plume as they were either in the plume or at such a position to be able to yield useful information. From these wells the environmental screening factor data was not always consistent over the three monitoring periods chosen for use in analysis. Nor was the environmental screening factor data in sufficient quantity for trend analysis to justify any correlation with changing benzene contamination concentrations. As such the trends identified cannot be taken as statistically viable results but only as potential trends.

These factors indicate that the contaminants may potentially be managed by monitored natural attenuation.

Environmental Screening factors

pH is the range 6.5 to 6.9, which is acceptable for microbial activity.

Dissolved oxygen levels, in the range 0.15 to 1.75 mg l^{-1} indicate that the groundwater is not highly aerated. Given the difficulties of sampling groundwater without aerating it, it is likely that the reported figures may over-estimate the dissolved oxygen in the aquifer and that anaerobic degradation process are likely to play a significant role in any natural attenuation at the site.

Sulphate concentrations vary between 7 mg l^{-1} and 610 mg l^{-1} with the average being approximately around 141 mg l^{-1}. BH 2, 9, 11 and 12 are located within the plume and all have lower than average concentrations. This indicates that sulphate may be used

up as an electron acceptor in natural attenuation.
Iron….nitrite?

Aquifer Suitability
Whitechurch Sand, isotropic, no major aquifer involved. Therefore based on figure 3.3 in the guidelines, the aquifer is suitable for natural attenuation.

Risk Assessment
No groundwater risk assessment model was applied to the data, but based on the fact that there are no receptors within 1500 m involved, the risk was considered to be very low. This is reinforced given that the weight of evidence from the US indicates that BTEX plumes rarely travel further than 100m from the edge of the source in this type of aquifer.

Constraints
It would be essential at this stage to get an undertaking from the owner, or any prospective purchaser, that a long term monitoring exercise can be put in place. If such an agreement cannot be reached, then alternative treatment options would have to be considered.

This is again a decision point, where, in consultation with the regulator, a decision has to be made on whether Natural Attenuation is a feasible approach. It is also possible that it may be felt that further data has to be gathered before making a decision. Our decision was that there was sufficient data to indicate that Monitored Natural Attenuation was a potentially viable treatment option. Further monitoring to refine characterisation of contamination on the site would have to clarify the environmental screening factor data (*e.g.* electron acceptors, pH, and other similar variables) with monitoring visits in sufficient number to consider seasonal variation.

3.1.2 Assessment of Natural Attenuation

3.1.2.1 Lines of Evidence

Primary: the concentration of BTEX at two wells was plotted against time. Both wells showed an initial increase followed by a drop in concentration. The final set of data (October 1998) shows that the plume is collapsing (Appendix 2). The 1000 $\mu g l^{-1}$ and 100 $\mu g l^{-1}$ benzene concentration isolinear contours are within a maximum of 10 m of each other, this is most likely due to rapid degradation of peripheral areas of low contamination. It must also be remembered that not all boreholes sampled for 1997 were sampled in 1998 leading to the 1998 isolinear diagram having less information on which to be based.

Secondary: data to support this was not available in 1995, but became available following further sampling between October 1995 and October 1998. Analysis of this data shows that there were sufficient quantities of electron acceptors (dissolved oxygen, sulphate and nitrate) to enable complete biodegradation of the BTEX. There was correlation between contaminant concentrations and electron acceptor concentrations consistent with natural attenuation.

Tertiary: laboratory microcosm studies to confirm biodegradation under various

conditions (aerobic, denitrifying, sulphate reducing etc.) were not carried out.

3.1.2.2 Design of Site Investigation

Based on information available in 1995, the strategy that is recommended would be to install 2 or 3 further boreholes down-gradient of the source and instigate a quarterly sampling regime, for the first year, looking at both contaminant levels, electron acceptors and degradation products. After the first year, the sampling regime should be reviewed and adjusted as appropriate. It may also be considered appropriate to install a sentinel well between the outer edge of the plume and the river, one either side of the plume and one up-gradient. These details would be discussed and agreed with the regulator. Consideration of the issues that these recommendations address is required as part of this DSS stage.

The 1998 report shows that 5 further boreholes were installed within the identified plume area and a six-monthly sampling regime instigated.

3.1.2.3 Define Objectives

No local receptors were present, therefore risks associated with further migration are low.

In case MNA does not proceed as predicted, a contingency plan should be drawn up. Such a contingency plan should consider the potential points of failure with the use of MNA at the site and criteria, which, once met prompt the use of an alternative remedial option. Integration of the alternative remedial option with MNA would be preferred.

For the purposes of this study we did not model the process (contaminant behaviour and fate modelling), but felt that there was sufficient data available to be able to be able to carry this out. Modelling the data allows the rate at which the plume is collapsing to be predicted, and hence a timeframe can be put on the overall monitoring process. Assuming the results of modelling were favourable, a cost / benefit comparison should be carried out and then the overall assessment should be discussed with the regulator in order to get an agreement to move on to the Implementation stage. N.B. In this case the modelling was redundant as plume collapse could clearly be demonstrated over the monitoring period.

3.1.3 Implementation

The objectives, including endpoint, acceptable time frame and conditions that would trigger the contingency plan, must be set out and agreed before commencing. The implementation is then an iterative process whereby further data is gathered, compared to the model predictions and if necessary used to further refine the Conceptual Site Model. For each set of data, it is important to check that that objectives are being met and whether the endpoint has been reached. When the endpoint is reached completion has to be agreed with the regulator before the assessors can sign off the project.This requires further site investigation and data collection was completed so as to calibrate, resulting in calibration of t the CSM and directsuch that guidance is achieved for any further additional site characterisation. The additional design of the site investigation should also- should establish "lines of evidence" forprovide data to demonstrate NA, along the lines of evidence approach and should providee sufficient site specific input data to forecast the future behaviour of the contamination usingvia solute fate and transport models.

As many as ~~T~~three "lines of evidence" wea~~r~~re required~~ available~~ to demonstrate NA:~~.~~

- Primary-historical contaminant data to demonstrate contamination reduction~~was~~is
- Secondary-measurement of change in chemical and geochemical data to prove a loss of contaminant mass and identify the mechanism.
- Tertiary-use of laboratory microbiological tests to show the presence of an indigenous contaminant-~~-~~degrading microbial community. This line of evidence was~~is~~ only required when the primary and secondary evidence proved~~s~~ inconclusive.

Where appropriate, analytical models were recommended~~may be used~~ to complement the lines of evidence.

3.1.3 Assessment

The~~is~~ third stage in the Agency's DSS required an assessment of the ability of~~s evidence to the effect that~~ NA processes ~~will~~to continue to ~~continue to~~ protect the identified receptors,~~,~~ and -reduce the~~that~~ future migration of the contaminant plume (and thereby~~will not~~ restricting~~ult in~~ significant additional pollution of groundwater). Moreover,~~,~~ remediation by MNA must be completed over a reasonable ~~and that the~~ timeframe~~ over which contamination is reduced is reasonable~~. - The a~~A~~ssessment should be based ~~relies~~ upon a combination of comprehensive site characterisation and evaluation of natural attenuation to confirm its current effectiveness, where necessary followed by predictive modelling to estimate future contaminant fate and transport in groundwater.

~~In summary~~Thus the major steps in the assessment stage wea~~r~~re as follows:

1) d~~D~~efinition of~~e~~ objectives for the assessment;
2) selection of appropriate model to predict long term effectiveness of MNA;
3) definition of the parameter values for model;
4) model validation;
5) model prediction;
6) sensitivity analysis;
7) assessment of model predictions;
8) consideration of other factors (for example:~~incl.~~ change in land use, presence of breakdown products, assimilative capacity of the aquifer, and r~~R~~emobilisation of contaminants).

During this assessment phase, consultation with ~~agreement with~~ the Agency was~~ will then be~~ encouraged~~ required such that MNA is identified as an effective remedial solution in protecting identified receptors~~. Where NA could not be adequately demonstrated from sufficient field observations, ~~T~~the DSS ~~required~~ also recommended use of a fate and solute transport model to predict the effectiveness of MNA. ~~that an appropriate . Also the timeframe for MNA should be acceptable, an appropriate demonstrating to verify model predictions was preparedshould be set-up according to expectationsa appropriate arrangedsshould be put in place dFinally, adequate controls are required to ensure long term operation and any predicted plume expansion should be acceptable to the Agency.~~

3.1.4 Implementation

The implementation stage specified~~covers~~ the long term monitoring requirements necessary to demonstrate that MNA was remediating the plume~~the remedial objectives a re achieved~~ in line with the predictions made during the assessment.

Overall, ~~This process entails increased cost as the levels of uncertainty and conservatism in the assessment are reduced. As described in the Agency guidelines, the purpose of the performance monitoring is to demonstrate that NA is effective as a remedial strategy in protecting the water environment.~~ t~~T~~he main steps in the implementation of MNA~~performance monitoring~~ weare ~~summarised~~ as follows:

- d~~D~~efinition of the~~e~~ objective for MNA;
- consultation ~~and agree~~ with Agency;
- preparation of~~e~~ a monitoring plan (including~~.~~ monitoring points, borehole locations, groundwater sampling strategy, frequency and duration of monitoring, contingency measures);
- consultation ~~and agree~~ with Agency;
- construction or modification of~~y~~ monitoring boreholes;
- commencement of monitoring;
- review of ~~monitoring~~ results and revision of the~~e~~ scheme if appropriate;
- when MNA objectives have been met, consultation with the Agency;
- ~~ation~~cessation of~~e~~ monitoring.

3.1.5 Application of the Agency's DSS

Screening (risk assessment and CSM)
The site investigation data were reviewed and the following information gathered. A conceptual site model (CSM) was constructed. This enabled visualisation and assessment of contaminant-pathway-receptor linkages and, therefore, potential risks including:

- impact to discrete off site receptors; and
- expansion of the plume into uncontaminated groundwater.

The salient points from the **contaminant** site data that were used to construct the CSM were as follows:

- activity at the site ceased in 1991;
- no major spill incidents had been reported at the site with the most likely cause of contamination ~~were~~beingidentified as minor spills and leaks during transfer activities;
- the major contaminant was identified as BTEX ~~(from light end fuels)~~;
- a contour plot of the plume was~~for has been~~ produced and supplied as part of the case study information (A~~a~~ppendix 1);
- soil vapour data showed low levels of VOCs indicating aged contamination or contamination with semi-volatile or non-volatile hydrocarbons;
- free product was observed in test pit T-17 and in shallow well R but not in any other borehole.

Groundwater flow velocity was estimated to be ~ 20-40 –m y^{-1}. The groundwater contours suggested flow in a south westerly direction, with the flow mechanism in the Whitchurch sands determined to be inter-granular.

The closest putative receptor was identified as the open water 500 m downstream from the plume. It would take the contamination between 12.5-25 years to reach this receptor at a flow rate of 20 –40 m y^{-1}. The closest potable water was ~3 km from the site. It would take the contamination ~70 years to reach this potable supply. Given that BTEX compounds were ~~well~~ known to be readily biodegradable and there was no significant free product, the putative receptors were not regarded as being under imminent threat from the contamination.

Following the initial review of the SI data, it was decided that no urgent action was required and it was therefore appropriate to proceed to the next stage of the DSS. This decision would have been taken in consultation with the regulator (in the case of a special site, the Agency, otherwise the local authority).

Screening (identification of technical, regulatory and practicability constraints)
The results of the assessment of the contaminant properties and environmental characteristics were as follows:

- the contaminants were highly volatile and soluble;
- BTEX is known to be moderately sorbed with the degree of sorption dependent on organic carbon content of the aquifer~~)~~;
- pH was in the range of 6.5-6.9, within the range which is acceptable for microbial activity usually occurs (5-9);
- DO ranged between <0.15-5 mg L^{-1}. Field measurement of <1~~2~~ mg~~.~~ L^{-1} are generally taken to be anoxic;
- sulphate and iron were the other principal electron acceptors, both at low concentrations in the presence of significant amounts of BTEX.

BTEX components are generally regarded as biodegradable with more rapid degradation occurring in aerobic conditions. In this case DO was detected at a range of concentrations in the shallow and deep wells indicative of environments suitable for both aerobic and anaerobic degradation. Alternative electron acceptors were present at~~data was highly~~ variable concentrations. However, the data suggested that there may have been some relationship between sulphate and benzene levels *i.e.* low sulphate levels tended to be found where benzene was present in higher concentrations. As such, taken together these factors indicated that contaminant degradation was occurring in the groundwater~~s may be remediated by NA~~.

For this site, sufficient evidence was available from the initial SI to suggest that MNA c~~w~~ould be a viable remedial option. At this stage in the process, the DSS requires that the practicability of MNA for the site be determined through consultation between the problem owner and the regulatory body. For the purposes of this report, it is assumed that such negotiations were successful and the investigation proceeded to the next stage.

Demonstration of Natural Attenuation
To demonstrate that NA was occurring at a sufficient rate to achieve remedial objectives, primary (1), secondary (2) and possibly tertiary lines of evidence were required.

1. Contaminant concentration data from 1997 and 1998 were compared. Compared to the 1997 survey, results from 1998 indicated a substantial change in plume location and decrease in the benzene concentration. The total groundwater containing >10,000 μg L^{-1} benzene was reduced. The area of the plume containing benzene at between 1000 - 10,000 μg L^{-1} had also shrunk and had shifted south slightly. The reduction in benzene concentration to below 100 μg L^{-1} occurred within 3 – 5 m of the 1,000 μg L^{-1} isoline contour. This was probably due to the rapid degradation of peripheral areas of low contaminant concentration where there was a relative abundance of oxygen. Thus data

from the site suggested that there was a primary line of evidence (plume collapse) in favour of NA occurring at a sufficient rate.

2. Unfortunately there was no geochemical data available in 1994. Analysis of the 1997 and 1998 data suggested that oxygen, sulphate and iron were present in and upstream of the plume. Electron acceptor levels were depleted in areas of high contaminant concentration, suggesting that micro-organisms were degrading the contaminants, but that degradation was limited by electron acceptor concentration. However, we were unable to derive statistical trends between contaminants and the electron acceptor concentrations.
3. Given the conclusive data indicating plume collapse and the evidence suggesting electron acceptor limitation of contaminant degradation, microbiological studies were not felt to be necessary.

Taking into account the results of the demonstration stage, assessment of NA would then proceed as follows.

Assessment of Natural Attenuation

The essential steps for the assessment of NA were applied to the data from the site. The site was a considerable distance from the nearest receptor (surface water, 12.5 years). As such, and especially considering the evidence of plume collapse, the risks associated with further migration were deemed to be small. As plume collapse was evident from the field data from 1997 and 1998, application of a model was deemed to be unnecessary.

At this stage it was also necessary to conduct a cost/benefit analysis of MNA compared to other risk management options (in this case other remedial options; Table 3.1).

Table 3.1: Cost analysis for remedial methodologies

Technology	**Cost per m³**
Natural Attenuation	1-25[1]
Bioventing	10-50
Bioreactors	30-150[23]
Injection and recoveryPump and Treat	5-80[34]
Air sparging or biosparging	10-30

1. Large sites might be even cheaper than £1 per m^3, a more effective manner of costing natural attenuation would be to consider the following range: £500-700 per borehole per sample time.

2. Land farming will be cheaper if existing off site facilities are used.

23. The costs will be highly dependent on the type and volume of contamination. The treatment of low volumes will be expensive.

34. Cost for groundwater treatment only.

Clearly, MNA could provide thee lowestbest/cost benefit cost of all the remedial options, assuming there was sufficient time to complete the remediation. Moreover the use of MNA would minimise the use of natural resources and therefore would be the most sustainable approach. At this stage further consultation with the regulators would be required before proceeding with the Implementation stage.

Implementation of natural attenuation

from the available dataIn consultation with the regulators, a monitoring plan would be devised. A suitable monitoring plan for this site would probablyrequire might incorporate an initial 6 monthly monitoring programme using the boreholes already in emplaced to determine the success of ongoing NA at this site. If the plume changed direction or migrated further towards possible receptors, a revised monitoring scheme would be required possibly including placement of new monitoring wells. In the event of further plume shrinkage over the first 2 years, monitoring cwould be continued on a yearly basis until a firm prediction of contaminant concentrations could be made andthe remedial objectives had been mettion was deemed acceptable. Upon further consultation with the regulatory body to establish whether or not MNA objectives had been met, monitoring would cease.

3.1.6 Conclusion

From the screening procedure, it was clear that MNA could be an appropriate remedial strategy for this site. The subsequent demonstration through primary and secondary lines of evidence and the assessment of plume status presented further strong proof that MNA would be successful. Given that the evidence of plume collapse was strong, application of a solute fate and transport model was not required. The cost/benefit analysis showed that MNA was the least expensive remedial option and therefore following discussion with the regulator an implementation plan could be developed. Through application of the Agency DSS, extremely close communication would have to beis maintained with the regulators and, as such, the possibility of unforeseen mistakes should be very llow.

3.1.4CONCLUSIONS

THIS SITE APPEARS TO BE PARTICULARLY APPROPRIATE FOR THE DEMONSTRATION OF MONITORED NATURAL ATTENUATION, DUE TO THE LACK OF POTENTIAL RECEPTORS CLOSE BY AND THE TIME AVAILABLE FOR MONITORING. THE FAVOURABLE HYDROGEOLOGY OF THE SITE, TOGETHER WITH THE GEOCHEMICAL PROPERTIES OF THE GROUND, ENHANCE THE LIKELIHOOD OF BIODEGRADATION OF THE CONTAMINANTS PRESENT. THIS CONCLUSION IS REINFORCED BY THE OBSERVED COLLAPSE OF THE PLUME, AS DERIVED FROM THE FINAL SET OF DATA.

3.2 Aamerican Ssociety for Ttesting and Mmaterial MNAmna Pprotocol

Aims, Intent and Background to the procedurTe

The ASTM DSS procedure was intended as a screening procedure for the multitude of contaminated sites in America or those sites world-wide that are dealt with by American USmultinational based companies. The DSS is a single flowchart with a straight-forward, logical sequence of stages and decision points (Figure 3.2). The main criteria for MNARNA decision making are the observations of contaminant plumes behaviour and, more importantly, plume stability.

The primary line of evidence in the ASTMis tiered approach is whether the plume is expanding or shrinking. A shrinking plume iswas taken as evidence that natural attenuation processes were are successfully remediating the plume. A stable plume was is also taken to be evidence of natural attenuation in that the attenuation rate is equalled to the rate of contaminant migration. Primary lines of evidence are considered sufficient to demonstrate MRNA in sites with adequate historical data.

Secondary lines of evidence are required if the first line of evidence is inadequate or inconclusive. Under the ASTM DSS Ssecondary lines of evidence include measurement of ing the natural attenuation rate or geochemical data trends indicating naturally occurring biodegradation. The Ttertiary lines of evidence are optional when the primary and secondary lines of evidence have failed to draw a conclusion. These include solute transport modelling, assimilative capacity and microbiological studies.

This evaluation presented herein was carried out using the American Society for Testing and Materials (ASTM) decision support system "Committee E-50 on Environmental Assessment" (current edition published August 1998; 2). The literature is highly structured and detailed covering the background of natural attenuation in the USA through to monitoring strategies and indicators of natural attenuation. The appendices provided in detail the various natural attenuation rate determining models from the simple mass balance approach to multi-dimensional models. The appendix also provided a working example for illustration.

3.2.1 Initial response, site characterisation and CSM

Site characterisation was required to obtain sufficient information on which to formulate a CSM and base a decision as to the suitability of the natural attenuation option and likely remedial goals. By following the DSS documentation the following assessment stages were undertaken:

1. As requested by the DSS, contaminant source was removed above ground and the relevant local authority (Environment Agency/Local Authority) informed.

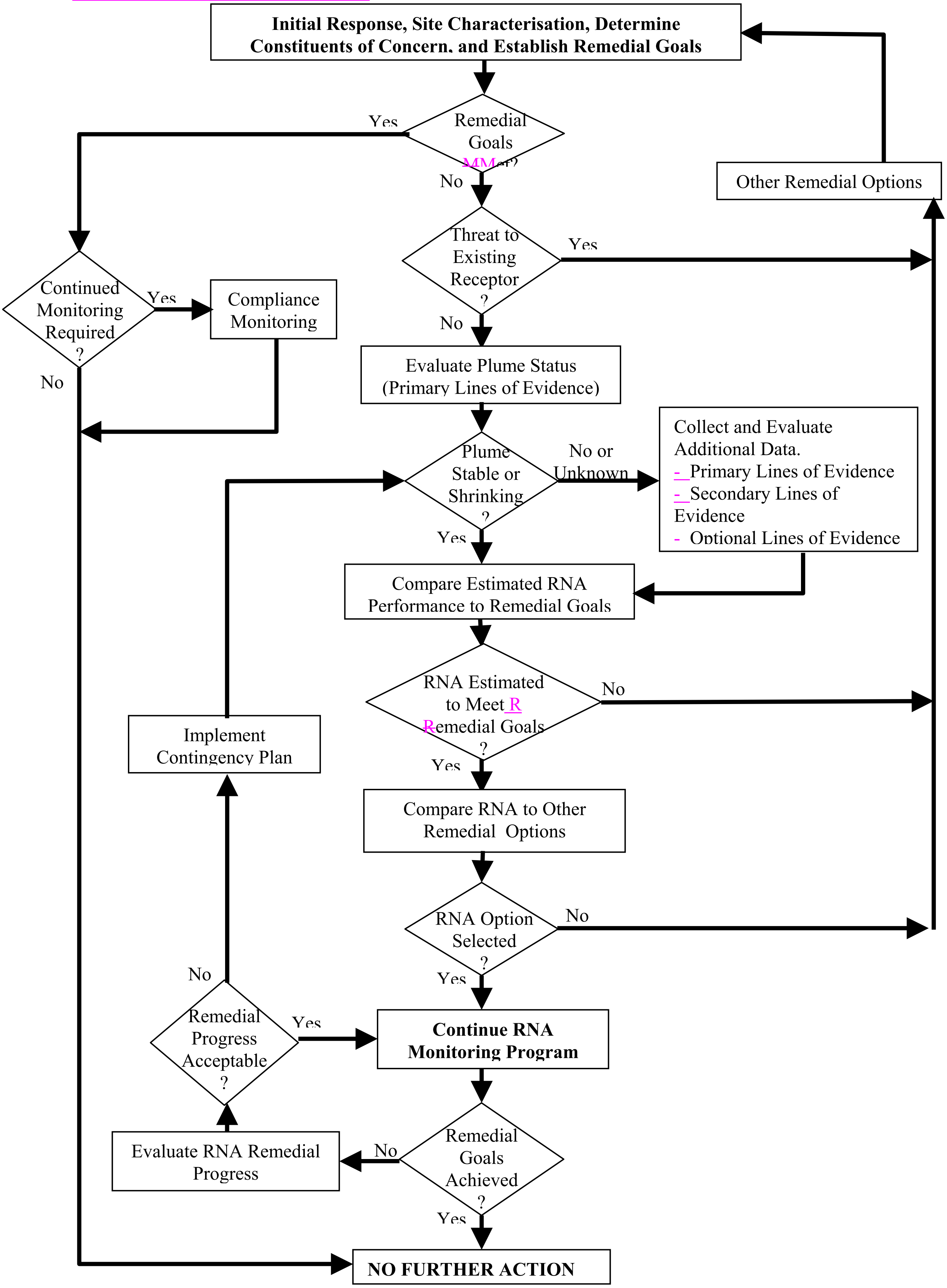
2. The ASTM DSS requires the use of a CSM to identify contaminant sources, pathways and receptors and the environmental factors that affect them. The CSM is similar to the one created during the application of the Agency's DSS in that the contaminant source, pathways and receptors were determined. The guidance required the CSM to be focussed upon the specific features of the site that were relevant to the objectives. In the case of the study site these features were taken to be as follows:

    - contaminant source area;
    - three dimensional distribution of the contaminants of concern;
    - distribution of constituents of concern and impacts to groundwater;
    - geologic units or structures that influence the migration of constituents of concern;
    - groundwater depth, flow and velocity;
    - location of potential receptors and migration pathways.

3. The CSM was constructed and the plume was determined to be shrinking. It was also determined that the contamination would take 12.5 years to reach a potential receptor. As required, the CSM was used to set remediation goals. In this case, the most precautionary level was the UK drinking water standard for benzene.

As information was gained from documentation or analysis of the monitoring information revealed the extent and behaviour of the contaminant plume, the CSM increased in clarity and usefulness. At certain points the data provided was insufficiently robust for the reliable identification of any trends (*e.g.* DO data).

Figure 3.2: American ASTM Decision Support System Flowchart for Remediation by Natural Attenuation (RNA, 2).



This evaluation was carried out using the American Society for Testing and Materials (ASTM) decision support system Committee E-50 on Environmental Assessment (current edition published August 1998). The literature is highly structured and detailed covering the background of natural attenuation in the USA through to monitoring strategies and indicators of natural attenuation. The appendices provided detail the various natural attenuation rate determining models from the simple mass balance approach to multi-dimensional models. The appendix also provided a working example for illustration. The three-dimensional models used are based upon the Domenico model **[Reference 1]**, which is also used in Bioscreen.

See Figure 5: American ASTM Decision Support System Flowchart.

Initial response, site characterisation and initial conceptual site model

Site characterisation was required to attain sufficient information on which to formulate a Conceptual Site Model and base a decision as to the suitability of the natural attenuation option and likely remedial goals. Following the DSS documentation the following assessment stages were observed:

Contaminant source was cut off above ground and the relevant local authority (Environment Agency/Local Authority) informed.

The ASTM DSS requires the use of a Conceptual Site Model, a tool used to appreciate and identify contaminant sources, pathways and receptors and the environmental factors that affect them. The conceptual site model is similar to the one created during the application of the UK DSS in that the contaminant source, pathways and receptors were determined. The guidance requires the conceptual site model to be focussed upon the specific features of the site that are relevant to the objectives. In the case of the study site these features were taken to be as follows:

- contaminant Source Area;
- three dimensional distribution of the contaminants of concern;
- distribution of constituents of concern and impacts to groundwater;
- geologic units or structures that influence the migration of constituents of concern;
- groundwater Depth, Flow and Velocity;
- location of Potential Receptors and Migration Pathways.

As information was gained from documentation or analysis of the monitoring information revealed the extent and behaviour of the contaminant plume the conceptual site model increased in clarity and usefulness. At certain points the data provided was insufficiently robust for the reliable identification of any trends (*e.g.* dissolved oxygen data), although to some extent the amount of data provided was compensatory.

The remedial goals were established and the plume was noted to be shrinking. The plume, as characterised using benzene concentrations, was ascribed the most appropriate concentration value as a remedial target using the UK drinking water standards. UK drinking water guideline values are given for dissolved or emulsified hydrocarbons rather than specific organic contaminants such as BTEX. The UK drinking water standards are recommended, as with no specific groundwater contamination criteria applicable they are the most conservative guideline criteria available, this approach is in line with the Environment Agency's precautionary principle.

3.2.2 Evaluation of Plume Status

Evaluation of plume status

No imminent threat was identified to anything other than the aquifer directly below the site. From the data provided and the initial site interpretation isolinear diagrams (Figure 2.2 and 2.3Appendix 2), the plume was determined to be shrinking with the plume centre moving slowly northwardssouth. This confirmed that MNA had been justified from the primary line of evidence. The ASTM approach does not require any further lines of evidence if the primary line of evidence is realised with sufficient confidence as determined by the operator. The shrinking of the plume waіs deemed to be sufficient evidence to justify the primary line of evidence although further monitoring was required to ensure complete collapse.

3.2.3 Comparison of estimated MRNA performance to remedial goals

With the primary line of evidence providing enough data to ascertain that MNA was justified, the secondary and tertiary lines of evidence were not required.
We did, however, investigate the optional tertiary line of evidence (*i.e.* the use of the Bioscreen contaminant fate and transport model in place of the Domineco predictive model). The estimation of the effect of RNA using the Domineco based Bioscreen model gave results that were not in accordance with the observed field data from the initial site data investigation [Appendices 2]. Rates of physical processes and consequentially biodegradation were predicted to be in excess of actual values.

3.2.4 Comparison of MRNA costs to other remedial options

The comparison of costs between MNA and a number of other remediation strategies is shown in Table 3.1 (above, section 3.1.5). Given these cost comparisons, thThe cost of monitoring the plume over the degradation period was deemed unlikely to exceed the cost of any other remedial method.

Therefore, Tthe MRNA option selected was selected because of the:

- greater ceost implications involved with other methods;
- lack of risk to other receptors;
- evidence of natural attenuation already occurring, although further monitoring was required to ensure verification of ongoing NA.

3.2.5 3.2.5 Continuation of a RNA monitoring programme and remedial goal achievement

Given the changes in plume contamination concentration observed over the monitoring period, it was decided that there was a strong possibility of natural attenuation continuing. The rate of plume collapse is difficult to predict. However, regular monitoring would provide the data required for such a prediction. Based on the data analysed thus far, it was decided that an initial 6 monthly monitoring programme would be required to determine the success of ongoing NA. However, if the plume changed direction or migrated any further, new monitoring wells would be required. In the event of further plume shrinkage over the first 2 years, monitoring would be continued on a yearly basis until a firm prediction of contaminant concentrations could be made and remediation was deemed acceptable. ~~From the data available, it was decided that if the plume changed direction or migrated any further north, new monitoring wells would be required. Based upon the uncertain results from the Bioscreen model it was deemed to be unwise to state an approximate date beyond 1998 by which contaminant concentration limits would be met and from which remediation could be deemed to be acceptable.~~

~~Given the changes in plume contamination concentration observed over the monitoring period, there was a strong possibility of natural attenuation continuing.~~

3.2.6 ~~3.2.6~~ Conclusions

From the low cost implications compared to other methods (Table 3.1), the lack of risk to other receptors and evidence of natural attenuation already occurring, this site was deemed acceptable for monitored natural attenuation. The ~~circumstantial~~ evidence from ~~of~~ the initial site investigation isolinear diagrams ~~and the trend towards decreasing concentration in the Bioscreen model results~~ enabled prediction of eventual success of the ~~monitored~~ MNA~~natural attenuation~~. ~~However, using the ASTM protocol this could not be supported without sufficiently robust data.~~

From the evidence collected from the site investigation MNA was~~is~~ felt to ~~have a good chance~~be likely to succeed ~~of success,~~ with remedial goals ~~are~~ expected to be reached at key stages of the remedial strategy. With a predicted good chance of MNA from the analysis of the primary data, ~~success shortcuts to~~ the secondary and tertiary lines of evidence were not deemed necessary ~~be taken where possible, in the application of the DSS,~~ thereby avoiding what the DSS regards as unnecessary~~excess~~ cost. However, c ~~(i.e. secondary and tertiary line of evidence investigation is not required). C~~ontinual ~~checking~~ monitoring as described above ~~of natural attenuation progress~~ and the opportunity to loop back to an earlier assessment stage if required are ~~further~~ used as safeguards in the ASTM DSS. These ~~Safeguards~~ also enable the selection of alternative remedial options if natural attenuation is not found to be sustainable.

~~3.3~~ NICOLE ~~REPORT~~ Report of the Draft NOBIS Procedure

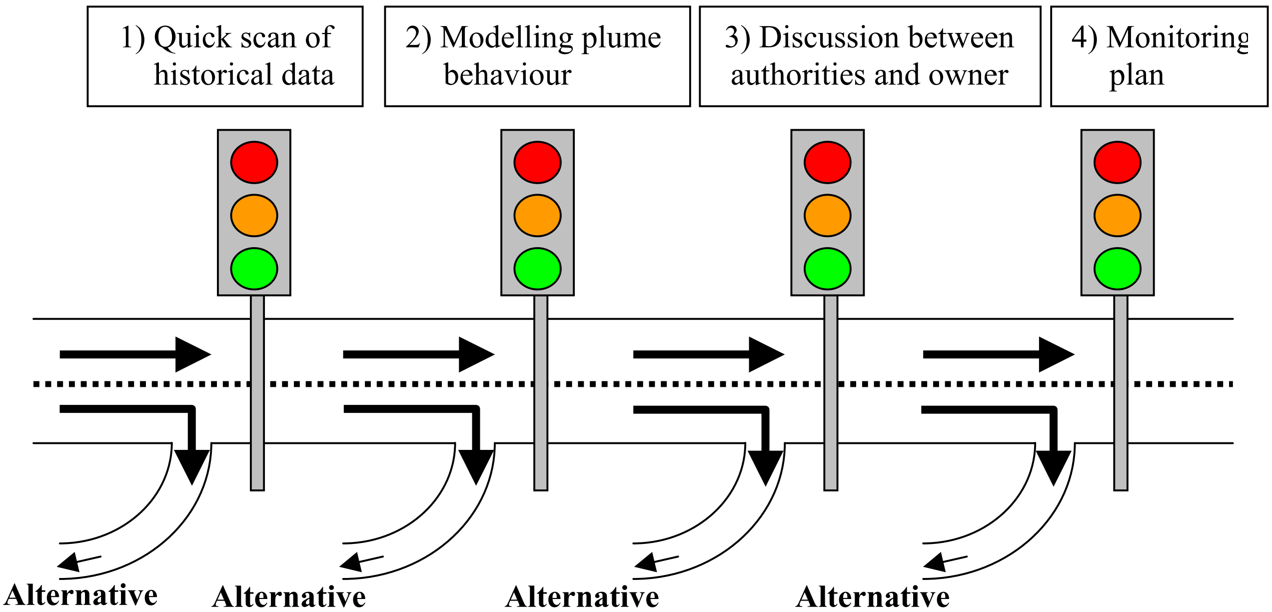
3.3 ~~3.3.1 AIMS, INTENT AND BACKGROUND TO THE PROCEDURE~~

~~The Draft NOBIS DSS guidance~~

This evaluation ~~has~~was ~~been~~ carried out based on a summary of the Dutch procedure that was provided (~~TNO-MEP-R 99/3134~~). No English translation of the detailed procedure (3) is currently available. ~~Attempts to get English translation have so far been unsuccessful.~~ The procedure ~~i~~was based on a traffic light system with a decision at each traffic light to continue towards the use of MNA as a remedial option or to use an alternative remedial system (Figure

3.3). The system was~~has been~~ developed for chlorinated solvents and BTEX. Although the chlorinated solvents section was complete, the first stage of the decision support system as it applies to BTEX wa~~i~~s still under ~~evalu~~ development at the time of this study. Available details of the individual traffic lights are presented below followed by the application of the DSS to the sample dataset.~~ation.~~

~~See~~ Figure 3.3~~6~~: Dutch NOBIS Decision Support System ~~Flowchart~~traffic light system (5).



3.3.1 Summary of ~~3.3.1 First traffic light~~Traffic Light System

The first traffic light ~~This stage~~ require~~d~~d regular monitoring of BTEX contaminants to confirm that NA was taking place. ~~study of c~~Concentration trends over time and relationships between BTEX and redox conditions should be studied~~. Redox conditions, in this situation, are an expression of the combined effect of electron acceptor reduction action on the soils chemical environment.~~ . ~~Such a measurement of either individual chemical concentrations or combined electrical conductivity can be used to gauge the potential for the natural attenuation of contaminants within the soil. The breakdown of contaminants uses those soil electron acceptors available.~~ If contaminant concentration has~~had~~ decreased with time or a relationship with redox was determined~~existed~~, the Dutch DSS deemed that there ~~would be~~was a chance of natural attenuation taking place. If not, then MNA was ruled out as a remedial option.

At the second traffic light, the DSS required that a solute transport and fate model be applied to determine the expected behaviour of the plume. Several models were suggested including MODFLOW with RT3D, METROPOL, BIOSCREEN and VERA. The model should be based on the field parameters and should show:

- The decrease in the amount of contaminant with time; and
- The change in position of the centre of the plume.

By the third traffic light, this DSS required discussion between the authorities and the problem owner as to whether MNA was the appropriate remedial option. The DSS gave no guidelines for discussion and evaluation but stated that the following factors should be taken into account:

- available time;
- available space;
- future use;
- possibilities of other remedial options;
- legal aspects; and
- public opinion.

Finally,- by the forth traffic light, MNA should be implemented. A long term monitoring plan should be prepared to enable evaluation of NA, the model used and to ensure protection of possible receptors (through the positioning of extra monitoring wells between the plume and receptors).

3.3.2 Application of Dutch DSS to sample data

3.3.1.1 Initial review of the data

Using the data provided for this case study it was ascertained that:

1. contaminant (benzene) concentration decreasedd over time;
2. electron acceptors/donors concentrations changed, although there was little correlation between the two..

These results indicated that natural attenuation may have been taking place, thereby enabling application of the DSS to proceed to the second traffic light.

Application of the solute fate and transport model3.3.2 Second traffic light

At this stage, the types and relative importance of information required for the application of a hydrogeological model is discussed in relatively simple terms. Bioscreen is mentioned as one of the models suitable for use. The Dutch Decision Support System (DSS) required that the output of the chosen model be in two figures:

depicting the contaminant load in the plume;
depicting contaminant development in the polluted area (Migration, degredation, spread).

The application of the BIOSCREEN model (6) is shown in Appendix 2. The model output presents graphs showing load over plume length. Given the incomplete field data provided, some default values from the scientific literature were incorporated when applying the model. Consequently, although plume collapse was predicted from the model output, this collapse was faster than that observed from analysis of actual field data. As such, the BIOSCREEN output was considered to be unreliable.

The Bioscreen model output is included in Appendix 3. The Bioscreen output presents one graph showing the data of load over plume length for each sample period rather than the 2

~~graphs required by the Dutch (one each for change over time and space). The information available in the two required graphs can be gleaned from the initial site investigation and isolinear graphs (Appendix 2). In this case, the data given by the Bioscreen model is unreliable, because of either the data inputted or the model itself. The quality of data provided required the use of some default values in the application of the Bioscreen model, a range of default values were used to avoid potential error and gauge the influence of those variables allocated default values on the Bioscreen output. Outputs from the use of variable default values were highly variable in predicting MNA success, hence the Bioscreen output had to be treated as unreliable.~~

Based on the analysis of graphs obtained through application of a model, the Dutch DSS ~~This system pp~~providesd~~d~~ a set of four potential end points as to the potential success of MNA, as~~,~~ ~~based upon the trends identified in the resulting graphs. These are as~~ follows:

- increase in load and increase in polluted area: *No Chance of NA*;
- increase load in stable area (unlikely scenario): *Fair Chance of NA, depend~~s~~ing upon availability of space and time;*
- decrease in load and increase in polluted area: *Good chance of NA, depending~~ds~~ on ~~conditions like availability of~~ space and time;*
- decrease in load and decrease in polluted area: *Good chance of NA ~~,~~ depend~~s~~ing ~~-~~upon time scale.*

~~Using the guidelines provided, there was considered to be a good chance of natural attenuation being viable~~
~~but that final acceptance of MNA as a remedial option it would depend upon the time scale. Time scale in this situation means the combination of the observed degradation rate and the time constraints imposed by other factors such as the combination of migration rate and the distance of the nearest receptor.~~

Discussion between authorities and problem owner~~Third traffic light~~
~~At this stage, this system provides for a discussion between the authorities and the problem owner. It is a decision point at which the DSS can only be continued further if it has been decided on a technical and scientific basis that natural attenuation is a viable option. From the interpretation of the site investigation data provided, this was seen to be the case.~~

With MNA selected as a viable remedial option, the decision on actual implementation is dependent on the criteria described in section 3.3.1 (third traffic light) and on discussions between the problem owner and the local authority. In the sample data set, the closest potential receptor was 500 m distant. However, through both application of a model and analysis of the field data the plume was determined to be collapsing. Therefore, MNA was deemed to be an appropriate choice of remedial option.

Preparation of the long term monitoring plan~~Further implementation of the natural attenuation remedial option can only occur under the Dutch DSS when criteria such as available time, available space, future use, possibilities for other remedial strategies, legal aspects and public opinion have been discussed by both the local authorities and the problem owner. In the context of this investigation, the available space required is that sufficient for a plume to~~

migrate within, over the course of the time it is expected to take (from modelling) to degrade to acceptable concentrations, providing there are no potential or additional receptors encountered.

Fourth traffic light

At this stage a long term monitoring plan is prepared. In this case, as with the other two DSS, the putative monitoring plan would include an initial 2 year sampling programme with 6 monthly sampling of monitoring wells. The DSS requires protection of possible receptors, therefore the monitoring plan would include the positioning of extra monitoring wells ("alert wells"), between the plume and the putative receptor. After the first two years, yearly monitoring would be continued until contaminant load had decreased sufficiently. In the event that contamination did not decrease sufficiently the DSS allows for a continuation of monitoring or for the use of additional measures to achieve contaminant targets. This plan is necessary to evaluate the model used, the efficacy of natural attenuation and that surrounding receptors are not at risk. A large amount of monitoring data was provided and as such it was possible to compare the predictions made using earlier data to run the Bioscreen model with the actual monitoring data from later monitoring visits. This comparison revealed problems with either the inputted data or the model itself, as previously discussed. However, isolinear and trend analysis pointed to continued biodegradation of the contaminant plume.

At this stage provision is made for installation of extra monitoring wells which would be required if the contaminant plume swung further to the north or if the centre of the plume migrated northwards. Had the Bioscreen model worked, the data from it could have been used to correctly place a compliance well and provide an expected time frame for MNA. The compliance well would have had to be put in place to allow sufficient time to undertake additional measures when necessary.

3.3.3 Conclusions

Conclusions

From interpretation of the technical and scientific data, monitored natural attenuation was deemed to be a viable option at this site. However this remedial option could only be utilised following discussion of other criteria including available time, available space (discussed earlier), future site use, possibilities for other remedial strategies, legal aspects and public opinion. The length of time for application of MNA would depend on discussions held at the third traffic light and upon the results of the monitoring plan described above.

4 FINDINGS OF THE BENCHMARKING PROCESS

4.1 Comparison of P~~p~~rocedures

The preceding section~~s~~ has~~ve~~ reviewed the application of three DSS to the same site data.

Each DSS required a different number of decision points, with the ~~UK~~Agency ~~-~~system having the most, ~~then~~ followed by the ~~the~~ ASTM and ~~finally~~ the Dutch system. ~~Both~~ All three DSS~~the UK and ASTM systems~~ utilised ~~-~~flowcharts of some kind.~~,~~ H~~h~~owever, the formats for these differed considerably. ~~The UK methodology consists of a generic decision matrix encompassing 3 smaller flowcharts covering screening, detailed assessment and implementation (performance monitoring). The screening decision matrix identifies whether legally, financially and practically MNA is a viable option. The detailed assessment decision matrix assists in determining if MNA will be the best option to meet defined objectives. The implementation decision matrix covers monitoring strategy design and implementation as well as continual checking and contingency plan options. Throughout the whole process and especially at key decision points, the regulator (Environment Agency or local authority) must be consulted.~~

The ~~U~~Agency ~~K~~ procedure ~~places a large~~ emphasised ~~on the~~ usi~~ng~~e ~~of~~ geochemistry in a **quantitative** fashion as a second line of evidence ~~to assess~~for MNA. Whilst this requirement increases the level of confidence in the decision to use MNA ~~makes more sense in terms of accuracy of assessment~~ it may introduce additional costs or make assessments more ~~complex and~~ lengthy. Within plumes, the geochemistry is ~~very~~ complex with competing oxidation/reduction reactions occurring, both aerobic and anaerobic. To obtain a mass balance from a field application is known to be ~~very~~ difficult. The assimilative capacity expression is based on the stoichiometry of several reactions for BTEX degradation, which are assumed to go to equilibrium and not compete with each other.

~~R~~Researc~~c~~h has shown that these processes do compete and compounds can go through many conversions along multiple degradation pathways (8). Thus, the mass balance based on assimilative capacity ~~is~~ may not give a wholly accurate picture of *in situ* conditions~~not realistic.~~. ~~The assimilative capacity expression does not include all potential electron acceptors and does not take into account rates, which also tends to create an exaggerated view of the anaerobic degradation contribution.~~ However, it should be emphasised that geochemical analyses~~try~~ can provide qualitative and some useful quantitative information.~~, supporting information.~~

~~**One of the criteria for assessment of suitability of MNA is that the plume should not expand by more than 10% of the distance to the nearest receptor". This is reasonable for many contaminants such as BTEX and Chlorinated Aliphatic Hydrocarbons (CAH), but not for highly water soluble and mobile contaminants like alcohols and MethylTetraButylethylene (MTBE). These plumes can detach and migrate from the source. The resulting "slugs" can attenuate as they migrate.**~~

In contrast the ASTM DSS methodology utilises a single, smaller decision matrix which makes no reference to regulatory interaction as ~~you~~ one proceeds through the process. The flowchart covers less of the practical detail of MNA than ~~does~~ the Agency's ~~UK~~ DSS, but presents it in a more logical order with guidance for each decision point presented in the text. The tiered approach is more pragmatic than the ~~UK~~ Agency approach. If the plume could~~an~~ be demonstrated to be shrinking or stable, then the geochemistry data were~~are~~ not required. Geochemistry wa~~i~~s only recommended where plume monitoring wa~~i~~s inadequate to demonstrate plume stability. This is likely to be necessary at complex sites where there are multiple mixed plumes and significant heterogeneity.

The Dutch DSS methodology uses a decision matrix that provides the choice of another remedial option at every decision point (or traffic light), although by taking this choice it appears ~~to mean~~that MNA may be prematurely ~~is~~ abandoned as an option. However, t~~T~~he Dutch DSS does~~oes~~ not then include any provision for ~~progress checking~~further monitoring or any ~~further~~ description of possible remedial alternatives that c~~a~~ould~~n~~ be used in combination with natural attenuation. The DSS consistes~~s~~ of a simple decision structure with only general references to the aspects of natural attenuation that need to be considered at each stage. However, it must be noted that the Dutch DSS is~~was~~ only available in summary form and important details regarding the decision matrix may well have been excluded.

To facilitate a comparison of the different ~~decision support systems~~Decision Support Systems a table has been compiled. The evaluation variables used for the comparison were based on the evaluation criteria and were developed through a number of meetings of the project team following an initial exercise of familiarisation with the site data and the various DSS procedures.

Th~~ee focus of the Table 2~~ evaluation criteria~~variables~~ used were:

- ~~**cin comparison were those evaluation criteria requested by the Environment Agency (**~~**ease of use**; how easy it would be for a recently qualified graduate to complete the process;
- **transparency of decision making**: how clear the process would be to an external auditor and/or other stakeholder (*e.g.* general public); and
- **robustness of conclusions**: how the procedure helps to minimise the risks associated with the decision making process through, *e.g.* the provision of contingency plans.~~, robustness of decision making, clarity of decision making, time taken and the cost effectiveness).~~

The ~~E~~evaluation variables i~~, i~~n Table 4.1~~2,~~a-c ~~-~~were chosen because ~~as~~ each one was ~~a~~ sufficiently discrete ~~variable~~, common to each DSS and concerned with at least one of ~~five~~ three~~of~~ the ~~Environment Agency's required~~ evaluation criteria. ~~In combination all the evaluation variables chosen were deemed sufficient for consideration of the relative merits of each DSS against the Environment Agency's evaluation criteria.~~

Each evaluation variable was considered independent of the others when comparisons were made. In assessing each ~~DSS for each~~ evaluation variable ~~-~~an objective approach was taken. To assist in gauging the relative performance of a particular DSS~~s~~ against a specific ~~n~~ evaluation criteria a ranking ~~comparative~~ score was used. Once the relative DSS performance against a specific evaluation criteria was complete a ranking score was applied (first (1), second (2) or third (3)). Where the performance of two DSS was the same and ranking was not possible (*i.e.* on balance the DSS's were ~~just as good as each other~~equally good) the ranking difference was split with the two matching DSS ranked as either 1.5 or 2.5 depend~~e~~ant upon the rank of the remaining DSS. Once ranking had been applied to each DSS for every evaluation criteria, the ranking score was totalled and averaged~~ for each DSS~~. Where all three DSS performed equally well against evaluation criteria no ranking score was applied.

Table ~~2~~4.1a-c includes a description of the strengths or weaknesses of a DSS that contribute to the relative ranking given for each evaluation variable for a specific DSS. Subjective ranking was deemed to be important as the entire exercise concern~~s~~ed learning from the impressions of ~~those~~ individuals w~~, w~~ith little experience of investigating M~~R~~NA~~ experience, who attempt to apply a DSS~~.

~~Table 4.11: Summary of Procedural Differences between the AgencyUK, ASTM and Dutch Natural Attenuation Decision Support Systems~~

Table 4.1a: Summary of Procedural Differences between the Agency, ASTM and Dutch Natural Attenuation Decision Support Systems Category: Ease of Use

Assessment Variable	Agency DSS	ASTM DSS	Dutch DSS[1]
Quality of documentation: Clarity	Information was provided covering all aspects of MNA: background, processes and procedures. **Rank = 1.5**	Information was provided in a practical guidance layout. Further details were contained in appendices. **Rank = 1.5**	Little guidance/background information was presented, however, the summarised information provided was not as complete as that from the other two DSS. **Rank = 3**
Quality of documentation: Technical content	~~A large amount of r~~Relevant technical supporting information was provided in tabular form with appropriate backup in the appendices. Information was detailed and suitably referenced. **Rank = 1**	~~A sufficient volume of r~~Relevant information was presented, but not in as much detail as the Agency DSS. Information was in tabular and textual format. **Rank = 2**	Little guidance/background information was presented in the summary document. **Rank = 3**
Coverage of MNA processes	Covered all the processes in MNA in brief or tabular form **Rank = 2**	Covered MNA processes in tabular form and provided more explanatory text than the Agency DSS. **Rank = 1**	Covered the aerobic, anaerobic, and redox interactions. **Rank = 3**
Guidance on sample strategy design and methods of *in situ* determinant analysis and sample preservation).	Focussing on borehole location strategy, considerations, sampling methods and frequency of monitoring. **Rank = 2**	Detailing locations and types of boreholes, referenced sampling and field analytical methods, and a brief summary of the potential use of the data. **Rank = 1**	Not contained in summary. **Rank = 3**

Assessment Variable	Agency DSS	ASTM DSS	Dutch DSS[1]
Guidance on obtaining and analysing geochemical data. (Practical guidance for analysis and interpretation of sample data)	Provides an idea of the expected monitoring suites that can be used and references sampling and analytical procedures. Contains tables of methods, references and lowest detectable limits for analysis. Covers a wide range of determinants. **Rank = 1**	Concentrates on a few typical determinants and references laboratory analytical methods for these determinants. **Rank = 2**	Not contained in summary data. **Rank = 3**
Guides the reader through an application of the MNA process.	The Agency DSS provided a large amount of backup information but was not as streamlined as the ASTM (*i.e.* not all decision points were clearly explained in the text). **Rank = 2**	The flowchart/decision matrix was referenced at each decision point with corresponding explanatory text. **Rank = 1**	The traffic light approach was straightforward but for each stage there was little supporting information. **Rank = 3**
Was there an illustrative example?	Yes **Rank = Not Ranked**	Yes **Rank = Not Ranked**	None was provided in the summary. **Rank = Not Ranked**
Guidance on obtaining credible biodegradation data	Factors affecting biodegradation rates were discussed. However, other information provided to obtain credible values was limited. **Rank = 2**	The DSS presented detailed guidance calculating degradation rates from other parameters as well as explanatory texts and references. **Rank = 1**	The summary DSS document does not mention any methods for determining biodegradation rates. **Rank = 3**
Guidance on the use of predictive modelling	The DSS detailed both Domenico and physical process mathematical models. Ten available models were referenced.	The Domineco model was described in detail, as were simpler models of mass balance and one-dimensional mathematical analysis models.	Five currently available computer based predictive models were recommended (*e.g.* Bioscreen, Bioplume etc)

Assessment Variable	Agency DSS	ASTM DSS	Dutch DSS[1]
	Rank = 1	**Rank = 2**	**Rank = 3**
References to external documentation	External documentation was referenced **Rank = 1.5**	External documentation was referenced **Rank = 1.5**	No alternative sources of information were recommended in the summary. **Rank = 3**
Glossary of terms	Yes **Rank = Not Ranked**	Yes **Rank = Not Ranked**	No **Rank = Not Ranked**
Ranking Score Totals	**14**	**13**	**27**

★1 Given that access to the full detailed procedure was not possible, satisfactory was generally the only possible ranking. This is less a reflection of the Dutch DSS rather of the summary which was ~~provided~~ available for analysis.

Table 4.1b: Summary of Procedural Differences between the Agency, ASTM and Dutch Natural Attenuation Decision Support Systems
Category: Transparency of Decision Making

Assessment Variable	Agency DSS	ASTM DSS	Dutch DSS[1]
Approach to lines of evidence for NA	Highly detailed. The more information provided and criteria met, the greater the confidence in the effectiveness of MNA. Lines of evidence were defined as: 1. primary: reduced concentrations of	Tiered. ASTM used a tiered approach with plume status as the primary line of evidence. Indicators of naturally occurring biodegradation comprised the secondary line of evidence, only used if the plume	Natural attenuation is deemed to be acceptable as a viable remedial option dependent upon the presence of oxygen, an observed decrease in contaminant concentrations or appropriate redox conditions. Later in the DSS, data

Assessment Variable	Agency DSS	ASTM DSS	Dutch DSS[1]
	contaminant. 2. secondary: evidence of contaminant mass reduction from chemical and geochemical data. 3. tertiary: microbiological study evidence. Solute Fate and Transport models were recommended as additional evidence of MNA. **Rank = Not Ranked**	status was inconclusive. Tertiary optional lines of evidence included solute transport modelling, assimilative capacity or microbiological studies were used if primary and secondary lines of evidence were inconclusive. **Rank = Not Ranked**	regarding decrease in load and affected area from the predictive model output were the required lines of evidence. **Rank = Not Ranked**
Guidance on obtaining lines of evidence data. (The requirements of the initial site investigation / characterisation and what to look for to justify required lines of evidence).	Focussed on what information was required from the site, processes involved, trends in determinants indicating biodegradation and use of data necessary for a comprehensive initial review. The Agency DSS gives details of many key parameters for MNA identification and states at what stage of the DSS they should be used. **Rank = 1**	Described the information required, processes involved and implications of variable changes all focussed on the specific line of evidence being addressed. The data requirements listed to justify MNA are less than the Agency DSS. **Rank = 2**	Not included in the summary document. **Rank = 3**
Decision making Process on initiating MNA	The decision was made based upon the amount of and the confidence in the information available. Decisions were made in ongoing consultation with the Agency. Decisions will be based largely upon the monitoring data, and not exclusively on predictive modelling.	Based upon the lines of evidence, a decision could be made by whoever was undertaking the investigation, free of regulatory consultation. There was the possibility that the regulator may not accept the final outcome. Regulation guidelines were available.	The decision to progress with assessment of the potential for MNA lies with the investigators based upon criteria for the first two traffic lights. Further decisions were made in consultation with the regulatory authorities and the problem owner.

Assessment Variable	Agency DSS	ASTM DSS	Dutch DSS[1]
	Rank = 1	**Rank = 2.5**	**Rank = 2.5**
Guidance on presentation of analytical results.	Presentation guidelines for different determinants were discussed although practical guidance on method use was not included. **Rank = 1.5**	Presentation guidelines for contaminants of concern were detailed. Illustrations were included regarding use of the stated methods. **Rank = 1.5**	The only presentation methods discussed were those of the predictive model output. **Rank = 3**
Does the DSS explain the legislative framework?	The Agency DSS explained the legislatively framework in detail with the initial screening decision matrix predominantly concerned with legislative constraints. **Rank = 1**	Reference to legislatory concerns was minimal. **Rank = 2.5**	Although the need to consult the legislative authority was mentioned at traffic light three, further detail of any framework was not provided in the summary document. **Rank = 2.5**
Guidance on setting remedial targets	Remedial targets were set using (6). This provided guidance on the derivation of remedial targets to protect groundwater and surface water receptors. **Rank = 1.5**	Remedial goals were required to be determined by application of the ASTM Risk Based Corrective Action methodology. Additional criteria included source containment and time frame. **Rank = 1.5**	There was no reference to the determination of remedial targets in the Dutch DSS summary. **Rank = 3**
Ranking Score Totals	**6**	**10**	**14**

Table 4.1c: Summary of Procedural Differences between the Agency, ASTM and Dutch Natural Attenuation Decision Support Systems Category: Robustness of Conclusions

Assessment Variable	Agency DSS	ASTM DSS	Dutch DSS[1]
Points at which receptors were considered	Receptors were considered in the first step of the screening process. **Rank = 1**	Receptors were considered early following characterisation of the site and comparison with remedial goals. **Rank = 2**	The receptors were considered later on following predictive modelling. **Rank = 3**
Ability to consider changing external factors	Decision matrices provided opportunities to choose alternative remedial options. **Rank = 3**	A contingency plan was considered important. Extensive periods of work weren't required before discounting NA and considering alternatives. **Rank = 1.5**	Consideration of alternative remedial options could only be made at each traffic light. It was unique in referring to public opinion as an influencing factor. **Rank = 1.5**
Guidance on alternative remedial solutions if MNA was inappropriate	There was little guidance included in the DSS. The consideration of alternative remediation technologies was included. **Rank = 2.5**	The DSS included names of specific alternatives for consideration, either alone or in tandem with natural attenuation. **Rank = 1**	Limited documentation regarding alternative remedial options was provided in the summary document. **Rank = 2.5**
Guidance on relation between MNA and other remedial solutions.	There was no detail as to how any alternative remedial options would integrate with MNA. **Rank = Not Ranked**	There was no detail regarding integration of methods or alternative remedial technologies with MNA. **Rank = Not Ranked**	There was no detail as to how any alternative remedial options would integrate with MNA. **Rank = Not Ranked**
Guidance on long term monitoring	Upon positive determination of natural attenuation, a section was dedicated to long term monitoring. The decision matrix gave practical advice on borehole placement, checking and when to implement a contingency plan. Time scales in the text may be of concern to problem holders (specifically BTEX	Guidance on long term monitoring was integrated as part of the decision matrix, and was supported with supplementary text.	Very little detail was provided for the design and implementation of a long term monitoring plan. There was no guidance as to borehole placement other than the recommendation of placing "alert wells" to check that migration is not affecting the receptors.

Assessment Variable	Agency DSS	ASTM DSS	Dutch DSS[1]
	monitoring for 5 years). **Rank = 1.5**	**Rank = 1.5**	**Rank = 3**
Guidance on contingency planning during MNA monitoring	The DSS required a contingency plan for which it provided clear criteria as to when it should be activated. The DSS suggested a plan for additional measures in the event that NA failed. No contingency plan options were detailed. **Rank = 2**	The contingency plan required by the DSS detailed when it should be activated and the potential actions involved (*e.g.* source removal, containment measures, consideration of a remedial alternative etc.) **Rank = 1**	The Dutch DSS has no provision for a contingency plan. **Rank = 3**
Guidance on necessity and location of sentinel wells.	The DSS strategy required sentinel boreholes and provided guidance details for location. The use of a suitable pollutant fate and transport model was recommended when deciding sentinel borehole locations. **Rank = 1**	The use of sentinel boreholes in the DSS was optional. There was no specific guidance upon the placement of such wells beyond the need for location between the plume and a receptor. **Rank = 3**	Sentinel or "Alert" wells were required and should be placed between the receptor and the plume at a sufficient distance to allow a suitable remedial response should contamination be detected. **Rank = 2**
Guidance on contact with regulator. (NB Reflects the legislative environment of the country of origin).	Contact with the regulator was expected to be continuous throughout with all decisions made in consultation with the Agency. **Rank = 1**	Contact with the regulator was expected to occur at the end of the procedure with enquiries made from time to time as to the Agency view on certain aspects of NA. **Rank = 2.5**	Consultation with the regulatory authority was expected to occur at traffic light 3 based upon findings of the predictive modelling stage. **Rank = 2.5**
Guidance on communication with other stakeholders	Liaison and negotiation were seen as key considerations and the DSS detailed a range of interested stakeholders. **Rank = 1**	Some potentially interested parties were considered in the glossary. **Rank = 3**	Considered consultation with the "problem holder" as a traffic light 3 action and not an initial requirement. **Rank = 2**

Assessment Variable	Agency DSS	ASTM DSS	Dutch DSS[1]
Guidance on completion of MNA	The DSS listed three criteria for completion: contaminant concentrations reaching background levels; remedial targets being met; and a high degree of confidence existing in the observed bioremediation trends such that remedial targets would be achieved. Completion agreed with regulator. **Rank = 1.5**	The ASTM DSS lists four key criteria for completion: there were no existing/potential receptors; remedial goals have been met or there is evidence MNA will continue; plume was stable or shrinking; institutional controls are in place and maintained. Completion agreed with regulator. **Rank = 1.5**	The Dutch DSS summary makes no mention of any stop or no further action criteria. **Rank = 3**
Ranking Score Totals	**14.5**	**17**	**22.5**

4.2 E~~E~~ase of U~~U~~se

Ease of use was defined as how easy it would be for a recently qualified graduate to complete the process. Of the three DSSs assessed, the ASTM was the easiest to use (ranking score 13), closely followed by the ~~UK~~ Agency system (ranking score 14). In part because only a summary document was available, the Dutch DSS proved the most difficult to use as is reflected in the comparisons included below (ranking score 27).~~ Consequently, in the following section only the UK and ASTM systems will be compared.~~

The structured nature of the documentation, the simple progression through the decision matrix and the information support provided made the ASTM DSS easier to use than the ~~UK~~ Agency system. In comparison, the ~~UK~~ Agency DSS had a number of minor disadvantages including the size of the decision support matrix, specifically the need for regulatory consultation at each major decision point (the regulators position was taken to be precautionary), and the quality of the tabular information backup. Regulator involvement was taken to reduce the ease of use because of the assessors need to integrate and understand regulator concerns (this may vary between individual assessors). Conversely ~~T~~the strengths of the ~~UK~~ Agency DSS included the clarity of the decision support matrix, the detail in the text as to what to consider and the quality of information presented in the tabular form.

4.3 ~~4.3~~ T~~T~~ransparency of D~~D~~ecision M~~M~~aking

Transparency of decision making was defined as how clear the process would be to an external auditor and/or other stakeholder (*e.g.* general public). The Agency system was seen to be the most transparent (ranking score 6), while the ASTM (ranking score 10) and the Dutch systems (ranking score 14) were less clearly structured. Again, because only a summary document was available, the Dutch DSS proved the least transparent as was indicated in its ranking.
~~Transparency of decision making was taken to mean the degree to which the decision points within the decision matrix were supported with background information, the logical data collation system up to the decision point and the criteria upon which the decision was to be made.~~

The ASTM DSS decision criteria were clearly explained for each stage and sufficiently supported with supplementary information for each decision point. Moreover, additional information in the form of appendices was available when required. Sampling information was given and specifically referenced in appendices. The decision points were backed up with text on primary, secondary and tertiary lines of evidence only.

The ~~UK~~ Agency DSS had a very good level of technical and regulatory information and a generally well structured format. However, it did not have a step-by-step guide which did leave some unanswered questions. The decision matrices were comprehensive in defining all the required stages, while the text detailed considerations to be made for each stage of DSS application. Data collection strategies and methods were either detailed or referenced in the text. In addition, the text included sampling considerations and potential sources of error. Primary, secondary and tertiary lines of evidence were discussed in detail ~~but only~~ as part of an overall requirement to collect as much information as possible. Decisions were to be made based upon the direct sample evidence in consultation with the regulator. Such decisions could have support from additional lines of evidence such as models and laboratory studies.

4.4 R~~R~~obustness of C~~C~~onclusions

Robustness of conclusions was defined as how the procedure helped to minimise the risks associated with the decision making process through, *e.g.* the provision of contingency plans.

The Agency system was seen to be the most robust (ranking score 14.5), while the ASTM (ranking score 17) and the Dutch systems (ranking score 22.5) were ranked as being less robust. ~~Robustness of conclusions was taken to mean the reliability and defensibility of decisions, the consideration of all possibilities in coming to conclusions and the degree to which findings were explained by background information.~~Again, the summarised Dutch DSS did not provide sufficient detail for a fair comparison with the Agency and ASTM guidelines. However, the Dutch DSS was unique in including a compulsory model application step, and this is discussed below.

4.4.1 Agency~~UK~~ DSS

The Agency ~~UK~~ DSS was the most robust of the three systems analysed. Given the extensive quantity of data required as lines of evidence of NA it was the most defensible approach. The most important requirement was for primary, secondary and tertiary lines of evidence. The degree to which regulatory involvement wa~~i~~s required throughout the process and at major decision points wa~~i~~s seen as an additional reason why the Agency~~UK~~ DSS was both robust and defensible. Indeed, ~~A~~although the regulatory involvement may cause some delays prior to implementation, it should also avoid ~~problems due to backtracking in unforeseen circumstances~~confusion and additional work if there is a disagreement. Moreover, such regulation can also facilitate repeat analysis and consideration of all pertinent concerns thereby ~~and~~ demonstrating~~e~~ ~~an open~~a transparent ~~and honest~~ approach. Application of the DSS to the data provided, showed that because of the successful compliance (barring regulator disagreement) with the first and second criteria (*i.e.* loss of concentration and mass), MNA was identified as a highly feasible remedial option. This result was arrived at through observation of the ~~initial~~ site ~~screening~~ data. ~~, not through application of the solute fate and transport model (**discussed later**).~~ The result was supported by additional evidence specific to the ~~UK~~ government regulatory regime and practical application of remedial action.

4.4.2 ASTM DSS

~~The findings of the application of the ASTM DSS are explained (*i.e.* the explanations / justifications for any trends identified), in tabular form and limited text, in the appendices.~~
The ASTM DSS methodology adopted a tiered approach to the identification of viable ~~RNA~~MNA. As with the Agency~~UK~~ DSS, the ASTM DSS required~~s~~ three lines of evidence. However, the secondary lines of evidence we~~a~~re only required if the plume monitoring data we~~a~~re inadequate to conclusively demonstrate plume shrinkage or stability. The ASTM DSS lines of evidence included the determination of site assimilative capacity, which was not

mentioned in the ~~UK~~ Agency DSS. Application of the DSS to the data showed that MNA could be demonstrated through plume monitoring without the need for any geochemistry. ~~Again application of the solute fate and transport model did not justify / prove MNA (discussed later).~~ Identified trends were supported in the text with explanations as to their possible meaning.

4.4.3 ~~Solute Fate and Transport Model~~Dutch DSS

Contrary to the Agency and ASTM DSS, the Dutch system required the use of a solute fate and transport model and recommended the use of the Bioscreen model. ~~The Bioscreen model was applied~~However ~~as part of the Dutch and ASTM DSS.~~ because of a lack of available data, a number of variables were entered as default values with the r~~R~~esult ~~s~~that the ~~from the~~ modelled plume collapse was more rapid than that observed from the field data.~~ did not conform to the observed concentration gradients~~ Consequently, inclusion of the model resulted in further uncertainty and therefore resulted in a less robust DSS in this case. ~~from the initial site investigation data interpretation. SOME VARIABLES were left as the default values in the model or were altered over a range so as to determine their relative influence in the model. The degree to which results can be deemed to be robust depended upon the quality of data and the model used. Data of insufficient volume or quantity was provided for the Bioscreen programme to provide reliable identification of trends. As the model used was recommended by the Dutch DSS, it had to take responsibility for any discrepancies arising with the data required to input into the model.~~ Neither the ASTM or Agency~~UK~~ DSS include a compulsory modelling step or recommend the Bioscreen model.~~ and it was applied here only because of a similar mathematical basis.~~

4.5 T~~t~~ime T~~t~~aken and C~~c~~ost E~~e~~ffectiveness

The time taken and cost effectiveness of each of the DSSs were assessed following completion of the ranking process for ease of use, transparency of decision making and robustness of conclusions. In addition to the amount of time taken to apply the DSS, cost effectiveness also includes the consideration of alternatives and the cost of any wrong decisions based upon inadequate of misleading data or information. Because of the number of stages in the decision matrix and the time taken to read and make sense of the literature, application of the Agency~~UK~~ DSS was slower than that of the other 2 systems. It should be noted, however, that the summarised Dutch DSS was not a detailed document and therefore it could not fairly be compared with the other two DSS.

The ASTM DSS was simpler and had a more straightforward documentation and decision matrix than did the ~~UK~~ Agency system. A feature of the ASTM system was that demonstration of plume collapse could be taken to be sufficient evidence for application of MNA, avoiding the need for additional assessment of contaminated sites. As such, application of the ASTM system was faster than the ~~UK~~ Agency DSS. ~~Both the UK and ASTM DSSs would have taken substantially longer had the Bioscreen 4 model not replaced the recommended predictive model.~~ This does not necessarily mean that the ASTM DSS is more or less cost effective than the ~~UK~~ Agency DSS in the long term as the robustness of a decision made under the Agency ~~UK~~ DSS may reap benefits in later stages. For example, ~~I~~if any decision regarding MNA comes under question at a later stage, ~~as~~ there will be more supporting evidence available using the Agency DSS than if the ASTM DSS was used.

~~Application of the Bioscreen model was time consuming, in the main because of the need to find and input data. For the purposes of this report this time can be ignored when considering of the relative performance of the different DSS approaches against the time criteria.~~

The point at which the regulatory authorities are~~are~~ to be notified is~~is~~ important as this may cause the relevant project to incur costs in addition to those forecast. Regulatory involvement in the ASTM DSS differs dependent upon the state within which the problem is located. Generally however, consultation for compliance with regulator clean up requirements occurs at the start of the project, with minor consultation throughout and final approval at the end of the DSS application. In the Dutch DSS -consultation with the local authorities is required at the third traffic light stage, that is after the initial review of data and application of the model. Unlike the ASTM and Dutch DSS, the ~~UK~~ Agency DSS requires~~s~~ constant consultation with the regulator, especially at major decision points. The constant monitoring required by the regulator under the ~~UK~~ Agency DSS may avoid any costly mistakes as they can be caught early on. T~~, t~~his is~~is~~ not the case with the ASTM or Dutch DSSs where the regulator generally expresses its opinion towards the end of the DSS application process. As such, ~~S~~should the application of MNA be rejected the ASTM and Dutch DSSs are ~~is~~ the ~~DSS~~ most likely to result in the greatest loss.

<u>5</u> ~~5~~ CONCLUSIONS

Given that only the summary document of the Dutch DSS was available in English, the only <u>fair</u> conclusion that could be drawn was that it that it ~~was~~ <u>provided satisfactory guidelines for the application of MNA</u>~~a 'satisfactory' system~~. Detailed conclusions were not drawn comparing the Dutch DSS to the ASTM and <u>Agency</u>~~UK~~ procedures.

Of the systems utilised, the ASTM proved easiest to use~~, most cost effective~~ and had the most transparent decision making system. The <u>Agency</u>~~UK~~ system, however, was ~~the most~~<u>more</u> robust in that it was the most defensible of the three systems<u>.</u>~~,~~ <u>M</u>~~m~~oreover it had the least potential for accidental delay.

One possible bottleneck with the ~~UK~~ <u>Agency</u> DSS <u>could result from the</u>~~, however, may be regulator based delay with the likelihood of a~~ large number of MNA assessments being submitted to the ~~Environment~~ Agency <u>as the regulator needs to be consulted regularly</u>. <u>This may have resource implications for the Agency.</u> To help offset this potential disadvantage, the ~~UK~~ <u>Agency</u> DSS ~~should~~ <u>could</u> establish clear procedure<u>s</u> and criteria for the submission of a MNA 'case' for a site at specific stage of the application, preferably at the end of each stage. ~~Currently the final decision of MNA implementation is based with the Environment Agency and is reliant upon on the strength of collected evidence.~~

Other possible improvements to the <u>Agency</u> ~~UK~~ DSS could include streamlining with more explanatory text, and not just legal reference (this could be done using the ASTM DSS <u>as an example</u>).
Guidance is required on what the range of models are available for use in both the ~~UK~~ <u>Agency and</u> ~~and~~ ASTM <u>systems</u>, as well as detailed information on the data requirements of any suggested models. <u>Such guidance is due to be published as an NGWCLC report later this year. Overall the Agency DSS compared favourably with the other DSSs and on many criteria was judged to be superior.</u>

6 REFERENCES

1 M.A. Carey, J.R. Finnamore, M.J. Morrey & P.A. Marsland, 2000, R & D Publication 95: Guidance on the Assessment and Monitoring of Natural Attenuation of Contaminants in Groundwater, Environment Agency, ~~WRC, Wiltshire,~~ UK.

2 American Society for Testing and Materials (ASTM), 1998, Standard Guide for Remediation of Groundwater by natural Attenuation at Petroleum Release Sites, ASTM Standard Guide E1943-98, Conshohocken, USA.

3 Network- for Industrial Contaminated Land in Europe (NICOLE) – TNO (Netherlands Organisation for ~~t~~ Applied Scientific Research). ~~, ?????????,~~ Draft Monitored Natural Attenuation Protocol.

4 DETR, 2000. Guidelines for environmental risk assessment and management ISBN 0 11 753551 6.
~~,????????????????????????????~~

5 Monitored Natural Attenuation: Review of Existing Guidelines and Protocols. TNO-NICOLE Report TNO-MEP-R99/313.~~C.J. Newell, K.R. McLeod, J.R. Gonzales, 1996, Bioscreen: Natural Attenuation Descision Support System Users Manual Version 1.3, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, USA.~~

6 C.J. Newell, K.R. McLeod, J.R. Gonzales, 1996, Bioscreen: Natural Attenuation Decision Support System Users Manual Version 1.3, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, USA.

7 Environment Agency, 1999, Methodology for the derivations of Remedial Targets for Soil and Groundwater to Protect Water Resources. R & D Publication 20. Prepared by Aspinwall & Company.

8 J. Heider and G. Fuchs 1997. Anaerobic metabolism of aromatic compounds. European Journal of Biochemistry, 243(3):577-96.

Appendix 1
Bench marking study information

CONTENTS

CONTENTS

Appendix 2
Monitoring Data Analysis

CONTENTS

Appendix 23
Bioscreen 4 Results

CONTENTS

APPENDIX 23.1 BioScreen Model Use

Using the data provided for the sample dates of November 1994, April 1997 and October 1998, the Bioscreen model was applied to predict the concentrations at distances down the plume. This site specific data was not sufficient to enable all the requirements of the Bioscreen model to be fulfilled resulting in the use of default values or a range of values for certain parameters. Certain assumption had to be made to attain information for the Bioscreen model to be as representative as possible. A precautionary approach was adopted in that wherever possible the worst case scenario was used (*e.g.* in measuring isolinear graphs, selection of variables etc.). Appendix 3.1 Table 2.1 details the types of information required by the Bioscreen model and the source of information inputted. In comparison to the observed trends in the initial site data interpretation, the Bioscreen model overrated the capacity of the site soil microbial population and the physical processes to biodegrade or dissolve, dilute and disperse the contaminant plume.

This calls into question either the quality of the data used to run the model, the default values inputted or the model itself. From further investigation of the influence of varying biodegradation rates upon the models outcome it could be seen that the Bioscreen model may be overestimating the influence of the physical parameters upon the plume contaminant concentrations. The presence of the no degradation line below the site data for comparison is evidence of this. Biodegradation rates may be excessive although this cannot be substantiated. The ability of the model to accurately predict either a potential time frame or a maximum plume migration distance is unreliable. Sentinel boreholes placed according to the data generated would be unrealistic in assessing risks from groundwater contamination**.**

The following table and figures are the input and output of the Bioscreen 4. The output tables for each sampling period are based on the data given in Appendix 3.1 Table 2.1 and where a variable is uncertain the worst case is taken so as to take the most precautionary approach.

Appendix Table 2.~~ix 3.~~1: Bioscreen data input details.

Model Data Requirement	Value (units)	Data Source and Justification
Hydrogeology Hydraulic Conductivity Hydraulic Gradient Porosity	 0.012 (cm/s) 1:500 (0.002) 30 % (0.3)	All data required for this section could be obtained or simply calculated directly from the information provided.
Dispersion Plume length	 Varies	The programme could estimate the dispersivity of the contaminant plume from the length of the plume. The plume length value was changed for each sample date.
Adsorption Soil Bulk Density Partition Coefficient Fraction of Organic Carbon	 1.7kg/l 38 (L/Kg) 0.001 (Default)	There was no direct data in the information provided so alternative sources had to be found. The soil bulk density data for silty sand was taken from the ASTM Risk Based Corrective Action model database, partition coefficient data and the fraction of organic carbon data were taken from the Bioscreen users manual (default values).
Biodegradation 1st Order decay coefficient Solute Half life	 162 (Calculated) 4.6 (Default) Not required	The initial site data interpretation resulted in graphs of contaminant concentration over time. In theory it may be possible to determine a rate of biodegradation from a regression analysis of this data. However, the possibility of heterogeneous biodegradation rates over the plume and the uncertainty as to what variables contribute to the graph profiles mean that any determined rate would be unreliable. As such, any data taken from a concentration plot for just one borehole over time may not be sufficient for a decision regarding natural attenuation to be reached. Despite this, the biodegradation rate determined from the graphs, the default value provided in the literature and the default value divided by ten were used to determine the influence of the biodegradation rate variable upon contaminant concentrations with distance.
General Site Data	Varies	Measurement of the perimeters of the plume from the isolinear graphs in the initial site investigation (worst case).
Source Data Source thickness in saturated zone. Source zones. Soluble Mass.	 53.5 ft (16.3m) Varies 71 Kg ~~53.5 ft (16.3m)~~ ~~Varies~~ ~~71 Kg~~	The source thickness in the saturated zone could not be determined from the information provided, therefore the depth of the deepest borehole had to be used. The source zones could be determined from the isolinear graphs in the initial site interpretation. The soluble mass of the contaminant spill could be approximated from the concentration in the soil back calculated from the initial site investigation isolinear graphs.
Field Data For Comparison	Varies	Data obtained from the set of sampling records provided exhibited the worst case scenario.