EVALUATION OF SOIL & GROUNDWATER REMEDIATION STRATEGIES FOR DECOMMISSIONING NUCLEAR FACILITIES ON THE BASIS OF SUSTAINABILITY ASSESSMENT INCORPORATING NET PRESENT VALUE

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ABSTRACT

The decommissioning of nuclear facilities and remediation of radiological and non radiological contaminated land is currently being undertaken at some Magnox nuclear licensed sites in the UK. Sustainability needs to be considered so that well balanced remediation strategies are chosen that accommodate the long time frames decommissioning can take. Sustainable remediation options assessment involves selecting feasible soil and groundwater strategies to meet risk reduction goals whilst maximising the environmental, social and economic benefits.

This study describes two Magnox nuclear decommissioning sites, Bradwell site in England and Chapelcross site in Scotland. A conceptual site model (CSM) was developed for land and groundwater contamination at each site. Identification and screening of suitable remediation strategies was followed by a sustainability assessment. The Sustainable Remediation Forum UK (SuRF UK) framework was used, incorporating a Net Present Value (NPV) for the economic element and a Multi Criteria Decision Analysis (MCDA) was applied using a software tool called Hiview.

The exercise showed that feasible soil and groundwater remediation strategies were identified using the SuRF UK Framework and Hiview MCDA software. The process showed for complex sites it can be timely developing a detailed CSM but it makes screening remediation strategies a much easier process although detailed understanding of techniques is required. The study has shown that a cost estimate can take longer than a sustainability assessment, due to there being limited case studies and examples available within literature due to commercial sensitivity.

This is the first time the Sustainable Remediation Forum UK (SuRF UK) Framework has been applied using Hiview MCDA software to two nuclear decommissioning sites. It is also the first example of applying the SuRF UK Framework to remediation options assessment for radioactive contaminated land. The process showed scoring as a single assessor can introduce bias and that stakeholder involvement for weighting the importance of indicators would be recommended in order to get a true representation. Applying sensitivity analysis and testing alterations in weightings is crucial in ensuring

that an assessment is robust. Sites with site specific quantitative data resulted in a more robust assessment and remediation strategies which had the ability to be flexible long term were the more sustainable options.

DISCLAIMER

The opinions expressed in this dissertation are entirely those of the author except where indicated in the text.

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Chapter 1 Introduction

The decommissioning of nuclear facilities including the remediation of radiological and non radiologically contaminated land is currently being undertaken at some of the Magnox nuclear licensed sites in the UK. A report by the Nuclear Energy Agency (NEA) identified that the four main obstacles to land remediation occurring on a decommissioning site are site priorities, regulations, lack of waste disposal routes and stakeholder opinions (NEA, 2014). The decommissioning process involves reducing the higher hazards and delivering the site into a phase called Care & Maintenance.

The remediation of contaminated land and groundwater has been undertaken at some Magnox sites already following remediation options appraisal. This thesis will focus on land contamination at two Magnox decommissioning sites and will undertake a sustainable remediation options assessment incorporating a Net Present Value (NPV). The last ten years have seen an increase in sustainable practices being incorporated into development and contaminated land. Historically the risk management process for contaminated land and groundwater has been perceived as sustainable in its own right due to controlling the risks from contamination. However, this may not always be the case, some remediation techniques have their own set of impacts. For example, negative impacts on natural resources and waste creation and certain plant can consume large amounts of energy.

Sustainable remediation options assessment focuses on identifying the optimum remediation strategy that maximises benefits while limiting the impacts. In 2007, the UK's Sustainable Remediation Forum (SuRF UK) was set up in order to develop a framework for sustainable soil and groundwater remediation. Since the issue of the SuRF UK framework, there have been only three case studies showing its application and none of these relate to nuclear decommissioning sites and specifically radiological contaminated land. This thesis will show how the framework can be applied at two decommissioning nuclear sites which have radiological and non radiological contaminated land and groundwater which require remediation.

Remediating non radiological contaminants is well developed outside of the nuclear decommissioning industry but remediating radiological contaminated land and the difficulties that can arise with it such as radiological control and cost of waste disposal can make this more challenging (Hill, 2010). Although remediation options assessment has been undertaken for decommissioning nuclear sites, sustainable remediation options assessment utilising the SuRF UK framework has not. This thesis will be the first application of the SuRF UK framework at a Magnox nuclear decommissioning site and will be the first time its been used where radiological land contamination exists. The two Magnox decommissioning sites which will be the focus of this thesis are:

a. Bradwell Site: Radioactive Caesium- 137 (Cs-137) and Strontium -90 (Sr-90) soil and sub surface water contamination at the site has lead to several remediation attempts since the late 1970's. Site investigation and then remediation by selective excavation and capping of the soil was undertaken in 2013-2014 (Magnox, 2013 & 2015).

b. Chapelcross site: Chlorinated Solvent soil and groundwater contamination exists at the site, further site investigation and monitoring has identified that remediation of the plume is required (Magnox, 2015 & 2014/15).

As part of managing land contamination issues at Magnox sites, a land quality process has been established, which involves identifying Areas of Potential Concern (APC's). If land remediation is required, this will need to be timed around other decommissioning activities and interfaces that could be occurring within the same vicinity at the site. Decontamination and demolishing of buildings, construction of processing plants for waste, replacement of underground services such as drains and infilling of voids are all interfaces which will occur during decommissioning. These are all important considerations which will affect a sustainable remediation options assessment (Magnox, 2013).

In order that effective and efficient clean up of the UK's nuclear legacy occurs the Government set up the Nuclear Decommissioning Authority (NDA) in 2005 to oversee the decommissioning process (Rahman, 2008). The NDA are responsible for ensuring that the right decommissioning options are implemented. All waste products radioactive and non radioactive must be safely managed by the right skills, resources and correct technology as well as ensuring local communities are not socially and economically disadvantaged. Demonstrating efficient, effective and successful decommissioning could put the UK Government in a strong position to exploit these unique resources, skills and technological advancements in other markets. The skills and techniques developed based on strong safety and environmental credentials means building of new nuclear plants, decontamination of land and development of safety and environmental protection systems world wide could benefit from nuclear decommissioning (NDA, 2015).

There are three stages within the International Atomic Energy Agency (IAEA) decommissioning process of a site which can be adopted, these are 1. Immediate dismantling; 2. Safestore Enclosure and 3. Entombment. The strategy being taken with all Magnox sites is Safestore Enclosure where high level radioactive waste is removed and non radioactive buildings and plant are dismantled. A robust structure is designed to protect remaining radioactivity in reactor buildings and plant for many decades, known as "safestore structure". The sites are then monitored for around 60-70 years known as a Care and Maintenance Period (C&M) while radioactivity decays to safe levels to make remaining decontamination and dismantling simpler and safer. This final stage is known as Final Site Clearance (FSC). In order to prepare for the C&M phase the decontaminating and dismantling of all buildings outside the biological shield of the reactor is undertaken and is referred to as Care and Maintenance Preparations (C&MP) (Bayliss & Langley, 2003 & Rahman, 2008).

C&MP can take twenty to thirty years, in the case of Bradwell site an accelerated C&MP date was given for the site to be completed within a five-year period (2010-2015), which included remediation of the land contamination. The options assessment and identification of a suitable remediation strategy was undertaken in 2012, with remediation occurring in 2013-14. As the implemented strategy at the site occurred over a two-year timeframe from 2012- 2014, this study will ensure the same time context is taken into account when assessing other remediation options against the strategy implemented.

Optimised C&MP is being undertaken at Chapelcross site (commenced in 2013) with the aim to get to an Interim C&M state by 2017. Interim C&M requires significant hazards to be reduced to a minimum, services isolated and buildings made secure and where possible no longer manned. Asset care is undertaken for 6 years during which the site will continue to be managed, monitored and maintained. C&MP will then recommence for a period of approximately 5 years, the site will be reduced to four safe stored reactor buildings and with all other buildings being decontaminated and demolished (Magnox, 2014).

Due to Chapelcross site being located in Scotland and Bradwell site in England, different regulatory regimes apply. The different regulatory regimes and how these affect each site will need to be taken into account. A conceptual site model will be developed for each site identifying the relevant contaminant linkages and screening of remediation strategies to identify those suitable to go through to a sustainability assessment. Cost estimates will be created for each remediation strategy and a Net Present Value (NPV) calculated. The NPV will be used within the sustainability assessment which will draw on the SuRF UK framework and Brief Case (Contaminated Land: Applications in Real Environments (CL:AIRE, 2010 & 2013).

This thesis will evaluate remediation options by taking them through the SuRF UK framework. It will also take account of a NPV under the economic dimension of the assessment, which is crucial for the Magnox Sites due to the long time frames through C&M until FSC and cost burdens on future generations. Sustainable remediation options assessment will become an increasingly important area for nuclear decommissioning, as they have to accommodate a wide range of stakeholders interests as well as being cost effective. Due to the half life of some radioactive contaminants means new remediation techniques could occur in the future, so maintaining some flexibility within a strategy may be more beneficial long term. The SuRF UK framework ensures that the remediation options assessment process considers the variety of issues across the social, environmental and economic arenas such as cost, flexibility of a remediation and long term intergenerational effects, which ensures that a well balanced remediation option is taken forward.

1.2 Aim and Objectives

The aim of this dissertation is to evaluate (on the basis of a Sustainability Assessment incorporating Net Present Value (NPV)) alternative feasible soil and groundwater remediation strategies for specific land contamination issues for sites moving into Care and Maintenance (C&M). The objectives to be undertaken in order to achieve the aim are listed below:

Objective a. Identify and describe a specific area of land contamination at each of two Magnox sites through development of a CSM.

Objective b. Identify and describe suitable remediation strategies which could be used for each of the two sites and how these will break the linkages in the CSM for each site.

Objective c. Calculate the NPV and undertake a Sustainability Assessment of the alternative remediation strategies for each of the land contamination issues being looked at.

Objective d. Discussion of the NPV and Sustainability Assessment for each land contamination issue with reference to the literature review undertaken in Section 2.8.

Objective e. Evaluate and conclude the most suitable remediation strategy(s) for each land contamination issue, taking into account the sustainability assessment and NPV and what improvements, further work and research can be undertaken.

Chapter 2 Literature Review

2.1 Guidance for managing contaminated land at nuclear licensed sites

The management of contaminated land at nuclear licensed sites (NLS) can vary depending if radiological, non radiological or both types of contaminated land exist. Where radiological land contamination exists, Safegrounds guidance needs to be considered as well as the relevant regulatory regimes. Safegrounds stands for Safety and Environmental Guidance for the Remediation of contaminated land on UK Nuclear and Defence Sites and is part of the CIRIA learning network. Safegrounds does not apply to non radioactive contamination on a site, but the same overall land quality management system described within the guidance can be followed for a nuclear licensed site whether radiological or non radiological contamination exists (CIRIA, 2009). The different procedures and guidance for managing contaminated land at a nuclear licensed site will be looked at in this chapter below:

2.2 Safegrounds guidance for managing contaminated land at nuclear licensed sites

Safegrounds provides guidance and case studies on good practice management of radioactive contaminated land on nuclear sites in the UK (CIRIA, 2015). Safegrounds has five key principles for managing contaminated land, these are:

1. **Protection of people and the environment;** To achieve a high level of protection of people and the environment for the current day and going into the future.

2. **Stakeholder involvement;** The site owner should involve stakeholders to help inform decision making for managing contaminated land

3. **Identifying the preferred land management option;** A consultative process should be followed for carrying out assessment of possible options for managing contaminated land. Factors that should be considered are stakeholders, health, safety and environmental impacts and technical, social and financial factors.

4. **Immediate action;** Areas where there is known or potential contamination will need to be prioritised and investigated as soon as possible to

determine what action needs to be undertaken. Immediate control measures may have to be put in place until a suitable remediation strategy has been developed and agreed with Regulators.

5. **Record-keeping;** Records should be kept on any land contamination, the management options implemented and the decision process that led to this and where remediation has been implemented the validation records relating to this (CIRIA, 2009).

   Safegrounds good practice guidance for the management of radioactive contaminated land on nuclear licensed and defence sites (CIRIA, 2009) is based on the same principles as the Environment Agency's (EA) model procedures for the management of contaminated land- CLR 11 (figure 1) (EA, 2004). CLR 11 should be consulted alongside the Safegrounds guidance when undertaking the land quality management process so as structured decision making can be made.

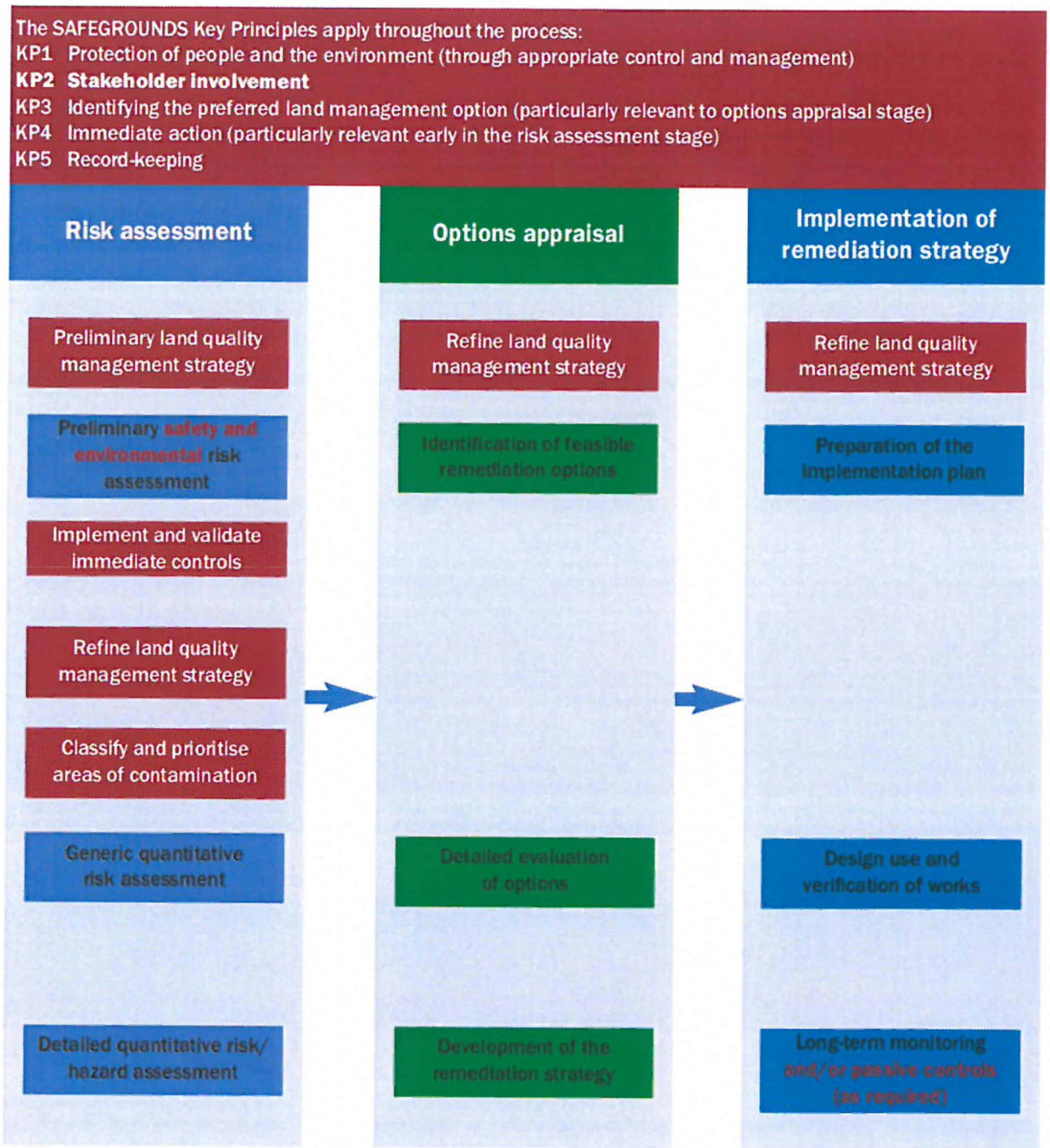


Figure 1. Summary of CLR 11 decision flow diagram with modifications highlighted in red to show Safegrounds alterations (CIRIA, 2009).

An overall land quality management system is required whether managing radioactive, non radioactive or both forms of land contamination. A preliminary land quality management strategy will be established to provide a basis of the objectives to be achieved now and in the future for all aspects of contaminated land on a site. It is a live document requiring continual updating as more site investigation and data becomes available to refine it (CIRIA, 2009).

The regulation of radiological risks requires that they should be reduced to be "As Low as Reasonably Achievable Practicable" (ALARP). The 2006 Office of Nuclear Regulation (ONR) Safety Assessment Principles (SAPs) for Nuclear facilities defines the criteria for delicensing being that risk of death is no more than one in a million per year and therefore land is considered under the SAPs to be radioactively contaminated if risk is more than this. This is a requirement under Safegrounds principle 1 to ensure high levels of protection of people but ensuring that the costs are not massively disproportionate and society is not put at detriment (ONR, 2006). In the USA certain sites would have been grossly disproportionate to delicense under the 1×10^{-6} per year risk target. These sites have followed the International Atomic Energy Agency (IAEA) guidance where land can effectively still be delicensed but has "restricted release" which means restrictions will be applied to ensure the dose will not exceed an upper dose limit of 300 sieverts per year for its future use (IAEA, 2009 & CIRIA, 2012).

2.3 Office of Nuclear Regulation (ONR) and Nuclear Installation Act 1965 (NIA65)

For radiological land contamination present at Bradwell site the ONR regulates under the The Nuclear Installations Act 1965 (NIA65) and the EA cooperate by exercising their regulatory functions (ONR, 2014). The ONR expects operators to be responsible for safety and will expect thirty-six licence conditions (LC) to be adhered to. Table 1 refers to the LC's and LC 34 has particular importance to the management of radioactive land quality and the decommissioning process. LC34 ensures that so far as is reasonably practicable, any spread of radioactive contamination is minimised and monitored on site and doses to workers and members of the public are within acceptable limits and ALARP (ONR, 2014).

The ONR regulate the keeping and use of radioactive material and accumulations in situ. The LCs allow the ONR to control and regulate radioactive contaminated land amongst other areas on a nuclear site. The EA are involved in remediation of radioactive land where a remediation scheme may require an Environmental permit for permanent disposals of radioactive contaminated groundwater or any excavated soil or rubble (ONR, 2014). The difference comes down to if the waste is being treated as an "accumulation" or "permanent disposal". If a NLS decides to accumulate either in an engineered or natural feature this must be done with intention to take further action at a later date, such as at FSC to remove the waste which will have then decayed further by this point. If "disposal" is chosen then this is with the intention to take no further action apart from monitoring (EA & Natural Resources Wales (NRW), 2013).

Table 1 Licence Conditions of particular interest during Decommissioning and Land Quality Management (ONR, 2014)

Licence Condition Number	Licence Conditions
4	Restrictions on nuclear matter on the site
5	Consignment of nuclear matter
6	Documents, records, authorities and certificates
7	Incidents on the site
11	Emergency arrangements
12	Duly authorised and other suitably qualified and experienced persons
13	Nuclear Safety Committee
14	Safety documentation
17	Management systems
18	Radiological protection
25	Operational records
32	Accumulation of radioactive waste - arrangements must be in place to ensure the production and accumulation of radioactive waste on site is minimised and stored under suitable conditions with records.
33	Disposal of radioactive waste All radioactive waste must be disposed of in a specified manner.
34	Leakage and escape of radioactive material and radioactive waste
35	Decommissioning

The safety of a NLS (LC 13- Table 1) and its entire lifecycle must be substantiated and documented within a "Nuclear Safety Case", so as arrangements are in place should events or emergencies arise (ONR, 2013). The safety case needs to be proportionate to the extent, nature and potential harm that may be posed by contamination and the extent it has of migrating. Many site specific factors will have to be considered when assessing the extent contamination has of migrating, such as geology, hydrogeology, pathways and proximity of identified receptors.

Demonstration of good engineering practices should be applied to control and remediate the land and any restrictions associated (ONR, 2014). The Health and Safety at Work Act, 1974 a major piece of legislation governing the health, safety and welfare of workers and the public at NLS ensures risks are reduced to ALARP to all activities within the scope of the Health and Safety at Work Act (ONR, 2014). The safety case has to show that risks to public as a whole are ALARP. The ONR will expect radioactive contaminated land to be managed so as the risk to the public is preferably below 1 in a million per annum (CIRIA, 2009). Best Available Techniques (BAT) should be used with respect to decommissioning and to minimise radioactive wastes being created which could have an impact on radiation doses to the public. BAT means limiting discharges, emissions or waste through implementing practical, suitable measures (Defra, 2011).

2.4 Land Quality Expectations from Office of Nuclear Regulation (ONR), Environment Agency (EA), Natural Resources Wales (NRW) & Scottish Environment Protection Agency (SEPA).

The ONR, EA, NRW and SEPA realise the importance of setting clear expectations for land quality and in June 2014 issued regulatory expectations. They stated that land quality decisions should be informed by an assessment of the options, taking account of sustainable development considerations. Considerations for remediation options assessment included:

- Physio-chemical nature and current state of contaminants;

- Actual or potential risks to people and the environment under current conditions;

- Pros and Cons of each implemented option;

- Impact that any delay in implementing the option might have upon the spread of contamination;

- Actual or potential risks, costs of any option;

- Nature and volume of any wastes that would be generated, and disposal routes;

- Lifecycle impacts on people and the environment;

- Practical issues of implementation associated with each option;

- Intended site end states (interim/ or final);

- Extent to which each option addresses any concerns raised by stakeholders.

The paper recommends consideration of in-situ alternatives other than excavation. Re-use of materials, sorting and segregation, treatment and applying protocols for sentencing material and waste from regulatory control are preferred (ONR, 2014).

"The Decommissioning of Nuclear Facilities" issued by the EA and NRW in 2013 outlines the expectations for managing and disposing of radioactive waste during decommissioning (EA & NRW, 2013). Operators need to consider all practicable options for the management and disposal of radioactive waste generated from decommissioning activities and if Low Level Waste (LLW) is to be generated then options for on site[*1] in situ[*2] disposal should be considered.

2.5 Guidance for non radiological contaminated land

For the two Magnox sites being looked at, the legislative context will differ due to their location and nature of radiological or non radiological contamination present at each site. Chapelcross site, Scotland has non radiological contamination, therefore The Contaminated Land (Scotland) Regulations 2000 will apply. Since devolution to the Scottish Parliament for responsibility for environmental matters in 1999, regulations were made in Scotland to

**1 On-site- Dig it up and put it somewhere else on site (e.g. in a void)*
**2 Do not dig it up and declare it disposed of where it remains in-situ.*

provide legislation for Part 2A (SEPA, 2009). Part 2A is based on applying the principles of risk assessment and determining if contamination exists by assessing if pathways and receptors create contaminant linkages which could lead to significant harm or pollution of controlled waters (CIRIA, 2010).

The Part 2A regime deals with unacceptable risks that land contamination may pose to human health and the environment and only where unacceptable risks are clearly identified, should land meet the definition as contaminated (Defra, 2012). For many of the Magnox sites permits will exist for discharges of liquid wastes. These circumstances where substances have been allowed to enter water in compliance with an Environmental Permit for the site will not be considered contaminated land or water (Defra, 2012).

Scottish Governments Statutory Guidance was amended in 2006 due to the introduction of the Water Environment and Water Services (Scotland) Act 2003. The Position Statement for Assigning Groundwater Assessment Criteria for Pollutants (WAT-PS-1-01) provides guidance on compliance points for hydrogeological risk assessment. It states that a 50m assessment point should be set from the down gradient boundary of the source. However, it does recognise there are circumstances where an assessment point of 250m is reasonable and still protective of groundwater as well as allowing sustainable development. These circumstances include:

-Present or planned land use limits the exploitation of the groundwater resource;

- The topography is steep or inaccessible, which limits development for activities that require groundwater supply;

- Naturally occurring concentrations of contaminants are in excess of quality standards, therefore any treatment will render development of groundwater economically less viable (SEPA, 2014).

2.6 Magnox Company Procedures for Land Quality Management

Management of Land Quality at Magnox Sites is controlled by Company Standard "Arrangements for the Management of Land Quality (S-154)" (Magnox, 2013). The Company Standard ensures sites have clear objectives with deadlines and in line with Safegrounds guidance a land quality management system is required. This will require that a land quality strategy and characterisation plan are generated for radiological, non radiological and mixed land contamination that apply three management principles throughout:

Principle 1: A Satisfactory Land Condition shall be met and demonstrated at all times, there are no compelling grounds to take regulatory action.

Principle 2: A fit for purpose C&M Entry State shall be determined and implemented, there should not be need for intervention during C&M.

Principle 3: The timing of achievement of the Final End State (which could be around 80 years into the future, referred to as FSC) shall be justified and relates to Government policy on decommissioning. The 'generic arguments' for leaving radioactive contamination in place or deferring until FSC are:

-The preference of the NDA to retain flexible final site end state definitions until planning commences for the final stages of restoration;

-The potential benefits from decay of radionuclides

-The increased ease of remediation on an otherwise cleared site of above ground structures;

-The likelihood of efficiencies in disposal of radioactive waste from remediation of radioactively contaminated land in the context of dealing with large volumes of other radioactive waste arising at FSC;

-The non-foreclosure of in situ or on-site disposal opportunities;

-The low risk associated with the contamination (i.e. finite resources are better spent elsewhere)' (Magnox, 2013).

Ensuring that a satisfactory land condition is present will require demonstration of sufficient characterization. Where radioactive contaminated land is present, a safety case will be required. The standard identifies areas of contaminated land as APCs which are listed on an index and site map. The process ensures APCs are 'sentenced' and prior to C&M all APC's must fall into one of the below:

- 'Former-APC' has demonstrated through characterisation not to be contaminated; or has been fully remediated;
- 'Recorded Contaminated Land Area' (RCLA). Areas of known or potential contamination which cannot be sentenced as 'Former-APCs' and do not meet the criteria for an MCLA.
- 'Maintained Contaminated Land Area' (MCLA). Areas of contamination that through C&M will need maintenance of specific physical features or require a specific monitoring regime;

Throughout the process options assessment may be required if the answer is no to any of the three principles. The C&M entry state for Land Quality requires that there will be an unlikely need for intervention during C&M and remaining contamination will be routinely monitored to provide assurance and to detect any movements and significant deterioration (Magnox, 2013).

2.7 CLR 11 and Nuclear Guidance on Conceptual Site Model's, Risk Assessment & Remediation Options Appraisal.

CLR 11 (EA, 2004) identifies that a Conceptual Site Model (CSM) is a primary planning tool required to support the decision making process for managing contaminated land and groundwater. CLR 11 (EA, 2004) and nuclear specific guidance such as the Nuclear Industry Group for Land Quality Guidance on Qualitative Risk Assessment for Land Contamination outlines (NIGLQ QLRA) the input data required for development of a CSM (NIGLQ, 2012). This includes information on: History of the site; Spillages/accidents; Regulatory actions; Appearance of the site; Topography; Geological setting; Hydrogeology (flow direction); Surface features; Water and soil quality and other influences (e.g. if natural contamination or condition of the surrounding land). NIGLQ QLRA guidance recommends CSM's are best displayed as a series of diagrams, maps, cross sections and other diagrams, but appropriate to the site conditions (NIGLQ, 2012).

Identifying gaps and any uncertainties in data and information through this process is important so that further information can be gained and integrated to refine the CSM (EA, 2004). The NEA and Safegrounds guidance, highlight the importance of the conceptual model evolving and better understanding of risks, so as it can be determined whether remedial action is required (NEA, 2014 & CIRIA, 2009). The contaminant linkages in the CSM will need to be considered to ensure remediation options can demonstrably break the linkages (EA, 2004). A minimum of a QLRA is required (NIGLQ, 2012). If this identifies that further risk assessment is required a Generic Quantitative Risk assessment (GQRA) will be undertaken and this will determine if a Detailed Quantitative Risk assessment (DQRA) is required. Routine monitoring is required to detect any significant or unexpected migration of contamination. For nuclear sites dependent on the results, LC34 assessments may be required if it is determined there is potential for off site migration of radioactive contaminants (Magnox, 2013).

CLR 11 provides tiered decision making via flow diagrams for identifying feasible remediation options through its options appraisal process (EA, 2004). Options Appraisal forms the second stage in CLR 11 model procedures and focuses on three main stages in the process: 1. Identifying feasible remediation options, 2. Detailed evaluation of the options and 3. The remediation strategy (EA, 2004). Safegrounds recommends prior to identifying feasible remediation options, screening should be undertaken if necessary to identify those options which are practicable (CIRIA, 2009). Safegrounds recommends screening factors may include: effectiveness or relevance; legality; time frame; grossly disproportionate in terms of costs/ benefits and technical practicability. Safegrounds highlights the importance of not screening out on basis of cost alone (CIRIA, 2009). Screening ensures that clearly defined criteria are set so as only those strategies possible of being put into practice in the time frame are taken forward. Evaluation of the options against screening factors is important to show the reasons why options pass or fail and should be clearly recorded (CIRIA, 2009).

CLR 11 refers to screening as "identification of feasible remediation options" and objectives set to screen options should be site specific and where possible provide remediation criteria. This criterion should ideally be a measure, but not necessarily quantitative, so as options can be assessed against it. CLR 11 states that objectives may want to include: timeframe the remediation strategy is required within; practicability of implementing/ maintaining; technical effectiveness; durability; sustainability, i.e. how well the strategy performs under energy use, material resources, environmental impacts to off-site locations, such as a landfills; costs & benefits of the strategy; legal, financial and commercial context of the site and the views of stakeholders on how unacceptable risks should be handed.

A list of feasible remediation options along with an explanation should be developed to be assessed in the next stage of options appraisal. Its highlighted at this stage that information on the broad characteristics of remediation options may help in deciding which satisfy the site objectives (EA, 2004).

2.8 Sustainability and Options Assessment Techniques & Tools

Defra has a role in overseeing sustainable development across central government and has incorporated the concept of sustainability into all dimensions of Government. The Sustainable Remediation Forum UK (SuRF UK) has developed a framework and set of environmental, economic and social categories with relevant issues to be considered as indicators under each category for an assessment (CL:AIRE, 2010). Table 2 shows some of the suggestions proposed by SuRF UK from a review of published sustainability indicators in 2009 along with indicators used by other industry tools such as: Golders Sustainability Evaluation Tool (GoldSET); Risk Reduction, Environmental Merit and Costs Tool (REC) and Sustainable Remediation Tool (SRT) (Beames et al, 2014).

Table 2. Indicators measured under the different Sustainability Assessment Techniques/ Frameworks (Beames et al, 2014).

		CO_2 Calculator	SRT	REC	GoldSET	SuRF UK
Environmental						
Clean-up (during operations)						
On-site	Primary energy consumed and CO_2 emissions (e.g. excavation, drilling, groundwater extraction and purification)	X	X	X	X	S
	Energy consumed and CO_2 emissions produced cleaning soil on-site	X	-	-	-	-
	Energy consumed and CO_2 emissions produced laying clean fill soil	X	X	-	-	-
	Other air emissions (SOX, NOX, PM10)	-	X	X	-	S
	Water consumption	-	-	X	X	S
	Waste generated on-site	-	-	X	X	S
	Short-term ecological impact on-site	-	-	X	O	S
Off-site	Energy consumed and CO_2 emissions produced transporting waste soil off-site	X	X	X	-	S
	Energy consumed and CO_2 emissions produced transporting workers, materials and equipment	X	X	-	-	-
	Energy consumed and CO_2 emissions produced treating dumped water off-site	-	-	X	-	-
	Energy consumed and CO_2 emissions produced cleaning soil off-site	X	-	-	-	S
	Soil consumed off-site	-	-	X	-	S
	Waste generated off-site	-	-	-	O	S
	Short-term ecological impact off-site	-	-	-	O	S
Site re-use	Soil quality	-	-	X	O	S
	Groundwater quality	-	X	X	O	S
	Surface water quality	-	-	X	O	S
	Erosion of contaminated soil	-	-	X	O	S
	Sediment quality	-	-	-	O	S
	Free phase product removal	-	-	-	O	-
	Contaminated groundwater migration	-	-	-	O	S
	Long-term ecological impact	-	X	X	O	S
Economic						
Clean-up (during operations)	Total costs	-	X	X	X	S
	Net present value	-	-	X	X	-
	Litigation costs	-	-	X	O	S
	Additional costs due to delays and technology failure	-	-	X	O	S
	Additional costs due to logistical challenges	-	-	X	O	-
	Technological uncertainty on cost	-	X	X	O	-
	Permit and regulation related costs	-	-	-	O	S
	Use of financing opportunities	-	-	-	O	S
	Local business opportunities created	-	-	-	O	-
	Local employment opportunities created	-	-	-	O	S
Site re-use	Increased economic value of area	-	X	-	-	S
	Reuse of property by developer	-	-	-	O	S
	Corporate reputation of developer	-	-	-	O	S
	Local business opportunities created	-	-	-	O	-
	Local employment opportunities created	-	-	-	O	S
Social						
Clean-up (during operations)	Workers' health and safety	-	X	X	O	S
	Community health and safety	-	-	-	O	S
	Duration of operations	-	-	-	X	-
	Nuisances and hindrance to community	-	-	-	O	S
	Legal requirements met	-	-	-	O	S
	Good management practices	-	-	-	O	-
	Ethical practices and local equity	-	-	-	-	S
	Site security	-	-	-	-	S
	Uncertainty and evidence	-	-	-	-	S
	Community involvement	-	-	-	-	S
Site re-use	Soil vapor intrusion impact on human health	-	-	X	O	-
	Protection of potable water supply	-	-	-	O	S
	Preservation of historical or culturally significant buildings or space	-	-	-	O	S
	Public space created	-	-	X	O	-
	Impacts on the landscape (esthetic)	-	-	-	O	-

Key.
(X) Quantitative.
(O) Qualitative.
(S) Proposed by SuRF-UK.
(-) Not Considered.

GoldSET one of the tools shown in table 2 is a semi qualitative tool based on a multi criteria analysis which compares options by scoring performance against indicators. The methodology follows a five step process of 1. Defining the problem statement and objectives; 2. Options Development of feasible solutions; 3. Indicator selection; 4. Scoring and Ranking and 5. Interpretation and decision making. The indicators within GoldSET are mainly qualitative but are well spread over the three pillars. Quantitative indicators include total costs, NPV, Co2 emissions, water consumption, waste generated and duration of operations (Golder Associates, 2011).

REC another tool was developed in 1995 and integrates three separate tools from a risk reduction, environmental merit and a cost calculation to compare remediation strategies. REC is based on quantitative data inputs mainly under the environmental and economic pillars of sustainability. It does show some consideration of social aspects, although this is limited to just three indicators of worker's health and safety, soil vapour intrusion impact on human health and public space as shown in table 2 (Beames et al, 2014).

The risk reduction element of the tool considers exposure to humans, ecosystems and other receptors and how this will improve as a result of the remediation. Time is considered within the risk exposure by comparing a do nothing option with other options so as degrees of risk reduction can be compared. The environmental element compares the environmental costs and benefits of remediation and highlights remediation strategies which reduce impacts on environmental resources. The cost element is estimated for the operation of the remediation on a yearly basis and accounts for initial costs, operational, replacement and overhead costs. The NPV is calculated for each remediation alternative by applying a fixed discount rate. REC costs are based on best estimates but apply a safety margin dependent on the uncertainty within the estimate (Beames et al, 2014).

SRT was developed by the United States Air Force Centre for Engineering and the Environment (AFCEE) in June 2009. The main aim in developing the tool was to plan for future implementation of remediation at sites and evaluate remediation already in place by comparing it against sustainability metrics. SRT can only be applied to sites where excavation, soil vapour extraction, pump and treat, enhanced in situ bioremediation, permeable reactive barrier, in situ chemical oxidation, thermal remediation and long-term monitoring/monitored natural attenuation are viable.

SRT is based on Risk Based Corrective Action (RBCA) tiers, tier 1 a qualitative level where if a quick evaluation is suitable this may be sufficient, whereas tier 2 more detailed site specific factors are required. SRT is a Microsoft excel tool and some of the metrics that are calculated include carbon dioxide emissions, total energy consumed, technology cost and safety/risk of injury to workers as shown in table 2 (CLU-IN, 2012). The SRT tool can also import data from a cost engineering software application called Remedial Action Cost Engineering and Requirements (RACER) (AECOM, 2014).

SuRF UK proposes a tiered approached to sustainable remediation assessment as shown in table 3 overleaf, starting with a tier 1 qualitative appraisal using a scoring system such as a simple 'yes' and 'no' or 'good', 'neutral', 'better' to see which option is the most suitable. Moving to a more complex tier 2 semi quantitative method such as Multi Criteria Analysis (MCA) then tier 3 full quantitative assessment like Cost Benefit Analysis (CBA) (CL:AIRE, 2010). A sustainability appraisal benchmarking exercise undertaken on the three tiers identified that a tier 1 assessment can take around 0.5-1 days, a tier 2 can take 1-3 days and a tier 3 can take a week. A tier 1 can work with generic data, a tier 2 requires more quantified data and a tier 3 would require site specific data. It was highlighted that it can be difficult for a single assessor to undertake a tier 2 in order to represent all stakeholder views fairly (Smith & Kerrison, 2013). Sensitivity analysis is recommended as part of an assessment so as assessors can see how alterations in data, assumptions or stakeholder views may influence an overall assessment. This will determine if the assessment is robust or if small changes could affect the overall result (CL:AIRE, 2010).

Table 3. Application and available approaches for different tiers of Sustainability Assessment (Holland et al, 2011).

Evaluation Type	Type of Analysis	Applicability	Available Approaches
Tier 1	Qualitative evaluation based on the most significant sustainability elements of the project (e.g., energy consumption, extent of stakeholder participation)	Smaller-scale sites that have time, budget, and resource constraints; demonstrate low risk or reduced complexity; *and* would not likely benefit significantly from a higher tiered evaluation	- Checklists - Best management practices - Industry guidelines - Rules of thumb - Matrices - Rating system
Tier 2	Semiquantitative analysis that focuses on a few site-specific information areas to supplement Tier 1 evaluation results	Sites that are moderately complex *or* that necessitate a greater consideration of and involvement by stakeholders	- Spreadsheet-based - Scoring and weighting systems - Site-specific characterization - Monitoring data assessment - Risk projections - Exposure simulations - Emission calculations - Simple cost-benefit analysis
Tier 3	Site-specific, in-depth, quantitative analysis of practices, processes, and technologies	Sites that are significantly complex, may necessitate significant consideration of and involvement by stakeholders, *and* have availability of data	- Life-cycle assessment - Detailed cost-benefit analysis - Spatial and temporal boundary evaluation - Energy analysis models - Social return on investment analysis - Social accounting and auditing - Net benefit models

The variety of techniques that can be applied to undertake a sustainability assessment are shown in table 4. It shows the different techniques and their application under the three pillars of sustainability. The table shows the coverage of each technique under each sustainability pillar and if it covers a very limited (narrow) to wide ranging (wide) analysis. For example, ecological footprint analysis only focuses on appraising a narrow area under the environmental pillar and will not consider areas such as natural resources, waste and emissions to air, whereas all these areas (wider) would be considered under a cost benefit analysis. The tools used to undertake assessments can only be used to guide and aid a decision, the final solution chosen is down to the assessors and stakeholders (Bardos et al, 2011).

Table 4. Techniques and tools to apply to sustainability assessments (Bardos et al, 2011).

Technique	Environment	Economy	Society	Type	CLM Application?
Scoring/ranking systems (including multicriteria analysis)	Narrow to Wide	Narrow to Wide	Narrow to Wide	Both	Yes
Best available technique (BAT)	Narrow to Wide	Narrow	-	Qual	Yes
Carbon footprint ("area")	Narrow	-	-	Quan	Yes
Carbon balance (flows)	Narrow	-	-	Quan	-
Cost-benefit analysis	Narrow to Wide	Narrow to Wide	Narrow to Wide	Quan	Yes
Cost-effectiveness analysis	Narrow to Wide	Narrow to Wide	Narrow to Wide	Both	Yes
Eco-efficiency	Narrow	-	-	Quan	-
Ecological footprint	Narrow	-	-	Quan	-
Ecosystem services (Vejre et al., 2009)	Wide			Both	Yes
Energy/intensity efficiency	Narrow	-	-	Quan	Yes
Environmental risk assessment	Narrow to Wide	-	-	Both	Yes
Human health risk assessment	-	-	Narrow	Both	Yes
Environmental impact assessment/ strategic environmental assessment	Narrow to Wide	-	-	Qual	Yes
Financial risk assessment	-	Narrow	-	Quan	Yes
Industrial ecology	Narrow to Wide	Narrow to Wide	-	Quan	-
Life-cycle assessment (based)	Narrow to Wide	-	-	Quan	Yes
Quality-of-life assessment	Wide	Wide	Wide	Qual	-

Notes:
Qual = Qualitative.
Quan = Quantitative.
Both = Qualitative and/or quantitative.
CLM = Contaminated Land Management.
- = Technique has no known coverage.

2.8.1 Sustainable Remediation Forum UK (SuRF UK) Categories and Indicators.

The SuRF sustainable remediation White Paper on Integrating Sustainable Principles, Practices, and Metrics into Remediation Projects outlined the significant barriers to implementing sustainable remediation (Ellis & Hadley, 2009). The barriers identified were a lack of a well-defined and agreed frameworks and metrics within regulatory structures and a lack of incentives to encourage innovation and adaptation of sustainable remediation practices (Ellis & Hadley, 2009).

SuRF UK defines sustainable remediation as "the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impact, and that the optimum remediation solution is selected through the use of a balanced decision-making process". SuRF UK has developed "A framework for assessing the sustainability of soil and groundwater remediation" and "The SuRF UK Indicator set for sustainable remediation assessment" (CL:AIRE, 2010 & 2011). The framework although not mandatory provides best practice guidance on choosing sustainable remediation options and applying the SuRF UK indicators through the options process can make sure a well balanced, underpinned decision process is employed (CL:AIRE, 2011).

The overarching SuRF UK set of environmental, economic and social categories is shown in table 5 overleaf. The SuRF UK framework helps provide a clear approach to the three pillars to achieve sustainability. However, it is up to the individual sustainability appraisal i.e. individual assessor or group of assessors to determine the weight given to each sustainability pillar and if this should be equal or different justifying the reasons. SuRF UK recommends that 6 key principles are followed which include:

1: Protection of human health and the wider environment

2: Safe working practices

3: Consistent, clear and reproducible evidence based decision making

4: Record keeping and transparent reporting.

5: Good governance and stakeholder involvement

6: Sound science

SuRF UK strongly advises on early stakeholder engagement in the assessment procedure, as this can help remove the subjectivity and increase confidence within the assessment. The framework recognises that there may be cases where a single assessor may have to undertake a sustainability assessment, like small or internal projects where stakeholder interests may be limited (CL:AIRE, 2010). A CL:AIRE case study on a sustainable remediation options assessment of a shell terminal in Madeira acknowledged that it had limited stakeholder involvement with only representatives from key stakeholders. The likely views were considered within the assessment such as there may be a bias of regulating authorities towards environmental factors and neighbours and communities towards social factors. But overall it was considered that a reasonably balanced assessment was undertaken (CL:AIRE, 2013).

Table 5. SuRF UK overarching categories (CL:AIRE, 2011).

Social	Economic	Environmental
1. Human Health & Safety	1. Direct Economic Costs and Benefits	1. Air
2. Ethics and Equality	2. Indirect Economic Costs and Benefits	2. Soil and Ground Conditions
3. Neighbourhood & Locality	3. Employment and Employment Capital	3. Groundwater and Surface Water
4. Communities and Community Involvement	4. Induced Economic Costs and Benefits	4. Ecology
5.Uncertainty and Evidence	5. Project Lifespan and Flexibility	5. Natural Resources and Waste

The benefits of the SuRF UK framework and Indicators is a structured process that can be followed to guide a sustainability assessment. The categories and indicators provide areas for stakeholders to think and debate so that correct indicators can be chosen and justified. The SuRF UK Steering Group publishes examples of case studies to share experiences, although only three currently exist on the CL:AIRE website and no new case studies have been uploaded since 2013 (CL:AIRE, 2013). Useful aids and publications on the CL:AIRE website such as the URS Tier 1 Sustainable Remediation Assessment Spreadsheet and briefcase aid organisations in undertaking a sustainability assessment (CL:AIRE, 2013 & 2014).

The framework can work for any size of site, project or timescale. The fundamental concepts of structure and setting of consistent boundaries make it robust and easy to follow and as sustainability is a subjective process this needs to be considered within these decisions. Setting of boundary conditions ensures the assessment is focused from the outset, the system boundary outlines project goals and objectives for which options are compared and the life cycle sets the inputs and outputs to be included. Two other key boundaries which SuRF UK requires to be set are a geographical area and time boundary (Bardos et al, 2011).

2.8.2 Office Nuclear Regulation Safety Assessment Principles and Safegrounds guidance for Options Assessment

ONR SAPs for Nuclear Facilities, suggest a number of areas that should be included in options assessment process, some of these include (ONR, 2006):

- worker and public safety, and those potentially exposed in the future;
- prevention or reduction of the environmental impact, now or in the future;
- waste minimisation, availability of waste treatment plant and disposal routes;
- future requirements for investigation, monitoring, surveillance and characterisation;
- technical practicability and availability of technology (Technological Readiness Levels (TRLs). The NDA provide guidance on a technologies level of maturity to determine if it is at a level to be used (NDA, 2014)
- interaction and dependencies with other facilities (i.e. Low Level Waste Repository (LLWR) in Cumbria, UK)
- Demonstrating effectiveness of remediation measures;
- possible burdens on future generations;
- costs

Safegrounds states that key assessment criteria of health and safety, environmental, technical, social, economic and costs should always be included in options assessment as well as other factors under these criteria such as waste management, sustainability and technical criteria. Safegrounds explains that the outcome of an options assessment is not a decision but it provides information so as the operator through consultation and involvement with stakeholders can develop a remediation strategy to best protect people and the environment (CIRIA, 2009).

2.8.3 Nuclear Decommissioning Authority (NDA) Technological Readiness for Options Assessment

The NDA has issued a guide on technological readiness levels (TRLs) for its estate and supply chain. Originally developed by NASA in the early 70's TRL was a means of assessing whether emerging technology was suitable for space exploration. It is now in use across many US Government agency's and is in common use in the UK (NDA, 2014). TRL refers to a technological process or technique, its readiness for operations at the present time and its level of maturity. The levels are on a nine-point scale from level 1 being basic technological research to Level 9 where a system operates over a full range of conditions as shown in table 6 below. The benefit of TRLs is clearly communicating if a technology is ready for use and providing a common understanding of it's maturity. Stakeholders can also evaluate technologies through a framework, understanding the process for technological development (NDA, 2014).

Table 6. NDA's Technology Readiness Levels (TRLs) (NDA, 2014).

Relative Level of Technology Development	Technology Readiness Level (TRL)	TRL Definition
System Operations	TRL 9	Actual system operated over the full range of expected conditions.
System Commissioning	TRL 8	Actual system completed and qualified through test and demonstration.
System Commissioning	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment.

Technology Demonstration/ Technology Development	TRL 6	Engineering/pilot scale, similar (prototypical) system validation in relevant environment.
Technology Development	TRL 5	Laboratory scale, similar system validation in relevant environment.
Technology Development	TRL 4	Component and/or system validation in laboratory environment.
Research to prove feasibility	TRL 3	Analytical and experimental critical function and/or characteristic proof of concept.
Research to prove feasibility / Basic Technology Research	TRL 2	Technology concept and/or application formulated.
Basic Technology Research	TRL 1	Basic principles observed and reported.

2.8.4 Economic Evaluation and Net Present Value (NPV)

NPV is an economic evaluation tool that applies a discount rate to convert all costs to 'present values' and can support selecting a remediation strategy by placing a monetary value on each possible remediation so like for like with costs can be compared between options (HM Treasury, 2011). HM Treasury sets discount rates which are applicable to the nuclear provision, this is the estimate of how much it will cost over 100+ years to decommission and clean up all the UK's nuclear sites (NDA, 2015). The discounted rates used for the nuclear provision take into account the high uncertainties surrounding timescales, technology and the societal needs.

Historically provisions were calculated by a uniform 2.2% per annum discount rate until 2011/12, this meant discounted values were always lower than the undiscounted totals, this being noticeable for long term provisions. Changes in the discounting rates have seen rates beyond 10 years remain at the 2.2% but for the first ten years a negative discount rate is now used showing the discounted value being higher than the un discounted value. This has been implemented because the rates need to represent the current cost of government borrowing and interest on UK gilts is currently less than the typical rate of inflation in the past (NDA, 2014). There are also many complexities and uncertainties when it comes to some of the nuclear sites in the UK, especially critical projects at Sellafield which are still at an early stage. The new discount rates are more applicable to these circumstances. The discounted rates from the NDA Annual Report and Accounts 2013/14 taking the above into account were set at:

- Short term rate: between 0 and up to including 5 years, -1.90% per annum;
- Medium term rate: after 5 and up to and including 10 years, -0.65% per annum;
- Long term rate: exceeding 10 years, +2.20% per annum.

The implementation of this new methodology in 2012/2013 increased the nuclear provision by £3.8 billion (NDA, 2014). Therefore, meeting the C&M dates are important to stay in line with the nuclear provision. Entering C&M will reduce the costs required from the nuclear provision as reduced management and monitoring will be needed. Therefore, understanding the land quality issues early on is important to ensure they are managed with as little intervention as possible throughout C&M (Rahman, 2008).

The NPV can help complement the sustainability decision making process by putting a monetary value against remediation strategies. This alone is not enough to make a remediation sustainable but can help in decisions particularly where remediation strategies may have scored equal or close. Sensitivity analysis can be applied to a discount rate the same way it is to a sustainability assessment (HM Treasury, 2011).

2.9 Radioactive and Non Radioactive Contaminated Land Remediation

This section will discuss the remediation techniques available for radioactive and non radioactive land contamination.

2.9.1 Remediation of radioactive contaminated land and groundwater

Experience of remediating radiological contaminated land at NLS is most developed in the United States and Germany. A report by the NEA in 2014 showed the most common remediation for radioactive and non radioactive contaminated land is excavation and disposal. Remediation of radiological contaminated groundwater showed pump and treat and in ground barriers as the most common approaches, with monitoring and pump and treat most commonly used for non radiological groundwater (NEA, 2014).

The costs and long term implications particularly for disposing of radioactive soil and increases in landfill tax for disposing of non radiological soil have required development of techniques to reduce waste volumes. Reducing radioactive soils by bulk monitoring via conveyor belts or in situ techniques of fixing by solidification, stabilisation or vitrification can reduce waste burdens.

A conveyor belt screening plant can include several process, devices and radiation detectors along various conveyors to ensure that soils are analysed and non radioactive soils are maximised for re-use. Conveyor belt screening systems mean that larger rocks can be screened out which are typically radiologically cleaner then the finer soils, which reduces the volume of radioactive waste soils. These rocks can then be further crushed to reduce their size to allow radionuclides on the surfaces of them to be detected easier. (US EPA, 1993).

A conveyor system can be larger and costly, so where space may be limited large areas of radiologically contaminated soil can also be 'bulk monitored'. This ensures the through put of material to meet remediation timescales and costs. A Gamma Excavation Monitor (GEM) is capable of rapid screening of large volumes of material, which can then be monitored in 1 tonnes bags via a High Resolution Assay Monitor (HIRAM) which generates the quantitative data to assess the final disposal route. Previous methods of monitoring radioactive land contamination with hand held probes, then soil sampling and awaiting gamma spectrometry analysis were slow. If the sampling density was not great enough, then this could lead to larger areas of soil being excavated to ensure that contamination was sufficiently removed (Beddow et al, 2013).

The GEM and HIRAM technology were developed from a drive to monitor larger volumes of soil to support future decommissioning and remediation of radiologically contaminated land in quicker timeframes. Nuvia developed the two techniques of the GEM and HIRAM after 2005 due to output from a National Physical Laboratory workshop highlighted the need to be able to monitor larger amounts than previously established limits of 200 litre drums. An agreement was made with regulators that an increased volume of one metre cubed was acceptable (Beddow, 2013).

Leaching of contaminants to reduce waste quantities and the impacts on future generations could help reduce disposal costs and make more efficient use of the Low Level Waste Repository (LLWR) in Cumbria, UK (NEA, 2014). Laboratory studies undertaken by Hazen and Tabak, 2005 show strategies for remediating radionuclides by biotransformation, bioaccumulation/biosorption, biodegradation of chelators, treatment trains and natural attenuation. Other techniques such as electroremediation, phytoremediation and soil washing have been applied to soils (CIRIA, 2004). Some of the strategies which have been used to remediate radioactive groundwater include hydraulic barriers, capping and permeable reactive barriers (PRB) (IAEA, 2014). Examples of the application of some of these techniques at sites are discussed overleaf.

2.9.2 UK- Excavation of radioactive soils with high resolution assay monitor

Hunterston A Site in Scotland a Magnox site remediated Cs- 137 contaminated land by isolating contamination within a slurry wall with a cap. The specification of works was issued in 2010 with completion of the final remediation in 2013 (Site Stakeholder Group, 2013). To install the wall, 2000m^3 of overburden soil was excavated and Nuvia provided a GEM for rapid screening of large buckets of soil. The soil was then placed in 1 tonne bags and run over a HIRAM to determine levels of contamination and classify the waste soil for disposal (Magnox, 2014). Installation of a continuous slurry wall of 311m was keyed 1m into the natural clay and glacial till. An impermeable cement stabilised cap completed the containment by using site won material to reduce the environmental impacts (Magnox, 2014).

2.9.3 UK- Phytoremediation trials

Phytoextraction field trials have previously been undertaken at Bradwell site in Essex. In 1998 Beta vulgaris was investigated to see how it would assist in the removal of Cs- 137, trials showed that Cs- 137 uptake rates were greatest at the lowest soil Cs- 137 concentrations. A further phytoextraction trial in 2000 recommended that in order to increase Cs- 137 removal rates, availability of Cs- 137 to the plant needed to be increased so more plant uptake could occur (Watt et al, 2002).

Phytoextraction can be a slow remediation technique especially in the case of Bradwell Site where Cs- 137 leaked into clay geology where it has the ability to bind to negative sites on the clay particles (Demmer et al, 2012). Application of chelating agents before harvesting plants has shown to increase extraction, but still leaves the secondary waste from harvesting the biomass (Hazen & Tabak, 2005).

2.9.4 United States, Permeable Reactive Barrier for remediating Strontium 90.

Remediation of a 1000 ft. groundwater plume containing Sr- 90 in Buffalo, New York, USA was undertaken using at PRB. A pilot trial undertaken in 1999 used a zeolite called *clinoptilolite,* this was largely effective in removing Sr-90 but the wall required better design (VanderMeulen, 2012). The pilot design included a 35ft wall made of steel sheet piling, which was driven into the ground. This created areas where zeolite was impermeable and lowered its effectiveness, coupled with the short length of the pilot wall meant that the groundwater found its way around the wall rather than through it. AMEC were approached in 2007 to design a new wall and further assessment was undertaken on two zeolites for their effectiveness demonstrating that a zeolite containing 85% *clinoptilolite* with a mixture of non reactive minerals was most cost effective.

The PRB was designed to catch the plume but not allow it off the former nuclear fuel site into surface water. The wall was constructed in 2010 at 860ft in length and 39 inches wide with a depth of 30ft containing around 2300 tonnes of zeolite, using a one pass trencher to limit workers contact with the soil. The 86 monitoring wells have shown that the wall is expected to last for two decades, requiring no care except for continued monitoring. Re-evaluation in 15-20 years will be required to determine if the zeolite needs replacing, it may be able to remain in place since the half life of Sr-90 is 28.8 years, its possible that safe levels will have been met (Vander-Meulen, 2012).

IAEA, 2014 highlighted key considerations for the performance of a PRB and the requirement to be able to measure water quality parameters to provide early warnings of a PRB's performance. Precipitation of local inorganic groundwater constituents can build up on PRB walls and reduce the permeability and reactivity of the wall over time.

2.9.5 Remediation of non radioactive land contamination

The extent of non radiological contamination at Nuclear sites is dependent upon activities and events that have occurred at the site over the years. Many chemicals like solvents, degreases and oils would have been used and have potentially leaked to ground due to failure of plant or accidental releases (EA, 2001). The majority of non radiological contamination at NLS in the UK contains hydrocarbons, chlorinated hydrocarbons or solvents. Remediation techniques discussed below will focus on chlorinated solvent contamination which is the focus at Chapelcross site which will be looked at within this study. Chlorinated solvents and hydrocarbons are amongst the most abundant contaminants in groundwater. The biodegradation product vinyl chloride (VC) from PCE and TCE as shown in figure 2 overleaf is even more of a threat as it is highly carcinogenic and can accumulate in ecosystems (Dogan- Subasi et al, 2014).

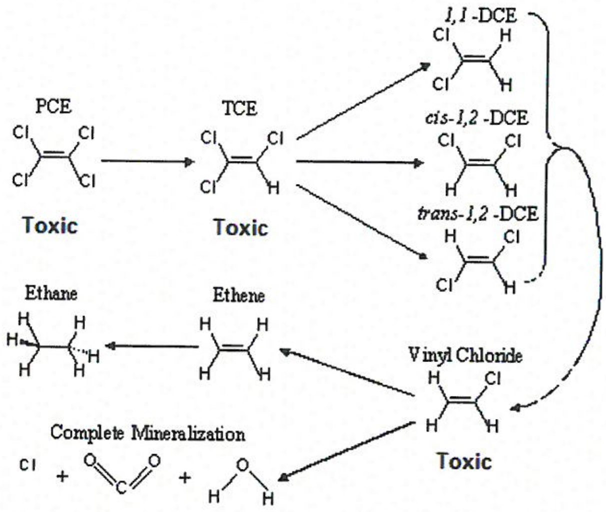


Figure 2. Breakdown products of PCE and TCE (The advocate Project, 2015).

At the majority of Magnox sites chlorinated solvent releases as dense non aqueous phase liquids (DNAPL's) would have occurred decades ago. Historically it was believed that if solvents were discarded to ground they would evaporate, there fore due to the Magnox Sites being operational since the late 1950's meant that in some cases solvents were inadvertently discharged to ground. Further understanding of the effects solvents could have on the ground and controlled waters and the development or environmental and waste regulations mean this activity could no longer occur on sites (Magnox, 2013).

DNAPL is likely to have undergone such processes as dissolution into the groundwater, fractures and diffusion into the matrix of the geology. DNAPL's can sink below the water table and move into small fractures and pore spaces, making it difficult to locate and delineate (EA, 2000). It is well documented for fractured sedimentary rocks that DNAPL can be strongly influenced by matrix diffusion processes due to fractures providing a pathway for groundwater flow, a large rock matrix porosity and sorption can enable large storage capacities (Parker et al, 2012).

Remediation approaches such as pump and treat, physical barriers and hydraulic barriers were the traditional approach to dealing with DNAPL. Developments are now moving towards chemical and biological treatments such as bioremediation, in situ chemical reduction/ oxidation and application of surfactants (Kueper et al, 2014). Permeably Reactive Barriers containing zero valent iron are now frequently used to treat chlorinated solvents, both in the UK and abroad. Examples of the application of some of these techniques are discussed below (section 2.9.6- 2.9.8). Remedial technology combinations may include a combination of physical, chemical and biological applications as shown in figure 3 in order to remediate DNAPL contamination. In some cases remediation techniques will often need to be combined and monitored natural attenuation may form part of a polishing strategy (Kueper et al, 2014).

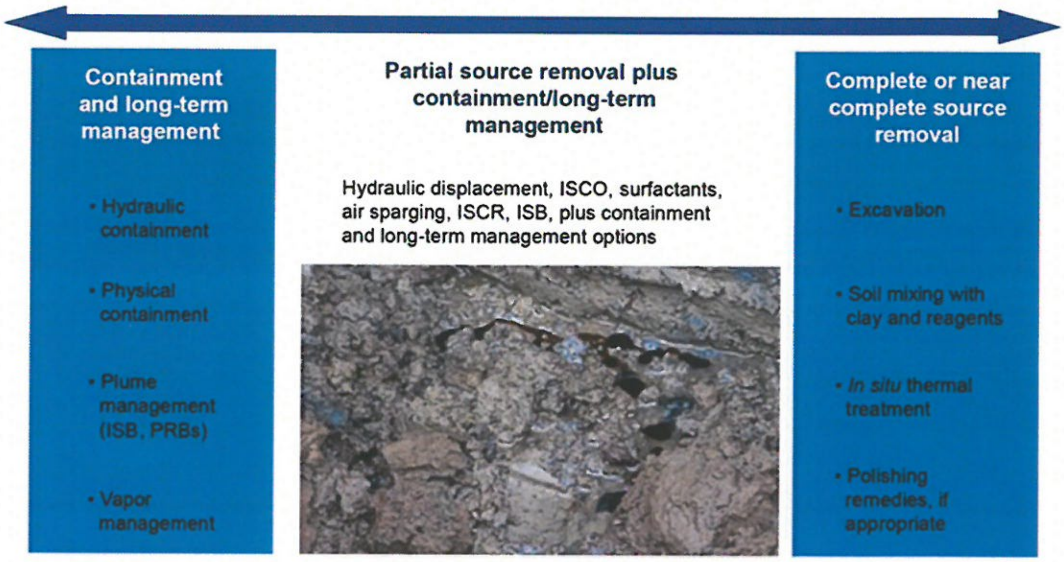


Figure 3. Different remediation techniques that could be applied to DNAPL contamination (Kueper et al, 2014).

2.9.6 In Situ Thermally Enhanced Soil Vapour Extraction

The application of thermally enhanced soil vapour extraction (TESVE) to remediate the unsaturated zone at Harwell Site in Oxfordshire was undertaken over a three-week period. It showed some six months later that *Dehalococcoides sp*. increased indicating that thermal enhancement creates favourable conditions for dehalogenating bacteria (Provectus Group, 2009). Considerations need to be given to temporary increases in vinyl chloride concentrations that can occur during enhanced bioremediation. *Dehalococcoides* are sensitive to pH, and the final reaction of vinyl chloride to ethene does not seem to occur below a pH of 6 (Kueper et al, 2014).

2.9.7 Hydrogen Release Compound 3D Microemulsion (HRC/3DMe)

Bioremediation and the use of *Dehalococcoides* for dehalorespiration of chlorinated solvents has been used widely in the United States (Hazen & Tabak, 2005). It has been combined with other faster working techniques at the source such as thermal, in situ chemical reduction (ISCR) and excavation. Products developed by companies like Regenesis such as Hydrogen Release Compound 3D Microemulsion (HRC/3DMe) is a controlled time release electron donor for groundwater and soil remediation.

3DMe is designed to optimise anaerobic degradation of contaminants. The incorporation of lactic acid, an efficient electron donor and long chain fatty acids, which provide additional electron donating capacity, make 3DMe an excellent hydrogen source. The fatty acids within the structure are slower to ferment and provide hydrogen over an extended time period. This process creates an anaerobic system, which helps increase the number of indigenous microorganisms to perform enhanced reductive dechlorination. Naturally occurring microorganisms replace the chlorine atoms on the chlorinated contaminants with newly available hydrogen effectively reducing the contaminant to ethane or ethane (Regenesis, 2015).

A case study undertaken, investigating the biochemical treatment of hexavalent chromium and chlorinated volatile organic plumes found that HRC/3DMe was still effective five years after injection and despite significantly contaminated up gradient conditions, still provided a reducing environment (Desrosiers et al, 2013). Studies into reductive dechlorination activity in fractures and low permeability zones demonstrated that even permeability interfaces with limited biological reactive zones can greatly reduce remediation time frames (Scheutz et al, 2010).

2.9.8 Surfactant & Co solvent flushing

Surfactants can increase the solubility of contaminants, chemical treatment can be applied directly to soils or the aquifer and may be part of an over all remediation strategy. Surfactants can have negative effects on bacteria by disrupting cellular membranes or reacting with proteins. The use of synthetic surfactants can often be toxic and pose a threat of additional contamination if not controlled. Bio surfactants possess the same properties but have the advantage of being biodegradable and most studies have shown that they are nontoxic to microorganisms (Kueper et al, 2014).

A case study of a site in Oscada, USA contaminated with perchloroethene (PCE) is an example where a food grade surfactant called 'Tween 80' was flushed through the source zone (Geosynthetic Consultants, 2004). Monitoring detected increased concentrations of volatile fatty acids generated from the fermentation of 'Tween 80' (Ramsburg et al, 2004). The residual surfactants and co-solvents left after flushing of the soil occurred changed the redox potential and served as electron donors to stimulate dechlorinating microorganisms (Kueper et al, 2014). It should be noted that surfactants can also have negative effects on the physiology of microorganisms and as well as stimulating dechlorination can also inhibit growth due to the toxicity of some surfactants.

Kueper et al, 2014 outlined that surfactant and cosolvent flushing remediation of source zone areas has received little attention in the last 10 years. Some of the reasons for this may be due to the high costs, complexity of implementation, a reduced performance in low permeability geologies and treating effluent waste created from the process. Some of the main factors which need to be considered when selecting a surfactant are public and regulatory perception, biodegradability and degradation products, toxicity to humans, animals and plants (Mulligan et al, 2001).

The limited uptake of this technology may also be due to the detailed knowledge of soil microbiology and the fate and transport of the surfactant and contaminant within the environment. Ensuring accurate control of potential downward or horizontal movement of contaminated groundwater in order that it does not further contaminate groundwater or migrate beyond a sites boundary are critical factors to be considered.

By increasing the rate of DNAPL removal to the aqueous phase by surfactants and cosolvents this then allows ISCO and oxidant addition to clean up the dissolved DNAPL. Verutek is the the copyright holder of this combined remediation which uses a plant based biodegradable surfactant/co-solvent mixture to desorb contaminants and solubilise NAPL contamination for destruction in place by an oxidant. Full scale field implementation has been undertaken in New York, USA for clean up of coal tar contamination and Denmark and Australia have undertaken field trials but not in the UK yet, however the CL:AIRE webpage currently has a request from Verutek to undertake its first field trail in the UK (CL:AIRE, 2015).

Chapter 3 Methodology

The methodology will outline and detail how each of the objectives identified in chapter 1 will be achieved.

Objective a. Identify and describe a specific area of land contamination at each of two Magnox sites through development of a CSM.

The two Magnox sites with land contamination issues to be assessed will be Chapelcross, Dumfrieshire, Scotland and Bradwell, Essex, England. Chapelcross site has non radiological chlorinated solvent soil and groundwater contamination. The site is at a stage where the QLRA (NIGLQ, 2012), further site investigation and Generic Quantitative Risk Assessment has informed that remediation is required (Magnox, 2013).

Bradwell site has radiological Cs-137 and Sr-90 soil and groundwater contamination. Remediation was undertaken at the site in 2013/14 after a remediation options assessment identified selective excavation and a capping system. This study will review the remediation strategy at the site against other possible remediation options which could have been considered (Magnox, 2012, 2013 & 2015).

A CSM will be drawn for both sites taking into account guidance from CLR 11, Safegrounds and the NIGLQ QLRA (EA, 2004, CIRIA, 2009, NIGLQ, 2012). The CSM will take account of up to date site investigations, monitoring data and in the case of Bradwell what additional knowledge has been gained from undertaking remediation. The CSM's will be hand drafted and drawn up in Auto CAD, this enables flexibility in altering the model through the developmental stages. The sources, pathways and receptors identified within the CSM will be documented.

Objective b. Identify and describe suitable remediation strategies which could be used for each of the two sites and how these will break the linkages in the CSM for each site.

Chapelcross site is currently at the point of identifying that remediation is required but has not been through the remediation options assessment process. Chapelcross site has an Interim C&M date of 2017, this will be taken into account when screening the remediation strategies.

Bradwell site an accelerated decommissioning site with a C&M date of 2015 has been through options assessment and has implemented a remediation strategy for its radiological contaminated soil and groundwater. The time constraints on the site meant that the choice of remediation strategy had to be installed, commissioned and verified by 2015. This study will assess what other remediation strategies could have met the 2015 date in light of the further information gained through implementing a remediation strategy at the site already. The initial options assessment will be taken into account when setting the objectives for screening and what techniques had been considered previously (Magnox, 2012). When referring to the date of 2015, since this is now the present time this process reflects the position of going through screening and options assessment as if it were still late 2012. This enables a time context of two years to be considered (Magnox, 2013).

Suitable remediation strategies will be identified for each site and the contaminant linkages present. The identification of suitable remediation strategies that are viable to take forward for sustainability assessment and NPV calculation need to ensure that they have undergone an initial screening against objectives. CLR11 and Safegrounds guidance on the comparison of contaminated land management options identifies it may be appropriate to screen initial remediation strategies on the basis of clearly defined factors or objectives. Screening factors may include some of the following: technical practicability, time taken to implement the strategy, durability of the strategy over the design life and site constraints such as space to accommodate remediation equipment, waste and interfaces with other projects in the vicinity (EA, 2004 & CIRIA, 2009). The objectives, assumptions and constraints will be clearly stated to determine what relevant remediation strategies meet these criteria.

Objective c. Calculate the NPV and undertake a Sustainability Assessment of the alternative remediation strategies for each of the land contamination issues being looked at.

Sustainability Assessment Methodology:

The SuRF UK Framework will be used for the sustainability assessment as it enables a structured hierarchical framework to be followed using qualitative, semi-quantitative or quantitative techniques. It represents a wide range of indicators over the three sustainability pillars. Although it is not prescriptive on how indicators are to be measured it does ensure that a holistic evaluation of all three dimensions is taken into account (CL:AIRE, 2011). Incorporating the calculation of the NPV will help broaden the economic dimension of the assessment and see how it can influence remediation strategy decisions (Beames et al, 2014).

A systematic and transparent method for options comparison should be undertaken as recommended within the Safegrounds and CLR11 guidance (CIRIA, 2009 & EA, 2004). These guidance documents will be considered in conjunction with the SuRF UK Framework to undertake the assessment at each site. The Safegrounds and CLR 11 processes of comparing remediation strategies for options appraisal are well understood but integrating the SuRF Framework alongside Safegrounds and CLR 11 is not been as widely practiced. There have been limited case studies showing the application of the SuRF framework so applying it to Bradwell and Chapelcross Site will see how the process can influence remediation choices for nuclear decommissioning sites (EA, 2004 & CIRIA, 2009).

The sustainability assessment will utilise the SuRF UK Brief Case which consists of checklists to help guide and frame a sustainability assessment (CL:AIRE, 2015). The sustainability assessment will outline what remediation strategies have been brought forward from the screening. The assessment boundaries of space, time, system and lifecycle will be outlined. The SuRF UK Indicator Set for Sustainable Remediation Assessment will be used to determine what categories under the Social, Economic and Environmental pillars are to be included within the assessment, documenting why categories are included or discounted (CL:AIRE, 2011). Once the categories which are to be included have been established the identification of indicators under each category will be required using the SuRF UK "Review of Published Sustainability Indicator Sets" (CL:AIRE, 2009). Safegrounds and ONR guidance for options assessment will also be considered (CIRIA, 2009 & ONR, 2006). A sustainability assessment spreadsheet will be developed to evaluate the remediation options. The assessment table will utilise the 'URS Tier 1 Sustainable Remediation Assessment Spreadsheet' available on the CL:AIRE website (CL:AIRE, 2015).

The URS Tier 1 Qualitative spreadsheet will be adapted using scores from 0-100 instead of qualitative statements such as good, fair or poor (CL:AIRE, 2014). The options will be scored between 0-100 where 0 represents very poor performance of the option against the indicator and 100 represents excellent performance. The spreadsheet will record the score given against each option and a justification for these scores and any uncertainties (CL:AIRE, 2010).

Safegrounds comparison of contaminated land options suggests a finer scoring scale to be used where more detailed information is available. In the case of both sites a combination of qualitative and quantitative information is available. More detailed information is available for Bradwell site from the remediation strategy which was implemented, such as cost data and information on quantities of waste. Chapelcross site will use more qualitative data but this will be supplemented by quantitative data from calculation of the NPV. For those indicators where quantifiable information is not available and only qualitative information, the scoring system will be applied and justified with a description for the basis of the score. Any uncertainties will also be recorded in the spreadsheet when undertaking the assessment (CIRIA, 2009).

The URS spreadsheet has various tabs outlining stakeholders, project constraints, boundaries, scope and methodology through to the execution of the assessment. Only the execution assessment tab will be used as the previous tabs will be addressed through using the SuRF UK briefcase. The assessment tab of the URS spreadsheet does not include a column for justifications for inclusion or exclusion of categories, this is included on another tab (CL:AIRE, 2014). In order to keep all my data for the assessment to one spreadsheet I will add a column for justifications for inclusion/ exclusion of categories; weights and indicators. A weight will be given to each indicator from 0-100, which will try and take account of stakeholders views when undertaking this. All the evidence based decision making and record keeping is then kept in one spreadsheet to be entered into Hiview (CL:AIRE, 2010).

Safegrounds guidance acknowledges that it can be useful to have an option that represents the "Status Quo" or "Do Nothing" as it will provide an absolute indicator of the potential improvement offered by other options (CIRIA, 2009). For the purposes of the sustainability assessment a "Status Quo'" option will be included which will consider each area at each site to have on going borehole monitoring. This will assume that no remedial action will be required in this time frame and that the monitoring regime will stay as it currently is. For Bradwell and Chapelcross the period of C&M until FSC for both sites is 68 years, with Bradwell sites FSC date being 2083 and Chapelcross sites FSC being 2085 (Magnox, 2015).

Multi Criteria Decision Analysis (MCDA)

A tier 2 semi quantitative multi criteria decision analysis (MCDA) has been chosen in line with tables 3 and 4 (section 2.8). A tier 2 assessment allows weightings to be applied, which reflect stakeholder considerations. The permissions and time required to set up workshops with all stakeholders would not be possible for the assessments so a best account of their views and opinions will be considered when weighting indicators.

As reviewed in the literature an MCDA (table 4) has a narrow to wide coverage under the three pillars of sustainability. This means that MCDA can accommodate a variety of data inputs from monetary and non monetary data, qualitative data, ranking scales and weighting systems. It is a flexible decision support process which allows for comparisons within a structured framework. It is up to the assessor or project team under the sustainability assessment to determine the methodology and evaluation criteria for how the MCDA will be undertaken. For example, will a qualitative scoring system be applied or will a combination of quantitative and qualitative data be incorporated within the assessment (De Montis et al, 2005).

MCDA allows for detailed and numerical analysis to be incorporated, such as NPV within the assessment. However, MCDA is poor where limited information is available such as site investigation data or maturity of remediation options for the site. Therefore, factual information which is not site specific may affect the quality of the MCDA output. MCDA is good where a wide range of stakeholder views need to be taken into consideration like at Bradwell and Chapelcross site (CIRIA, 2009). The Department for Communities and Local Government (DCLG) issued a document called "multi criteria analysis: a manual" in 2009 to provide further guidance on implementing the technique. MCDA can be used retrospectively to evaluate a project or can be undertaken to appraise a proposed scheme. This will work well for Bradwell and Chapelcross site and the different stages they are being evaluated at. There are eight steps in the MCDA process shown in table 7 (DCLG, 2009) which will be taken into account when undertaking the assessment.

Table 7 MCDA Eight Step Process (DCLG, 2009)

1. **Establish the decision context.**
   - 1.1 Establish aims of the MCDA, and identify decision makers and other key players.
   - 1.2 Design the socio-technical system for conducting the MCDA.
   - 1.3 Consider the context of the appraisal.
2. **Identify the options to be appraised.**
3. **Identify objectives and criteria.**
   - 3.1 Identify criteria for assessing the consequences of each option.
   - 3.2 Organise the criteria by clustering them under high-level and lower-level objectives in a hierarchy.
4. **'Scoring'. Assess the expected performance of each option against the criteria. Then assess the value associated with the consequences of each option for each criterion.**
   - 4.1 Describe the consequences of the options.
   - 4.2 Score the options on the criteria.
   - 4.3 Check the consistency of the scores on each criterion.
5. **'Weighting'. Assign weights for each of the criterion to reflect their relative importance to the decision.**
6. **Combine the weights and scores for each option to derive an overall value.**
   - 6.1 Calculate overall weighted scores at each level in the hierarchy.
   - 6.2 Calculate overall weighted scores.
7. **Examine the results.**
8. **Sensitivity analysis.**
   - 8.1 Conduct a sensitivity analysis: do other preferences or weights affect the overall ordering of the options?
   - 8.2 Look at the advantage and disadvantages of selected options, and compare pairs of options.
   - 8.3 Create possible new options that might be better than those originally considered.
   - 8.4 Repeat the above steps until a 'requisite' model is obtained.

Application of Hiview Software for MCDA

Hiview software is an MCDA tool which has been used within the nuclear industry and at Magnox sites for options assessment. It has been mainly utilised for assessment of radioactive waste management projects. For example, locations for underground repositories for radioactive waste for Nirex were assessed using this model (DCLG, 2009). Hiview will be used to model the sustainability assessment scores and weights that will be recorded in the URS spreadsheet. Hiview can be used for group decision making processes but can also be used as an individual decision making tool, so is suitable for Bradwell and Chapelcross site. Hiview has the ability to use qualitative and quantitative data so it can model the NPV and any qualitative scores alongside one another. As Bradwell has undergone remediation there is quantitative data available from the actual remediation which can be used in the assessment (Catalyze, 2012).

Hiview bases itself on the same eight steps described in the DCLG guidance (table 7). The first stage of the software is to build the "value tree" of the criteria. This will comprise of the starting node titled "Which Remediation", which will be the overall decision required. The branching nodes will be the three sustainability pillars of environmental, economic and social. The application of Hiview has traditionally looked at costs and benefits as the branching nodes from the starting node, so applying the SuRF UK framework to this software will be the first time it's been undertaken (Catalyze, 2003).

The Hiview software has the benefit of being able to convert scores into value scales which can then be weighted. Therefore, actual data or qualitative scores can be entered and will automatically be changed to a scale from 0 to 100, known as preference scores. The scores from the URS spreadsheet will be entered into Hiview and the option with the highest score will automatically get 100 and the option with the lowest score will get 0 (Catalyze, 2003). There is the ability to inverse scores so for NPV where lower costs are better a value of 100 will be assigned to the lowest score and 0 to the highest score.

The gaps between the preference scores of the other options are in the same proportions to the spread of input scores. A simple example explains this below:

- Input scores of: Option A: 10, Option B: 20 and Option C: 30
- These would become preference scores of A: 0, B: 50 and C: 100.

Option B would have a preference score of 50 as the input score is half way between the highest and lowest option.

Hiview provides a weighting system where all criteria under a node at any level can be compared. Weights will be given to each category based on a best account of stakeholders views and opinions which will be documented as part of the sustainability assessment process. The chosen SuRF UK categories under the environmental, economic and social pillar documented within the URS spreadsheet will be inserted into the Hiview software. The categories will form the branching nodes under the three pillars of sustainability of the decision tree, where the scores and weights are then input into the model. The software takes the weight given to each SuRF UK category and divides this by the total of all the category weights over the three pillars to give a cumulative weight. The cumulative weight is multiplied with the preference score created in Hiview to give an overall weighted score (Phillips, 2007). Depending on the number of categories chosen under each sustainability pillar and the weight given to each of these will mean that the overall weight for each pillar will differ.

Hiview can display a summary of the sensitivity of the whole model, which highlights areas which require further investigation. A sensitivity analysis will be undertaken to see where increases or decreases in cumulative weight under the different categories would influence a change in the overall 'preferred option'. The sensitivity analysis in Hiview displays the overall 'preferred option' and highlights the categories where increases or decreases in the cumulative weight under that specific category would change the most 'preferred option'. This enables the sensitive categories to be further interrogated to see where weaknesses may lie within the sustainability assessment.

Hiview uses a colour coding system on the chart presenting the sensitivity analysis. A red bar means that the cumulative weight is very sensitive and would only require a change of less than 5 points in cumulative weight to change the most 'preferred option'. A yellow line requires a cumulative change in weight of >5-15 points in order for the most 'preferred option' to change and a green line requires a cumulative change in weight of more than 15 points in order to change the most 'preferred option' (Catalyze, 2012).

Costs Estimates and NPV Calculation Methodology:

A cost estimate and breakdown will be undertaken for each remediation strategy at each site to show capital, variable, operational and maintenance high level costs. Actual cost data from contractor estimates and cost analysis available from literature and case studies will be used. The on site Magnox resource costs involved such as project management, environmental and radiological monitoring personnel already paid for on site have not been included in these high level cost estimates.

External contractor costs have been included for the level of detail required for this assessment but contractor names have not been disclosed due to commercial sensitivity. This dissertation will only look at the external high level costs for purposes of calculating the cost estimate. No contingent cost has been factored in at this point as this will vary across each strategy. This will also be dependent on the perceived risk associated at the time of the works so would be a decision made at a Management level within the project once at the point of more detailed cost analysis.

The NPV will be calculated by applying the HM Treasury Nuclear Industry discount rates to the cost estimates (NDA, 2014). The NDA 2014/15 Annual report and Accounts have not yet been published at time of writing this methodology so discount rates could alter from those discussed in the literature (section 2.8.4). The NPV will be incorporated within the Hiview software modelling at the same time as entering the sustainability assessment scores and weights within the model.

Objective d. Discussion of the NPV and Sustainability Assessment for each land contamination issue with reference to previous literature review.

The data analysis will discuss the application of the SuRF UK sustainability framework, categories, chosen indicators for each site and how Hiview software was used in modelling the scores and weights. The sustainability assessment and identification of the best scored remediation strategies will be identified from the output from the Hiview software. The Hiview data and sensitivity analysis will be discussed. The sensitivity analysis of the highest scored option will be discussed and compared against the other options to see how robust the overall weighted score is.

The cost estimates, discount rates and inclusion of NPV under the category of direct economic costs will be discussed. The results will be reviewed taking into account the data used and the affect of any assumptions or uncertainties. Sensitivity analysis can be applied to discount rates in the same way it would to a sustainability assessment (HM Treasury, 2011). This will be undertaken by comparison and consideration of different discount rates to see how this could affect the NPV outputs.

Objective e. Evaluate and conclude the most suitable remediation strategy(s) for each land contamination issue, taking into account the sustainability assessment and NPV and what improvements, further work and research can be undertaken.

Evaluation of the data analysis undertaken in objective d will evaluate which remediation strategy/s are the most sustainable taking into account the factors which have influenced the results of the assessment. Reviewing if the overall objective has been achieved, whilst reflecting on steps required in a sustainable remediation options assessment process. Evaluating the process of developing a CSM, screening criteria, identification of suitable remediation strategies, cost estimating and calculation of an NPV.

Evaluating the feasible sustainable remediation options will determine what considerations need to be taken into account in the future for remediating land at decommissioning nuclear sites. The evaluation will address improvements that could have been made if the study was to be undertaken again and recommendations for future work.

Chapter 4

Conceptual Site Models & Supporting data

4.1 Conceptual Site Model (CSM) for Chapelcross Site, Dumfriesshire, Scotland

The CSM for Chapelcross site will focus on an area of chlorinated solvent contamination of soil and groundwater at the site. CSM's will be developed to show the sources, pathways and receptors.

4.1.1 History of Chapelcross Chlorinated Solvent land contamination.

This section will give an overview of the history and events that led to contamination and reasons why remediation is required. Chapelcross operated from 1959 - 2004 and is now undergoing decommissioning. The site is currently in the C&M preparation stage with an Interim C&M of 2017 (Magnox, 2014). Figure 4 below shows the location of the site and the former Armature Treatment Bay (ATB) building which was used for cleaning motor armatures in solvent spray bays. It is estimated that approximately 7 tonnes of waste spent solvents were accidentally spilt or inadvertently discharged to the ground over 10-15 years from the ATB (Magnox, 2013).

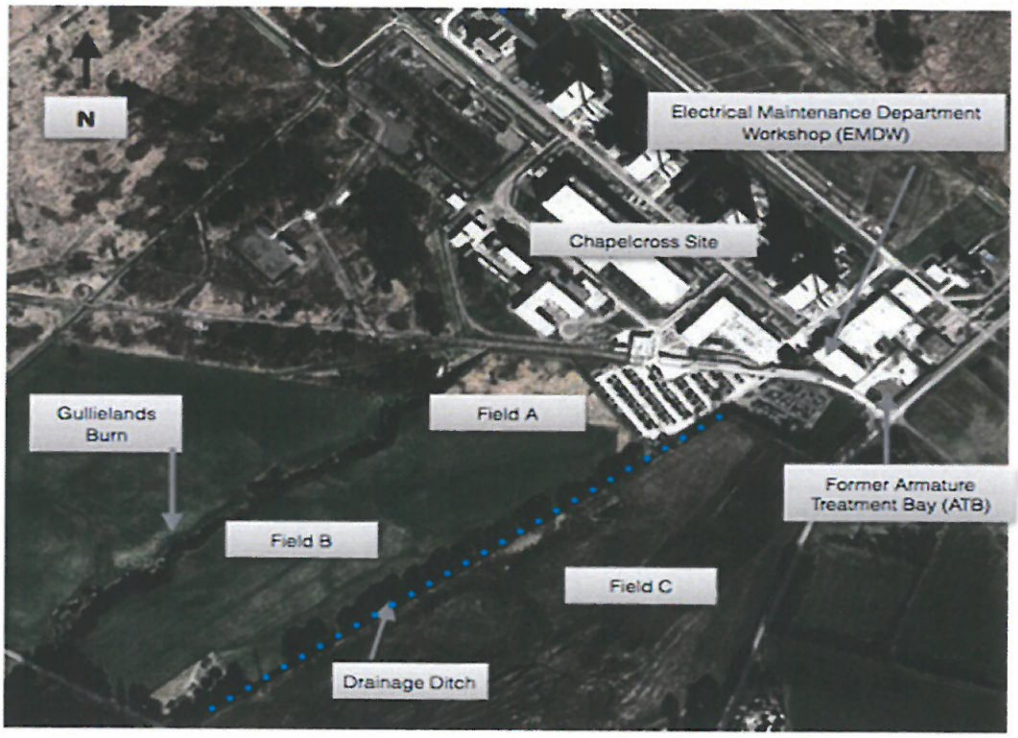


Figure 4. Location of Chapelcross Site and Armature Treatment Bay.

4.1.2 Previous remediation and site investigations

In 2007 partial remediation by source zone excavation was undertaken at the ATB area, a 20m by 30m wide excavation with a depth of 2.5m to 3m was undertaken with 1442 tonnes of solvent contaminated soil disposed off -site. The excavation was backfilled with clean fill and was meant to be capped off with tarmac but this did not occur and only gravel was laid consequently allowing rainwater to infiltrate (Serco, 2008). Samples taken from the sides of the excavations prior to backfilling, showed that high concentrations of tetrachloroethene (PCE) up to 76,000µg/kg were still present in sides of the excavation at 1.5m below ground level prior to backfilling (Serco, 2008).

Further site investigation was undertaken in 2012/2013 and as part of the investigation a trial using Regenesis HRC/3DMe (multi phase hydrogen release compound) was undertaken in two wells in the upper sandstones within the ATB source zone (Regenesis, 2015). The 3DMe was injected in the sandstones from 4m to 7m and 7m to 10m, a total of $2m^3$. Evidence of changes at two boreholes (BH55 and BH1 – Appendix 1) suggest that an enhanced rate of natural degradation occurred.

Time series data from 2002 to 2014 showing the chlorinated solvent concentrations within boreholes at Chapelcross is presented in Appendix 1. BH1 in the source zone shows chlorinated ethenes are on a general downward trend from 2002 to 2014, although all values are above Resource Protection Values (RPV'S). BH1 time series data graph shows that historically when Tetrachloroethene (PCE) concentrations have increased and then gradually reduced in groundwater, this is then followed by an increase in cis 1,2 dichloroethene (DCE) concentrations. This can be seen with the August 2008 concentrations of PCE peaking then reducing, followed by DCE then increasing in subsequent months.

The next peak in PCE concentrations in BH1 were observed in December 2012 with a concentration of 1250ug/l and March 2013 with a concentration of 1290ug/l. The more recent peak in PCE in 2013, could be due to the trial of Regenesis 3DMe enhancing the microbial degradation and forcing more parent compound into the dissolved phase (Kueper et al, 2014).

BH55 in the source area shows in the shallow response zone trichloroethene (TCE) concentrations have decreased with increases in DCE and vinyl chloride (VC) since the Regenesis 3DMe injections in April 2012/13. The time series graph shows that DCE is up to two orders of magnitude higher than the RPV and VC has increased from 9 µg/l in May 2013 to 499 µg/l in February 2014, showing that degradation is occurring.

BH56A in the shallow response zone shows high levels of DCE and VC at two orders of magnitude higher than the RPV. The time series graph shows in May 2013, that DCE is present at a concentration of 59ug/l. All previous and subsequent DCE monitoring results show DCE ranged from 877ug/l-1380ug/l, which suggests that the May 2013 result may be a sampling error and a possible erroneous result. BH56A in the deep response zone of 17.3-18.30m bgl shows that DCE and VC were above the RPV's up until February 2014 where concentrations then decrease to below the RPV (SEPA, 2014).

As stated in the literature chlorinated solvents have densities greater than water meaning migration of DNAPL can be achieved at a considerable depth and within fractures (EA, 2001). DNAPL also have the ability to enter the rock matrix where the matrix is composed of weakly cemented, coarse grained sediments. The St Bees Sandstones are not coarsely grained based on the petrographic analysis of BH55 and BH56a, describes the porosity as patchy fine vuggy porosity with pore sizes ranging from <20µm to 500µm with an average of 200 µm and no evidence of micro fracturing (Hyder, 2013). Vuggy porosity is caused by the dissolution of calcareous materials, such as the Sandstone formations present at Chapelcross site. This type of porosity can resist compression very effectively due to its spherical shape and is known as secondary porosity. Fractures and vugs are examples of secondary porosity, whereas primary porosity is intergranular, formed during deposition (Crains Petrophysical Handbook, 2015).

Due to the waste solvents being released gradually over the years, coupled with the pore sizes and limited interconnectivity suggest there is little to support that free phase DNAPL will have had sufficient force to drive directly into pore spaces. DNAPL is likely to have migrated to depth below the ATB through fractures in the St Bees Sandstone which are inter bedded with Mudstone. The DNAPL can then slowly dissolve back into the groundwater from the fractures at depth. The organic carbon partition co-efficient (KoC) describes the ability of the contaminant to partition between solid and liquid, a higher KoC means greater the contaminants affinity for organic carbon in soil or rock and therefore a slower rate of migration through groundwater.

Chlorinated ethenes have low KoC values therefore are more mobile in groundwater. The partitioning of chlorinated solvents between the aquifer solids and water is important in their fate and transport. Chlorinated solvents are considered moderately hydrophobic and although they partition onto aquifer solids, their ability is not as good as polycyclic aromatic hydrocarbons (PAHs) or polychlorinated biphenyls (PCBs) (EA, 2003). This can be seen from the time series data (Appendix A), BH55 within the excavated ATB area where contamination is present in the upper sandstone and the deeper zone of BH55 up to 25m depth.

The mid plume time series data from BH 26 show that TCE was generally decreasing with a slight increase in VC during October 2013 to December 2014. The time series graph for BH26 shows that concentrations of DCE appear to be seasonally influenced. Peak concentrations occurring in the winter months, which could be influenced by increases in rainfall infiltrating the source zone, with concentrations slightly reducing during the summer months.

BH64 (deep response zone) just down gradient of BH26 in the mid plume shows that DCE concentrations increased from October 2013 to February 2014, above the RPV. All other chlorinated ethene concentrations were below their respective RPV. This is likely to be associated with the 3DMe trial up gradient at BH55 & BH1 and migration of degradation products such as DCE from the higher concentrations of PCE and TCE observed in the source zone. BH64 in the shallow response zone shows that all chlorinated ethene concentrations fell below their respective RPV's from December 2012. Although concentrations of chlorinated ethenes are high at BH26 in the mid plume by the time they reach BH64 down gradient they have undergone degradation to significantly lower the concentrations observed.

The time series graph for BH 43 within the distal plume shows PCE has increased slightly from July 2013 forcing more parent compound into the dissolved phase, which has subsequently resulted in TCE increasing as well.

DCE has remained between 54-75 ug/l since August 2011. June 2010 and January 2011 were the only occasions when DCE fell below the RPV, which correlates with a decrease in concentrations of PCE and TCE and less break-down products such as DCE occurring at the same time.

BH 60 in the deep response zone (18-20m bgl) shows that there are no concentrations of chlorinated ethenes present. However, time series data for BH 60 at a 10-12m bgl (shallow response zone) shows that PCE, TCE and DCE are all present and have increased slightly from December 2013, with PCE and TCE being above their RPV's (SEPA, 2014). This shows that PCE and TCE from the source zone are able to migrate to the distal plume without undergoing degradation. Time series graphs for BH59 down gradient of BH60 show that PCE is present in the shallow response zone (4-6m bgl) but is below the RPV. The deep response zone (12-15m bgl) shows that no chlorinated ethenes were detected showing. Although small quantities of PCE may be migrating as far as 800m from the source zone they are generally within the shallower response zones and are not present within deeper zones below 12m.

Figure 5 shows that the upper and lower groundwater regime are not totally isolated from one another, quicker transportation rates in the lower groundwater of 200-700m/year compared to the upper groundwater of 2-5m/year could mean that PCE and TCE are transported from the source zone to the distal plume without under going degradation (Kueper et al, 2014).

Examples of the borehole logs for the site are shown in appendix 1, they show that the site consists of made ground over glacial till comprising of a reddish brown clay with sand, gravel and occasional boulders. The St Bees Sandstone formation beneath the glacial till comprises of medium strong dark reddish and brown sandstone, with very weak to extremely weak red brown mudstone layers. This is further underlain by the St Bees Shale Formation, which comprises of red siltstone and silty mudstone.

Figures 5 & 6 show the CSM's developed for the site taking into account the time series data from Appendix 1. Figure 6 shows the CSM of the contaminant linkages for the site, the principal linkage identified as source 1. Edges of the excavation from the partial remediation of the ATB in 2007 are still contributing to the plume by migrating horizontally through the St Bees sandstone to the St Bees Sandstone Formation groundwater regime.

Important uncertainties:

- Residual dissolved phase DNAPL at depth below ATB in fractures of the sandstone;

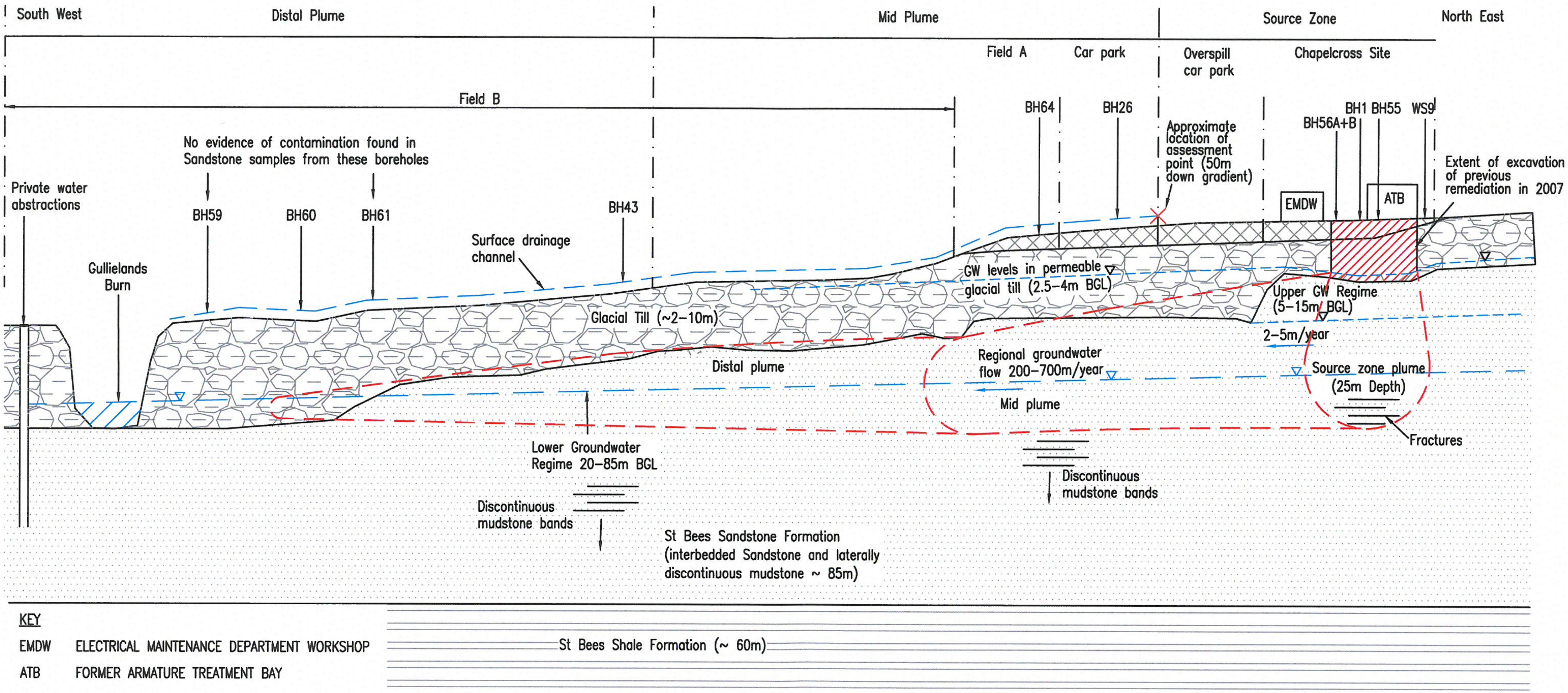
- Future impacts on the "Gullielands Burn" and Third Party Abstractions receptors if remediation is not implemented.

4.1.3 Regulatory Drivers for Remediation of solvent plume

The edge of the chlorinated solvent plume is approximately 800m from the source and outside the NDA land holding. Dumfries and Galloway Council are the lead regulator in terms of Part IIA and are expected to identify contaminated land within the area for non special sites and enforce remediation. The solvent plume contamination at Chapelcross has required Dumfries and Galloway Council to liaise with SEPA as this is a specific requirement when pollution of the water environment is being considered (SEPA, 2009). Magnox is in the process of pursuing voluntary remediation in liaison with SEPA and Dumfries and Galloway Council.

Chapelcross site is currently at the stage of identifying remediation criteria for soil and groundwater by utilising the Environment Agency's Remedial Targets Methodology (EA, 2006). This study will look at suitable remediation strategies that could be used once remedial targets have been set. SEPA Position statement (WAT-PS-1-01) 'Assigning groundwater assessment criteria for pollutant inputs' will be used to help derive assessment points and limits for the primary receptor groundwater. The assessment point will be set at 50m from the down gradient boundary in order to ensure groundwater meets remediation criteria prior to leaving the NLS (SEPA, 2014).

FIGURE 5 CONCEPTUAL SITE MODEL FOR CHAPELCROSS SITE – CHLORINATED SOLVENT BOREHOLE INVESTIGATION



Notes:

- Distal plume moves southward out of this sectional CSM view, slightly away from the Gullielands Burn
- Flow between the upper and lower ground water regime is impeded by mud stains but the two regimes are not considered to be totally isolated from one another.

References:

RPS, 2013; RPS, 2014; Hyder, 2013; Serco, 2008

BOREHOLE/WINDOW SAMPLE INFORMATION

WS9
Residual contamination at edges of excavation up to 20,300ug/kg PCE AT 0.8–0.9m bgl.

1.7–1.8m bgl, PCE identified at 415ug/kg (2012/2013 data)

BH1
2.25m – 5.45m bgl– PCE identified 75 μg/l in Dec 2013 & 730 μg/l – Feb 2014.

BH 26
9.20m bgl – DCE identified 289 μg/l Feb 2014 & VC – 7 μg/l– Feb 2014.

BH43
TCE identified at 20ug/l and DCE identified at 73ug/l in Feb 2014.

BH55
DCE identified at 8950ug/l and VC at 499ug/l in Feb 2014 at 5–6.8m bgl.

At depth 23.6–26.65m bgl DCE identified at 10,400ug/l and VC at 620ug/l in Feb 2014.

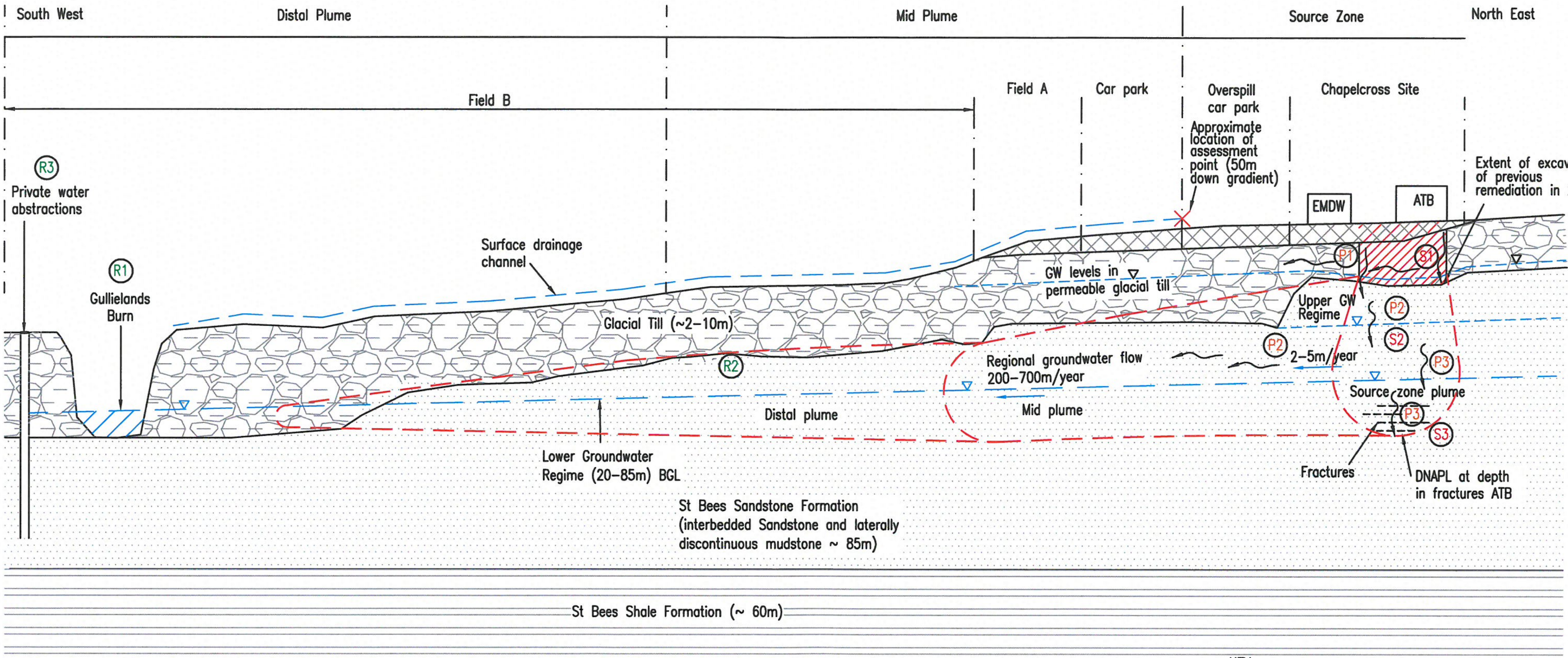
BH56A
17.30– 18.3m bgl– DCE identified 179 μg/l Oct 2013 & 77 μg/l – Dec 2013.

BH56A
6.0–6.8m bgl – DCE identified 1100 μg/l Dec 2013 & 877 μg/l – Feb 2014. VC – 94 μg/l– Feb 14.

BH60
21ug/l of PCE and 27ug/l TCE identifed at 10–12m bgl in Feb 2014.

BH64
18.45–20m bgl – DCE identified 103 μg/l Feb 2014.

FIGURE 6 CONCEPTUAL SITE MODEL FOR CHAPELCROSS SITE – CHLORINATED SOLVENT CONTAMINANT LINKAGES



Sources	Pathways	Receptors
S1 – Edges of partial remediation / excavation of ATB in 2007 – residual contamination in glacial till	P1– Migration of liquids through Glacial Till P2– Migration of liquids through St Bees Sandstone	R1 – Gullielands Burn Surface water R2– St Bees Sandstone formation Groundwater R3– Local abstractions Private water supply by 3rd party (approx 2 km away from site)
S2 – Dissolved phase plume in upper Sandstone formations in source zone.	P2– Migration of liquid through St Bees Sandstone P3 – Migration vertically through preferential paths in St Bees Sandstone	R1 – Gullielands Burn Surface water R2– St Bees Sandstone formation Groundwater R3– Local abstractions Private water supply by 3rd party (approx 2 km away from site)
S3 – DNAPL in fractures in the sandstone at depth beneath the ATB.	P3 – Migration vertically through preferential paths in St Bees Sandstone	R1 – Gullielands Burn Surface water R2– St Bees Sandstone formation Groundwater R3– Local abstractions Private water supply by 3rd party (approx 2 km away from site)

KEY

EMDW	Electrical Maintenance Department Workshop
ATB	Former Armature Treatment Bay

4.2 Conceptual Site Model (CSM) for Bradwell Site, Essex, UK, Caesium 137 and Strontium 90 land contamination.

The CSM's (figure 9 & 10) for the site focus on one particular area of radiological Cs-137 and Sr-90 contamination of soil and groundwater at the "North End" of the site. For the purposes of describing the CSM and contaminant linkages "North End" will be used throughout to describe the area of radiological contamination.

4.2.1 History and events of Bradwell Cs-137 and Sr- 90 land contamination.

Bradwell Site, Essex, UK operated from 1962- 2002 and is now undergoing an accelerated decommissioning programme with the aim of the site entering C&M in 2015 (at the time of writing). This section will give an overview of the history of the "North End" and events that have led to the radiological contamination and reasons why remediation was required. (Magnox, 2013). Figure 7 shows the location of the site and the "North End" where the contamination exists.

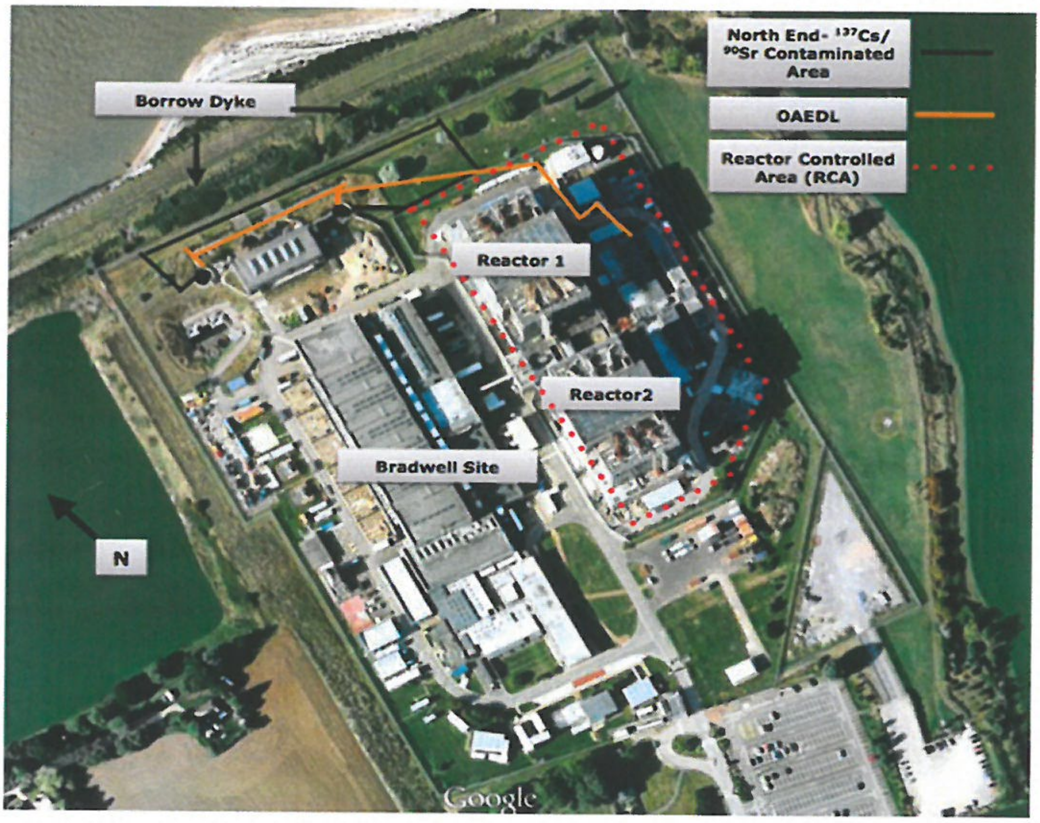


Figure 7. Location of Bradwell Site and "North End "

The Original Active Effluent Discharge Line (OAEDL) is the main radiological APC at the site and operated from 1963 until 1971. Liquid effluent was carried from the Active Effluent Treatment Plant (AETP) within the Radiological Controlled Area of the site to the cooling water outlet at the East or West syphon recovery chamber (figure 8). The effluent was then discharged to the adjacent estuary through cooling water outlets. In 1971 a number of draw pits along the line of the OAEDL collapsed and damage occurred to the line with leaking of radioactive liquid to the surrounding soils. The pipeline was replaced by a new line, with only some sections of the OAEDL removed along with a quantity of soil. This left a large proportion of the pipeline and contaminated soils in situ (Magnox, 2013).

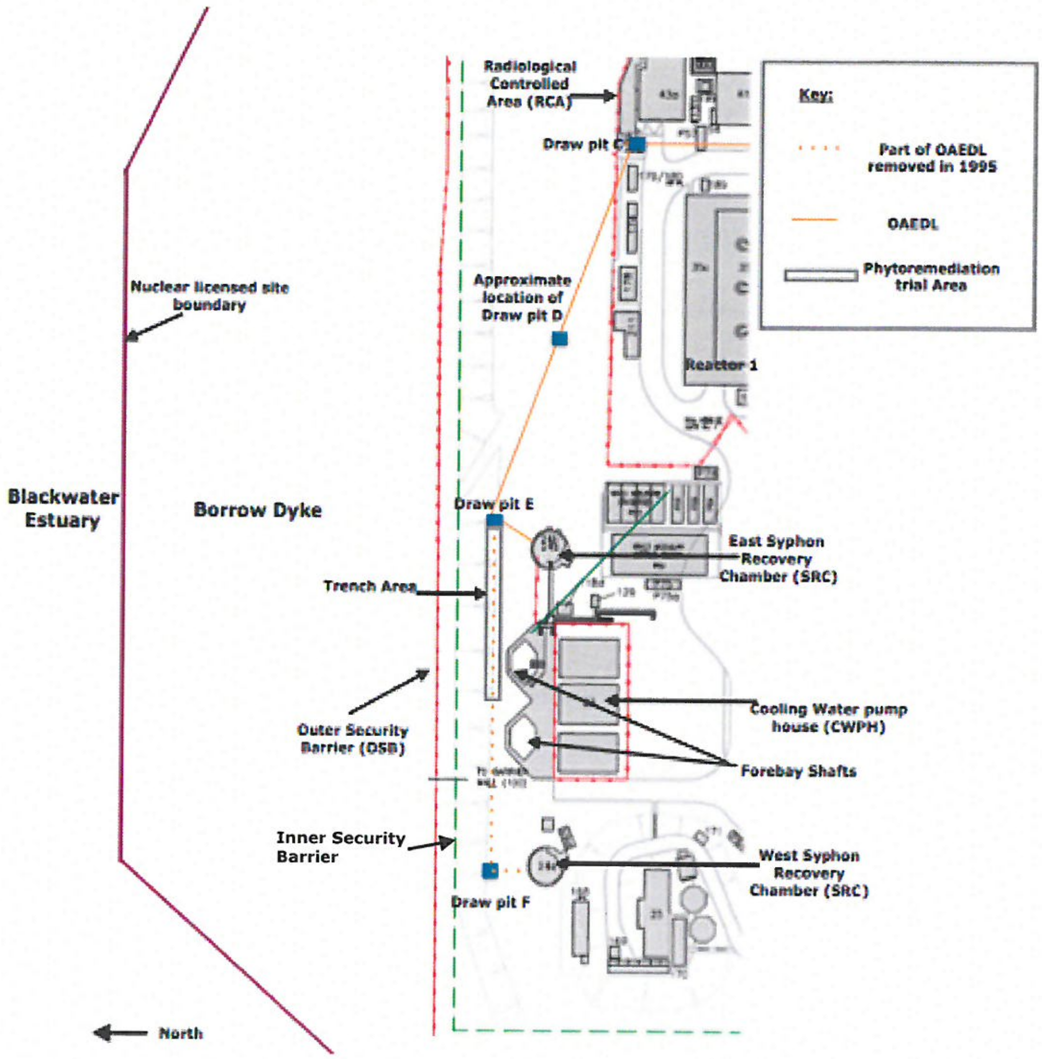


Figure 8. Location of Original Active Effluent Discharge Line and features of "North End"

During 1994/5 after the area received unusually high rainfall, the ground became very saturated raising the water table close to the surface. This caused contamination already in the soils to rise, which was likely to have mobilised residual contamination within the pipeline. Partial remediation of the radioactive soil occurred in 1995. The "Trench Area" shown in figure 8 was excavated and part of the OAEDL and soil removed. Phytoremediation trials were then undertaken in 1998/ 2000 within the trench area. In 2001 all vegetation was removed from the area around the trench and geofabric was laid and gravel installed to restrict vegetation growth (Watt et al. 2002). The area was still required to be radiologically controlled as surface contamination was present preventing general site access to the area (Magnox, 2013).

4.2.2 Site Investigation and Regulatory Drivers for Remediation of "North End".

A series of detailed site investigations in 2012/2013 showed levels of Cs-137 up to 10,000 Bq/g in small areas. The compliance issues associated with the "North End" were to prevent the migration (LC34) of radioactive contamination from the licensed site (Golder, 2013 & ONR, 2014). Radioactivity in food and the environmental (RIFE) sampling undertaken by the Environment Agency of the area showed that for 2013 gross beta in water from the coastal ditch was in excess of the WHO screening level for drinking water (1 Bq/l) but tritium concentrations were below the EU levels of 100 Bq/l. Low concentrations of artificial radionuclides (from permitted discharges) were detected in aquatic materials, the highest concentration of Cs-137 was 19 Bq/kg in sediment just along the estuary at Maldon, with Sr- 90 <2.0 Bq/kg in sediments. The 2013 report stated that there has been an overall decline in Cs- 137 concentrations in sediments over the last decade (CEFAS, 2014).

Figure 9 shows the CSM for the "North End" area and some of the investigative boreholes and sample results which were obtained during the 2012/13 works (Golder 2013 & Magnox, 2013). The CSM shows that Cs-137 is the dominant contaminant of concern and the highest contamination is found in locations of former draw pits, gullies, base of the open trench and adjacent to the OAEDl. Cs-137 has not migrated far from these areas due to the ability of it to tightly bind to clay (Demmer et al, 2012). There was an uncertainty surrounding contamination present below the OAEDL as the investigation only took samples adjacent to it, no drilling was undertaken through the

OAEDL to take samples beneath. Sr-90 has migrated to the OSB with 10Bq/l being identified in the Borrow Dyke water in March 2012 (Golder, 2013).

Compliance with LC34 throughout C&M was the major driver for the "North End" remediation in 2013/2014. The Westward flow of the Borrow Dyke had carried some of the radioactive contamination across the western boundary of the Nuclear Licensed Site. Figure 9 shows some of the data from the investigative borehole works undertaken and figure 10 shows the sources, pathways and receptors. The main contaminant linkage was considered surface runoff due to periods of heavy rain and past human activities documented.

In 1993 it was documented that the fire brigade pumped out a large volume of water from the cooling water bays onto the "North End" slope which could have mobilised surface Cs- 137 and Sr- 90 contamination down the slope towards the Borrow Dyke. The C&M safety case for land contamination at the "North End" was very conservative with a scenario of an infant drinking 2 litres a year of brackish water from the Borrow Dyke was assumed, this would result in a dose of 0.62μSv/yr. which is below the legal dose limit of 1000 μSv/yr. The Cs- 137 activity in the surface soils of the Borrow Dyke area is also consistent with natural background levels in the UK and is not considered a risk to the public so pathways of ingestion of water by site personnel or public were not considered within the case of the "North End" (Magnox, 2013).

4.2.3 "North End" Remediation of radioactive contaminated land.

Following a strategic assessment of options for C&M entry, a remediation strategy of selective excavation of Cs- 137, removal of the redundant OAEDL and capping of the area was undertaken in 2013/14. Selectively excavated soils were monitored via Hi-ram technology into one tonne bags (Beddow, 2013). An agreement was made with the EA for soils <200Bq/g Cs-137, which are classed as Very Low Level Waste (VLLW) to be re-used as an accumulation in situ on site until FSC. This reduced the burden of soils having to be excavated, packaged, transported and then buried at a permitted VLLW hazardous waste landfill (Magnox 2013).

Soils >200Bq/g Cs -137 were sent for direct burial as LLW to LLWR. However, undertaking full removal of the OAEDL resulted in a large amount of geotechnically unsuitable VLLW which was determined by the contractor as not being suitable for re-use and had to be disposed of at a permitted landfill. The contractor undertaking the work could not be confident in ensuring the cap would be load bearing for a vehicle if the VLLW was re-used. In hindsight the project team could have looked into the viability of applying quicklime to the soils to improve the structure and stabilise the soils for vehicular movements. It would have enabled VLLW waste soils to have remained on site, reducing the remediation time frame and costs associated with removal and landfilling.

Only two 1 tonne bags of LLW were excavated when removing the remaining OAEDL. This shows that the OAEDL and soil below was not as contaminated as initially perceived (Appendix 11). Installation of a low permeability capping system that was geotechnically suitable to still allow vehicular access was laid to prevent surface runoff of contaminants and reduce water infiltration into the sub surface, reducing migration of Sr- 90 into groundwater (Golder, 2015 & Magnox, 2013).

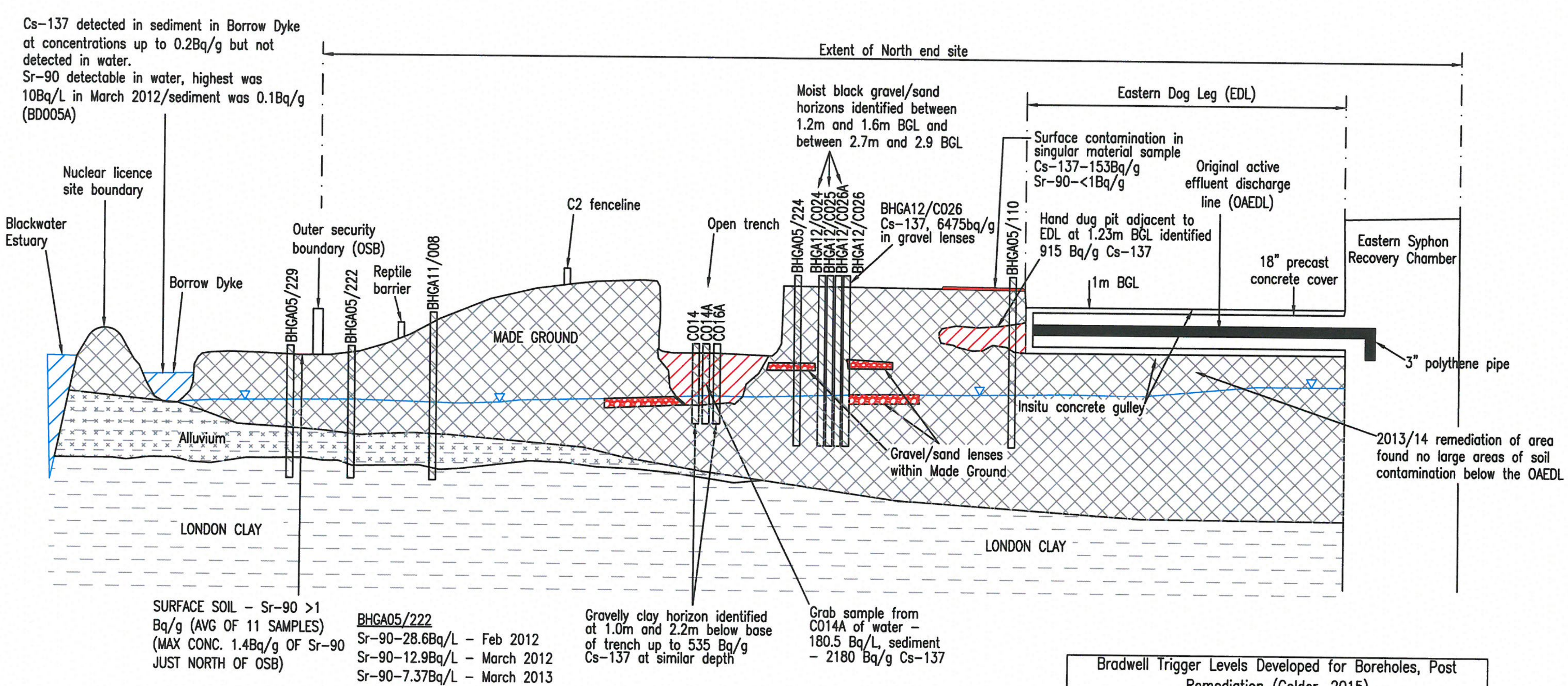
Important Uncertainties:

The uncertainties for the "North End" have been removed through remediation being undertaken already at the site, although there were some uncertainties which could still affect the choice of remediation strategy chosen in this study:

- During the initial remediation a variety of buried materials from plastics, metals, services were identified which could affect the success of certain remediation techniques.
- The variable nature of the VLLW soils encountered and the classification of some VLLW soil as geotechnically unsuitable for reuse meant that it had to be packaged, transported and disposed of at a permitted landfill site. If the project team had looked into the viability of applying quicklime to the soils then this may have reduced the quantity required to go offsite as geotechnically unsuitable VLLW.

FIGURE 9

CONCEPTUAL SITE MODEL FOR BRADWELL SITE, NORTH END. CAESIUM 137 & STRONTIUM 90 CONTAMINATION OF SOIL & GROUNDWATER – BOREHOLE INVESTIGATION



BHGA05/222
Sr-90-28.6Bq/L – Feb 2012
Sr-90-12.9Bq/L – March 2012
Sr-90-7.37Bq/L – March 2013

BHGA05/229
Sr-90-1.81Bq/L – March 2012
6.46Bq/L – March 2013

BHGA11/008
Sr-90-0.061Bq/L – March 2012
Sr-90-3.88Bq/L – March 2013

BHGA05/224
Sr-90-2.83Bq/L – Feb 2012
Sr-90-1.94Bq/L – March 2012

BHGA05/110
Sr-90-2.23Bq/L – March 2012

Bradwell Trigger Levels Developed for Boreholes, Post Remediation (Golder, 2015)

Borehole ID	Sr-90 Trigger Level (Bq/L)	Cs-137 Trigger Level (Bq/L)
BHGA05/110	5.3	28
BHGA05/224	3.4	0.3
BHGA11/008	2.7	0.3
BHGA05/222	34	0.3
BHGA05/229	2.2	0.3
Borrow Dyke Surface Water (BD005A)	12	N/A

References:

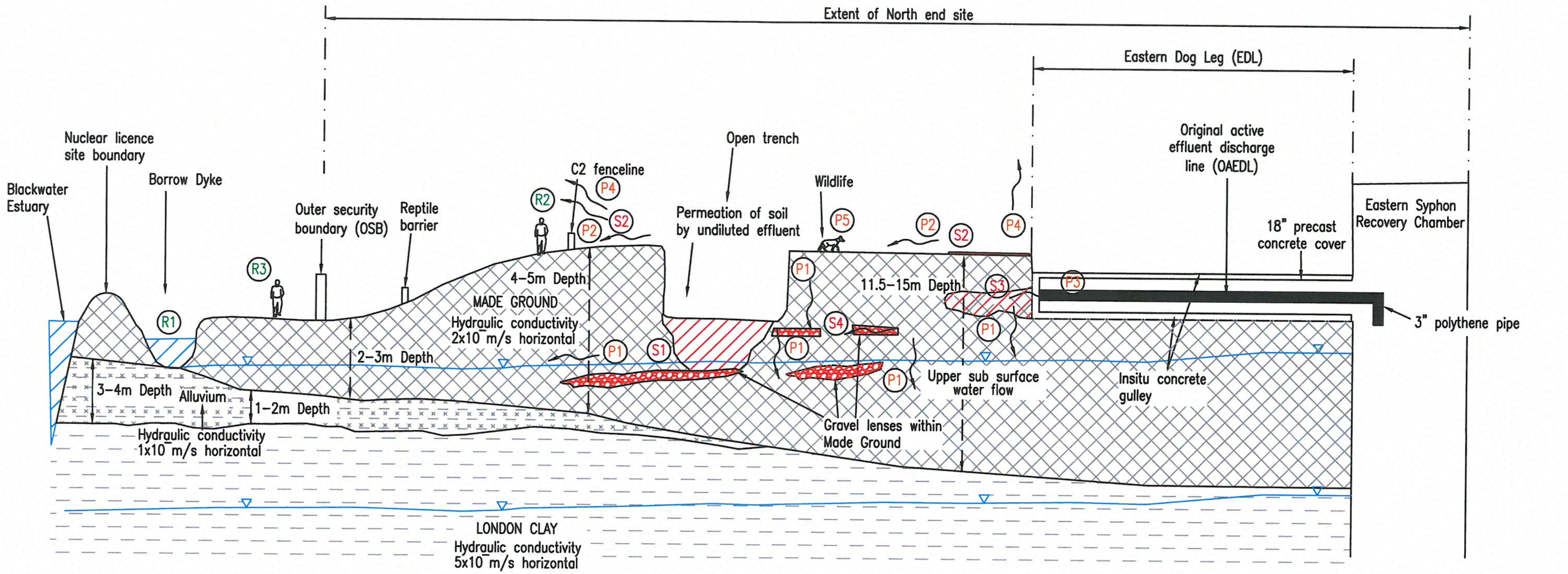
Golder, 2013; Golder, 2015; Magnox, 2013

FIGURE 10

NORTH

CONCEPTUAL SITE MODEL FOR BRADWELL SITE, NORTH END – CAESIUM 137 & STRONTIUM 90 CONTAMINANT LINKAGES

SOUTH



Sources	Pathways	Receptors
S1 – Open Trench– 1.0m and 2.2m below base of trench gravel lenses containing Cs–137 (BHGA12/C014A) Sr–90 in sub surface water (BHGA11/008, BHGA05/222)	P1– Infiltration of rainwater and migration through saturated zone	R1 – Borrow Dyke– Surface Water
S2 – Surface Contamination from previous remediation activities and events in area of OAEDL, North End Slope and North of Reactor 1. Cs–137 & Sr–90 in surface soils	P2 – Surface Runoff from high periods of rainfall. P4 – Erosion by wind or water, mobilises and spreads surface contamination. P5 – spread of contamination by wildlife, burrowing animals.	R1 – Borrow Dyke– Surface Water R2 – On site Personnel R3 – Off Site– Local walkers/ recreational activities in area.
S3 – Eastern Dog Leg (EDL) Cs–137 soil contamination Sr–90 – Sub surface water contamination (BHGA05/110)	P1– Infiltration of rainwater and migration through saturated zone P3 – Preferential flow paths through remaining OAEDL structure in place/ draw pits/ gravel lenses	R1 – Borrow Dyke– Surface Water
S4 – Gravel Lenses containing Cs–137 between 1.2m and 1.6m bgl South side of the Western part of the trench (BHGA12/C026) Sr–90 in sub surface water (BHGA05/224)	P1– Infiltration of rainwater and migration through saturated zone	R1 – Borrow Dyke– Surface Water

4.3 Identification of suitable remediation strategies which could be used for each of the two sites.

This section will look at shortlisting remediation strategies through establishment of objectives, assumptions and constraints (EA, 2004). A detailed description is given in the following sections on why remediation strategies passed or failed the screening process, with a high level overview of each remediation strategy for each site given in tables 8 and 9.

4.3.1 Chapelcross Remediation Overview

Chapelcross site is at the position of currently pursuing voluntary remediation. The identification of suitable remediation strategies has had to take into account some constraints at the site. The restricted space within the vicinity of the source zone due to buildings and roadways means limited access for large plant has discounted certain remediation techniques. This includes large scale excavation and disposal, soil washing, soil solvent extraction, thermal desorption/incineration and biopiles/windrows (EA, 2004). Pump and treat has also been discounted early on as such a technique can take many years and will not fit in line with the Interim C&M date and objectives of minimising active systems during C&M (Magnox, 2013).

4.3.2 Objectives, Assumptions and Constraints for remediating the Chapelcross solvent plume

The objectives are:

1. Demonstrably break the linkages identified within the CSM (figure 6) in order to meet remedial targets (to be set and agreed with regulators still);
2. Demonstration that a Satisfactory Land Condition can be met for the Interim C&M date of 2017 so as the site can go into a quiescent state, acknowledging that monitoring will run past this (Magnox, 2013);
3. The preferred remediation strategy should be one that reduces the need for further remedial intervention during Interim C&M and requires minimum maintenance and renewal of consumables or replacement (Magnox, 2013);
4. To provide cost effective performance and compliance monitoring post remediation, so as groundwater can be monitored effectively (Magnox, 2013).

5. The remediation strategy needs to meet the NDA's Technical Baseline and underpinning research and development requirements of a technological readiness level (TRL) of 7* or above (NDA, 2014).

*A TRL of 7 was included as one of the objectives as due to the short timeframes required to implement and verify a remediation it needed to be a demonstrated technique in a similar environment. The requirements throughout C&M of demonstrating a satisfactory land condition and reducing the need for further remedial intervention require the remediation to be robust. Technical confidence was considered within the Bradwell site options assessment undertaken in 2012 as an attribute for scoring. Instead it has been considered within the assessment at the screening stage because the time element is crucial for both sites assessments (Magnox, 2012).

The Assumptions are:

1. It is assumed that other decommissioning activities will not adversely affect the movement of surface and ground water in the area;
2. A preference has been assumed for remediation strategies that will not require active systems during C&M, like pumping in line with company Standard S-154 (Magnox, 2013);
3. The third party extraction approximately 2km away is unlikely to be affected by the plume (figure 5 & 6);
4. The distal plume edge is unlikely to discharge into the Gullielands Burn at the current time (figure 5 & 6).

The constraints are:

1. The ATB source area of contamination is sited in an awkward position near to the entrance of the site and main car park surrounded by occupied buildings. This area needs to maintain operability whilst remediation is occurring;
2. The generation of hazardous wastes should be minimised;
3. The end state of the NLS is to be delicensed at FSC with all land quality issues being addressed so as land is fit for its next use (Magnox, 2013);
4. The site must remain regulatory complaint throughout the full C&M period to FSC (Magnox, 2013);
5. The remediation strategy must not require a large footprint for equipment, facilities and waste due to constraint 1.

4.3.3 Screening of remediation strategies for Chapelcross solvent plume

Monitored Natural Attenuation (MNA) as part of Chlorinated Solvent Remediation Strategy

MNA includes the physical, chemical, or biological processes that occur to reduce contaminant mass, toxicity and mobility in soil or groundwater. MNA is typically a component of many chlorinated solvent site remediation strategies (Kueper et al, 2014). MNA has been included within three of the remediation strategy combinations discussed and would continue beyond the interim C&M date of 2017 to act as verification that remediation strategies have worked effectively (EA, 2001).

1. Air Sparging, Soil Vapour Extraction, Monitored Natural Attenuation (MNA)

Air sparging vigorously blows air through the groundwater to volatilise dissolved volatile organic compound (VOCs) which can then be removed via SVE from the unsaturated zone. The technique is less effective in low permeability soils such as the clay present in the upper 2-10m of glacial till at Chapelcross (figure 5) (United States Environmental Protection Agency (US EPA), 2012). This may require a heavier duty vacuum to remove vapours which could raise the water table which is already only between 2.5- 4m below ground level impeding the effectiveness of (objective 1). Stratified or highly variable soils mean vapours may potentially migrate outside of a vapour extraction area (US EPA, 2012). Air sparging and SVE would be able to remove sources 1 and 2 (objective 1) but how effective this would be due to the characteristics of the geology may be limited. The sandstone aquifer at Chapelcross could be affected by the effects of matrix processes and fractures could provide a pathway for groundwater flow and sorption (Parker et al, 2012). This means source 3 could take longer to remediate due to backwards diffusion.

Once air sparging is completed aquifers have shown to return to pre sparging conditions and diffusion may still occur, the introduction of oxygen via air sparging can negatively affect anaerobic conditions required for dehalorespiration of chlorinated solvents to occur (Kueper et al, 2014). This could affect the interim C&M date of 2017 being met and need for later intervention (objective 2 & 3) if pre sparging conditions return. Compliance monitoring would need to continue for longer to ensure this does not occur so may not be very cost effective long term (objective 4). SVE has a proven track record in the UK along with techniques like air sparging so would fulfil a TRL of 7 (objective 5) (Defra, 2010). It would require space for vacuum pumps, control systems, vapour treatment and a blower for air sparging so would require a large footprint but may still be applicable if mobile systems could be utilised (constraint 1 & 5) (Defra, 2010).

2. In Situ Thermal Treatment (ISTT), Soil Vapour Extraction (SVE), Enhanced Bioremediation & Monitored Natural Attenuation (MNA)

ISTT involves applying heat to assist in the removal of chlorinated solvents by either hot air injection, steam or electrical heating and can be undertaken in a short timeframe from weeks to months thus meeting objective 2 (Defra, 2010). In geologies where contaminants are present in low permeability layers, technologies like electrical resistance heating (ERH) and thermal conductive heating (TCH) can deliver heat directly to the low permeability layers. TCH has the ability to be flexible with depth of application but can require intensive drilling and has a large energy demand (Kueper et al, 2014) (source 3- objective 1).

ISTT can be coupled with other techniques such as enhanced bioremediation, which is usually a benefit which results from ISTT due to increased temperatures. Changes in the redox conditions after ISTT can increase the amount of dissolved organic carbon or water soluble organics in the aquifer. An increase in dissolved organic carbon can help stimulate biological activity as long as appropriate dechlorinating bacteria are present (Kueper et al, 2014). ISTT would break the linkage of residual chlorinated solvents (source 1- objective 1) adding to the plume by targeting the source and MNA would be required to ensure continued reductive dechlorination of the remaining groundwater plume (source 2- objective 1). Initial monitoring would be frequent becoming less as time series data proved that concentrations were on a continual down ward trend so cost effective monitoring could be achieved (objective 4).

A thermal treatment and SVE unit would require quite a large footprint, equipment could be brought in on a process trailer which will contain heating modules, vapour collection, back up generator, control cabins and monitoring system. It has the potential to be sited in a more appropriate area although connections and pipework would still need to be trailed into the source area (US EPA, 2004). ISTT and SVE have been applied at many dry cleaning shops and industrial sites where chlorinated solvent contamination is present so would fit a TRL of 7 in its application (objective 5). Waste streams generated are small such as SVE filters and the remediation would not require any renewal of consumables or active systems going into Interim C&M meeting objective 3 (US EPA, 2004).

3. Permeable Reactive Barrier (PRB)

A PRB prevents or reduces contaminant flux whilst allowing groundwater to flow through a barrier by either immobilising or transforming contaminants (EA, 2002). A PRB would address the dissolved phase plume (source 2- objective 1) and the higher contaminated sub soils at the ATB in the vadose area which are continually adding (source 1- objective 1) to the plume by intercepting them through the PRB. Due to the depth of the DNAPL and presence in fractures (source 3- objective 1) at around 25m beneath the ATB means installing a PRB at this depth would be difficult. Techniques such as pneumatic, hydrofracturing or injection can install PRB's to depths of >30ft (Interstate Technology & Regulatory Council (ITRC), 2011). Zero valent iron (ZVI) would be injected to form a PRB so as dehalogenation could occur as the chlorinated solvents pass through the barrier. Previous laboratory and full scale field applications show some ZVI PRBs have retained performance for 10 or more years. However, at some sites where injection methods have been employed decline has been relatively fast with reactive performance declining within 1–5 years (ITRC, 2011).

A PRB would need to be installed 50m down gradient of the source boundary so as it intercepts contaminants as they migrate in the dissolved phase plume (objective 1). Installing a PRB within the car park would cause less disturbance and would only require temporary relocation of car parking. The Environment Agency's screening criteria sheet for guidance on PRBs has been utilised and has shown that a PRB for the Chapelcross solvent plume fulfils the criteria as shown in Appendix 3 (EA, 2002).

A PRB would require minimal maintenance during C&M, although the media within the PRB would need replacing at some point and would need monitoring to check its performance (objective 3 & 4). More than 200 PRBs have been implemented since the early 1990's (ITRC, 2011) and over 80 pilot and field scale PRBs have been implemented in North America, Europe and the UK, therefore a TRL of 7 is considered suitable for this remediation strategy (EA, 2002 & CLU-IN, 2012). Although remediation by PRB takes longer than other remediation strategies it would be protective of receptors once installed and could be installed by the Interim C&M date (objective 2).

4. In Situ Chemical Reduction (ISCR), Enhanced Bioremediation & Monitored Natural Attenuation (MNA)

In situ soil mixing of ZVI and clay would address the highly contaminated sub soils in the ATB area, demonstrably breaking this linkage (source 1-objective 1) (Kueper et al, 2014).

The mixture of ZVI and clay would result in a permeability reduction by more than 99%, which would minimise the contaminant flux to the surrounding groundwater. The treatment results in two benefits, in that the ZVI degrades the chlorinated solvents and soil mixing with bentonite reduces permeability isolating the treated source zone soil from surrounding groundwater (Colorado State University, 2012).

ISCR can be fast and treat high concentrations but requires some soil removal prior to soil mixing but could still meet the C&M date (objective 3) (Kueper et al, 2014). In order to break the linkages of the dissolved phase plume (source 2) and DNAPl at depth (source 3) enhanced bioremediation would be applied. A trial using Regenesis 3DMe at Chapelcross has already been undertaken in the groundwater (section 4.1.2). Electron donor addition of Regenesis 3DMe to the groundwater has shown that changes suggest that an enhanced rate of natural degradation is occurring. A good lateral dispersal of 3DMe has occurred around 10m. This shows that through a combined strategy all sources could be remediated (objective 1) (Regenesis, 2015 & Kueper et al, 2014) ensuring that a satisfactory land condition is met by 2017 (objective 2).

Monitoring would be required throughout the remediation and for some years after. More intensive monitoring would be required in the first few years to ensure parameters are kept at there optimum for enhanced bioremediation. In order for *Dehalococcoides* to undertake reductive dechlorination a pH of above 6 is required (Kueper et al, 2014). At Chapelcross Site pH values of above 6 have been measured (Hyder, 2013). Dissolved ethene would need to be measured to show that complete dechlorination is occurring and once a continual downward trend has been established (objective 4) monitoring would be able to be reduced.

A TRL of 7 can be considered suitable for this remediation strategy as ISCR and ISB agents have been researched and developed in recent years with it being implemented in Europe, UK and USA (objective 5) (Huff, 2011, US EPA, 2000 & Kueper et al, 2014). The application of ZVI has matured with enhancements made to its reactivity, longevity and delivery (Kueper et al, 2014). Enhanced bioremediation has been adopted by companies such as Regenesis and is mainly used as a polishing technology where more aggressive approaches have been applied such as ISCR to high concentration source zones (Kueper et al, 2014).

5.Surfactant/ Co-solvent Flushing & In Situ Chemical Oxidation (ISCO)

Surfactants and co-solvents are good for enhancing solubility of DNAPL to the aqueous phase where ISCO can then rapidly destroy it as discussed in section 2.9.8 of the literature review (CL:AIRE, 2015). Achieving sufficient hydraulic control during such a strategy is important to ensure that untreated DNAPL does not escape to uncontaminated areas and beyond the site boundary. This requires detailed data to design a system that delivers the correct amount of surfactant to the right location whilst maintaining hydraulic control.

The incorporation of hydraulic control wells is usually required, with extraction rates typically higher than injection rates, to ensure adequate control over the injected chemicals and contaminant (ITRC, 2003).

This combined strategy could deal with source 1 and 2 by the surfactant removing the mass DNAPL and ISCO treating the dissolved phase plume. Surfactant/co-solvent flushing at the correct depths would also remove source 3 (objective 1). When combined with ISCO it would be able to rapidly remediate the contamination to meet the C&M date (objective 2).

A better understanding of the application of surfactant/ cosolvent flushing at depth at Chapelcross would be required need to ensure that further intervention is not needed during C&M (objective 3). This is required to ensure that the risk of DNAPL still being present at depth and rebounding after initial treatment does not occur (Stroo & Ward, 2010). Monitoring would have to be undertaken for several years to ensure that rebound was not occurring but could still prove cost effective over time (objective 4).

Meeting a TRL of 7 (objective 5) would not be possible as although experimental peer reviewed case studies for flush enhancing chemicals are abundant there are far fewer field based implementations which are in non peer reviewed publications (CLU-IN, 2015). The uncertainties with the hydraulic control of injected surfactants/ co-solvents and contaminants being released into non contaminated areas beyond the site boundary mean this strategy still requires further validation in a similar environment under the TRL levels and would not meet this screening objective.

Combining surfactant/ co-solvent flushing with other techniques like ISCO has gained more coverage since 2000 (Dugan et al, 2010). VeruTEK Technologies provides surfactant enhanced ISCO. It uses plant based and biodegradable surfactant/co-solvent mixtures to desorb the contaminants and solubilise them for destruction by activated oxidant. It looks like a promising technology with it being field proven in the US, Denmark and Australia and VeruTEK now requesting its first field project in the UK (section 2.9.8).

Table 8 Overview of screening of Chapelcross remediation strategies

Remediation Strategy	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5	Can constraints be met?	Can the assumptions bet met?	Through to options assessment?
1. Air Sparging & Soil Vapour Extraction (SVE) & Monitored Natural Attenuation (MNA)	Red	Red	Red	Amber	Green	Amber	Green	No
2. In Situ Thermal Treatment (ISTT) SVE, Enhanced Bioremediation & MNA	Green	Green	Green	Green	Green	Green	Green	Yes
3. Permeable Reactive Barrier (PRB)	Green	Green	Green	Green	Green	Green	Green	Yes
4. In Situ Chemical Reduction (ISCR), Enhanced Bioremediation & MNA	Green	Green	Green	Green	Green	Green	Green	Yes
5. Surfactant/ Co solvent flushing & In Situ Chemical Oxidation (ISCO)	Green	Green	Amber	Green	Red	Green	Green	No

Key:

Green	**Passes screening criteria**
Amber	**Further development/research into application of technique to site specific conditions required.**
Red	**Fails screening criteria**

4.3.4 Bradwell "North End" Remediation Overview

Bradwell "North End" (section 4.2) has already undergone remediation, this section will look at screening what other remediation strategies could have been shortlisted through establishment of objectives, assumptions and constraints. The original options assessment will be taken into account but other techniques will also be looked at, in line with current ONR and Magnox expectations. The initial remediation options assessment looked at:

1. Defer bulk management with no intervention or remediation;
2. Defer bulk management with targeted surface intervention;
3. Defer bulk management with targeted inventory reduction;
4. Defer bulk management with transport pathway reduction;
5. Defer bulk management with containment of main area with a barrier;
6. Prompt bulk removal of material, maintain and monitor so as area could be delicensed at FSC;
7. Prompt bulk management: full early remediation potentially suitable for prompt delicensing of area (Magnox, 2012).

The identified remediation strategies from this screening process are listed in table 9 and a detailed description is given on why the remediation strategy passed or failed. The original chosen remediation strategy that was implemented has automatically been included. Other remediation strategies that pass the screening process can then be directly compared by undertaking the sustainability assessment. This will determine if the implemented remediation strategy for the site was the most sustainable choice.

Due to one of the constraints that the remediation strategy should not require a large footprint for equipment and facilities, techniques such as soil washing have been screened out early on. Full excavation and disposal have also been screened out as it does not meet the constraint of minimising the creation of radioactive wastes. The LLWR has a limited capacity and undertaking full excavation of the "North End" would put unnecessary pressures on the LLWR. The costs of disposing of LLW and VLLW wastes would make this option very costly and would just mean burying the soil elsewhere. This is not in line with current ONR and Magnox expectations on radioactive contaminated land and looking at in situ alternatives other than excavation (ONR, 2014 & Magnox, 2013).

4.3.5 Objectives, Assumptions and Constraints for the "North End"

The objectives are:

1. Demonstrably break the contaminant linkages identified within the CSM (figure 10) for the "North End";
2. To provide a remediation strategy that reduces the need for further remedial intervention of the "North End" during the C&M Period and up to the FSC date of 2083 (Magnox, 2013 & 2015);
3. Remove the need for contamination controls during C&M so as access, monitoring and maintenance works in the "North End" can be undertaken during this period (Magnox, 2012 & 2013);
4. To provide cost effective monitoring so as any increase of radioactivity in soil and controlled water can be detected. (Magnox, 2013);
5. The remediation strategy needs to meet the NDA's Technical Baseline and underpinning research and development requirements of a technological readiness level (TRL) of 7 or above (NDA, 2014);
6. Meet the timescales of the accelerated date for C&M of 2015 (Magnox, 2015).

The Assumptions are:

1. Other decommissioning activities will not adversely affect the movement of surface and ground water in the area, this is of particular relevance to the turbine hall void and cooling water voids if proposals change for these to be filled (Magnox, 2013);
2. A preference has been assumed that remediation strategies will not require active systems during C&M, like pumping (in line with S-154) (Magnox, 2013);
3. If contaminated soils are left in situ until FSC it is assumed that the waste volume of contaminated material will not significantly increase* (Magnox, 2013).

** It is assumed that a remediation strategy will take into account the processes such as infiltration of rainwater and surface water runoff which could increase the spread of contamination if it is left in-situ. If the pathways are not broken, then this could increase the radioactive waste volumes to be removed at FSC.*

The constraints are:

1. The Borrow Dyke needs to be considered as a sensitive receptor from an ecological perspective;
2. The slope at the "North End" has a steep slope down before it flattens out to the outer security boundary, this could affect the access and implementation of certain remediation strategies (figure 10);
3. The generation of radioactive wastes should be minimised so as not to put unnecessary pressures on the LLWR (ONR, 2014 & Magnox, 2013);
4. The site must remain complaint with regulations throughout the full C&M period to FSC (ONR, 2014);
5. There should be no significant increases in the migration of contamination off site (ONR, 2014 & Magnox, 2013);
6. There should be no significant increase in the volume of land requiring remediation due to it being deferred (Magnox, 2013);
7. The remediation strategy cannot require a large footprint for equipment, facilities and waste, due to limited space because of other decommissioning activities occurring at the same time.

4.3.6 Screening of remediation strategies at the "North End"

1. Original Remediation implemented: Selective Excavation, removal of Original Active Effluent Discharge Line (OAEDL) and a Cover/Capping system

Excavation is still the most widely used technique for removal of radioactive contaminated soil (NEA, 2014). The aim of selective excavation was to reduce the highest levels of contamination so as to reduce the future liabilities at FSC. The activity criteria chosen was soil >200 Bq/g to be removed, which was not based on safety assessments but was considered an appropriate guide as it is the upper limit for some controlled burial sites and was agreed with senior management, ONR and EA (Magnox, 2013). The estimated volume >200 Bq/g was <100m3 of soil to ensure the constraints of waste going to the LLWR was kept in mind and the associated costs (Magnox, 2013).

The criteria of soils >200 Bq/g to be removed was an objective of the original remediation strategy but has not been included for this assessment. Currently de-licensing criteria at FSC requires soils >200 Bq/g to be removed but this could change in the period up to FSC (Magnox, 2013). The period to FSC could see many technological advancements to suitably deal with soils >200 Bq/g in a more effective manner. Guidance issued by the ONR, EA, NRW and SEPA in June 2014 since the "North End" remediation on regulatory expectations for land quality management at NLS recommended consideration of in-situ alternatives to excavation (ONR, 2014). Magnox Company Standard also highlights if the contamination is of low risk then it may be appropriate to leave in place and gain the benefits from further decay in situ (Magnox, 2013).

The NDA's preference to maintain a flexible approach and the future possibility of in situ on site disposal was another reason for removing this objective so as a more flexible approach could be considered towards other remediation techniques (Magnox, 2013). Removing the >200Bq/g criteria has enabled this process to look at what other remediation strategies which don't have to incorporate excavation could be used.

The CSM (figure 9) shows that Cs-137 and Sr-90 are present but Cs -137 has not been detected in the Borrow Dyke water and only at small amounts in the sediment. This supports surface runoff as the principal contaminant linkage (source 2, figure 10). The nature of Cs-137 tightly binding to clay, which is the case at Bradwell Site does not present a pathway of concern in sub surface waters (Demmer et al, 2012). Removing the objective of soils >200 Bq/g being excavated also reduces the risks of mobilising soil during excavation by wind and rain.

To demonstrably break the contaminant linkages (objective 1) removal of the OAEDI enabled preferential pathways that existed to be removed. A capping system removed the pathway of surface runoff, erosion by wind and spread of contamination by wildlife and reduced infiltration of rainwater. Capping systems involve placing natural earthen materials which can involve several layers of soils, non reactive materials or geosynthetic materials over the contaminated ground (EA, 2010). Geosynthetic materials and a layer of earthern material were used in capping the "North End". The cap has a life expectancy of in excess of 100 years (Golder, 2015) so no intervention during C&M is expected (objective 2). This enables contamination controls to be removed allowing access to the area during C&M (objective 3). An on going monitoring regime of boreholes, surface water and sediment in the Borrow

Dyke has been required to validate the cap and will continue for ten years at which point it will be reviewed (Magnox, 2015) (objective 4).

Selective excavation of radionuclides has been used in many countries and the UK (NEA, 2014 & Beddow, 2013). Capping and cover systems are used widely as remediation techniques (IAEA, 2014) therefore a TRL of 7 was considered suitable (objective 5). Selective excavation and capping was undertaken in a short time frame at Bradwell commencing in October 2013 and completing in July 2014, achieving the C&M date of 2015 (Golder, 2015) (objective 6).

2. Capping/ Cover System, with grouting of remaining Original Active Effluent Discharge Line (OAEDL), draw pits

A capping system has already been implemented at Bradwell but this remediation strategy removes the requirement for selective excavation and removal of the OAEDL and draw pits and has looked at grouting structures in situ to prevent preferential pathways (objective 1). A capping system would address all the objectives in the same way as remediation strategy number 1, except it would not undertake selective excavation. This would reduce the pressure on the LLWR. On site personnel, public walking by the fence during the remediation and workers undertaking the remediation would not be exposed to any risks from excavating high activity soils. The need to implement an on going monitoring regime as discussed under remediation strategy 1 would still be required but could be reduced gradually once confidence has been gained in the installed cap (objective 4).

Capping and cover systems are commonly used worldwide and within the UK especially at landfill sites (EA, 2010 & 2014). A TRL of 8 is therefore considered appropriate as the technology has proved to work in its final form and under expected conditions (objective 5). Such a system was used at Hunterston A in capping their VLLW area (Magnox, 2014) and is a very quick strategy to install so would meet the accelerated date of 2015 (objective 6). Although this strategy is similar to the remediation implemented at the site, it has been given a higher TRL as it would not involve the use of the HIRAM technology to selectively excavate radioactive soils, which has only been implemented at a few sites, unlike capping systems which are widely used.

3. Hydraulic in ground barrier and cover system

An in ground vertical barrier would contain the sub surface Sr-90 contamination (source 1) and would prevent any preferential pathways or migration via the saturated zone from the EDL and gravel lenses (source 3 & 4- objective 1). A hydraulic barrier would require the installation of catch pits or wells to collect the sub surface contaminated groundwater either for discharging via a permitted route or treatment (CIRIA, 2004). This would not meet the assumption that no active systems are allowed through C&M as it would require a continued maintenance burden.

A cover or capping system would still be required to address the surface contamination to ensure no contamination controls during C&M (objective 1 & 3). A temporary operational plant would need to be set up on the site requiring a large footprint (constraint 7). Most slurry walls have life expectancies of around 30 years or are installed with this duration in mind and monitored at 5 year intervals (US EPA, 1998). As the half life of Sr-90 is 28.8 years, a barrier may only be required for ~30 years (VanderMeulen, 2012), which should reduce the requirement for further remedial intervention during C&M (objective 2). Monitoring would still be required and the barrier would need around 5 yearly checks to ensure the integrity of it has not been compromised and is still functioning (objective 4).

A slurry wall has been previously demonstrated on other decommissioning nuclear sites such as Hunterston (Magnox, 2014) and are widely used throughout the construction industry (CIRIA, 2004), therefore a TRL of 7 is considered suitable (objective 5). Installation would meet the timeframe required for Bradwell site C&M date (objective 6). The steep slope at the "North End" with the limited space to the OSB fence means access for installing a hydraulic barrier would be limited and permissioning would be required over the Site of Special Scientific Interest (SSSI) outside the OSB (constraint 1 & 2). The constraints of the Borrow Dyke as a sensitive receptor and the SSSI Blackwater estuary mean that permissions would be required from Natural England for access which could affect the achievement of objective 6. European protected species such as reptiles and great crested newts are present in the area so breeding seasons would need to be avoided which could add delays to commencing the works (objective 6) (Natural England, 2015).

4. Phytoextraction

Phytoremediation is the use of plants to extract, degrade or contain contaminants from the soil or groundwater (Watt et al, 2002). Phytoremediation would reduce source 2 and the impact of the pathway of surface runoff, erosion by wind and spread by burrowing wildlife as the root system of the plants would hold soil together. Sr-90 in sub surface water and Cs-137 in soil would be reduced by uptake through root systems (source 1, 3 and 4) (objective 1). No active systems would be required throughout C&M but contamination controls would still be needed for access and maintenance works to harvest the biomass and associated waste disposal costs (objective 3- not met). No space would be required for equipment and facilities, except for when harvesting biomass and waste disposal.

Monitoring of the sub surface water and borrow dyke would be needed throughout C&M to ensure phytoremediation was consistently removing contaminants. Monitoring would be required for a longer duration due to phytoextraction being a slow technique (Demmer et al, 2012) and at regular intervals so would be less likely to be cost effective due to the duration (objective 4 not met). The trials undertaken at Bradwell site only looked at Cs-137 removal rates so more trials would need to be done into the Sr-90 removal (Watt et al. 2002).

More recent studies undertaken in 2012 using *Cannabis sativa* showed that it can absorb strontium with most absorption occurring in the roots. Observations noted that caesium did not reach the plant because of its inactive complex formation (Hoseini et al, 2012). The possibility that another remediation technique may have to be implemented during C&M is higher due to more investigative trials being required to gain further confidence in phytoextraction. Additional requirements such as chelating agents may be required to help removal rates. Controlling the release of contaminants in line with phytoextraction removal rates to ensure contaminants do not go beyond the site boundary would require hydraulic controls which would increase the costs of this strategy quite considerably (Hazen & Tabak, 2005) (objective 2 could be compromised).

Previous phytoextraction trials have been undertaken at Bradwell site, Cs-137 removal rates were limited due to the strong adhesions to the clay (Demmer et al, 2012). Further trials would be required to investigate the success of increasing the availability of Cs-137 to the plant and over what timescales. The US EPA and CLU-IN website (Pivetz, 2001 & CLU-IN, 2015) show examples of phytoextraction but due to its limited success in trials at Bradwell a TRL of less than 6 is considered appropriate at the current time (objective 5). Phytoextraction would not meet the accelerated C&M entry date as it is a long term remediation option and still requires further laboratory and pilot scale investigation before implementing at a full scale level (objective 6).

5. Permeable Reactive Barrier (PRB) and cover system

A PRB as described under the techniques for Chapelcross site is a barrier that can immobilise or transform contaminants (EA, 2002). A PRB is the passive capture operation and in the case of the "North End" would minimise the need for active systems during C&M (IAEA, 2014). A cover system would need to be installed to break the pathway of surface runoff, erosion and spread by wildlife and it would remove the requirement for contamination controls over the area during C&M (objective 3).

The PRB would contain a zeolite called *clinoptilolite* to remediate any sub surface Sr-90 that migrates through the barrier via ion exchange (source 1 ,2 & 3). Zeolites are used extensively as ion exchange media in existing wastewater treatment systems at nuclear sites and have been extended for use as media within PRB's treating radionuclides within groundwater. *Clinoptilolite* in particular displays a strong selectivity for the radionuclides, especially Sr-90 by ion exchange (Rabideau et al, 2005).

The case study discussed in the literature on the use of zeolites in a PRB showed how they were effective at removing Sr-90 (VanderMeulen, 2012). Infiltration of rainwater and migration via preferential pathways would be captured at the point of the PRB allowing for all the linkages to be demonstrably broken (objective 1). Suitably positioned boreholes and sampling locations in front, within the PRB and beyond would be vital in ensuring its effectiveness. The initial monitoring would need to be frequent but would be reduced once performance was demonstrated, reducing the costs of monitoring over time (objective 4). The media within the wall would have to be checked every 15-20 years (Misaelides, 2011 & VanderMeulen, 2012) to identify if and when it needs replacing. Some maintenance requirements would be needed during C&M but would fulfil objective 2 as it is unlikely that another remedial technique would need to be implemented on top of this strategy.

As discussed under the Chapelcross remediation options a TRL of 7 (objective 5) is considered suitable for PRB's, although limited PRB's have been installed to deal with radioactive contaminants the experience and examples represent that it can be technologically achieved to a robust level. Constraint 1 would prevent this strategy from meeting the timescales required for C&M entry (objective 6) and constraint 2 would mean implementation and access rights required would also delay the timescales. The Environment Agency's screening criteria sheet for guidance on PRBs has been used and discounted a PRB on the basis of timescales, effects on the SSSI, access restrictions and uncertainty over the acceptability of regulators (Appendix 2- EA, 2002).

6 & 7. In situ stabilisation (vitirification or cement)

In situ stabilisation can be undertaken by vitrification using electrical power to heat and melt contaminated soils to form a glass product or by binding/mixing contaminated soils with cement or chemicals to make a less mobile form (IAEA, 2014). Pathways of surface runoff, erosion and spread by burrowing animals would be removed and preferential pathways would be broken once soil was stabilised or vitrified (objective 1). Space would be required to accommodate equipment and plant which would take a long time to install and commission. Stabilisation by cement or chemical binders would require less space. Both techniques would need to ensure that they stabilise the surface layer of soil as well as sub surface soil so as objective 3 can be met. Stabilisation would reduce the need for further remedial intervention during C&M by fixing the contamination in situ (objective 2).

The strategy would require a groundwater monitoring regime for some time throughout C&M to establish that the strategy has worked effectively and no deterioration of the stabilised soils occurs. The frequency may be reduced over time but ground integrity inspections would be required to ensure the strategy is still demonstrably breaking the contaminant linkages (objective 1 & 4).

The US Department of Energy has shown that stabilisation bench scale tests have been effective using Polyethylene Encapsulation of caesium, strontium, cobalt and heavy metals (PERM) (CIRIA, 2004). The majority of stabilisation techniques occur ex-situ and stabilisation of contaminated soils and wastes has been used most widely in the USA and some EU member states. It is not readily used in the UK, partially due to uncertainty over durability and potential contaminant release (EA, 2004). A TRL of 6 has been given for in situ stabilisation and vitrification. Stabilisation has been used in the UK but would still require further trials in order to see if it was suitable for implementing at Bradwell site (objective 5). This would extend timescales which would not meet the C&M date (objective 6). No full scale field implementation has been achieved for vitrification and factors such as moisture content can affect the energy demands and cost to convert contaminated soil into a glassy product (IAEA, 2014 & CIRIA, 2004).

8. In situ electrokinetic remediation

Electrokinetic remediation can desorb radionuclides from soil in situ and is undertaken by installing electrodes with a DC current into the ground. It is most effective in clay soils, which are present at Bradwell, due to the negative surface charge and high moisture content (IAEA, 2014). Cs-137 and Sr-90 could both be removed by this remediation strategy, although preferential pathways may affect the implementation of the technology. The remaining OAEDL and other underground services containing insulating or metallic material would affect the electrical conductivity of the soil (pathway 3) (CIRIA, 2004 & IAEA, 2014). Electrodes would remove the Sr-90 and Cs-137 from the soil, breaking the pathways of migration via rainwater, surface runoff, erosion by wind and burrowing animals (pathways 1,2,4 & 5) (objective 1).

Removing all the sources of contamination by electrodes means objective 2 is met as no further intervention during C&M would be required and contamination controls could be removed (objective 3). Monitoring of sub surface water and the borrow dyke would still need to continue for a period of time after completion of the remediation to verify that Cs-137 and Sr-90 has been removed to acceptable levels. It would be able to be reduced over time so could provide cost effective long term monitoring (objective 4).

Electrokinetic remediation has not been demonstrated in the UK but applications in Europe have occurred and it is licensed in the USA (IAEA, 2014). Defra listed electrokinetic remediation as an emerging technology with growing availability but there have been few field scale case studies which make it a high risk strategy therefore on this basis a TRL of 5 has been given (objective 5) (Defra, 2010). Electrokinetic remediation timeframes based on the limited applications and case studies means that it would not meet the accelerated C&M date for Bradwell (objective 6).

Table 9 Overview of screening of Bradwell remediation strategies

Remediation Strategy	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5	Objective 6	Can constraints be met?	Can the assumptions bet met?	Through to Options assessment?
1.**Automatically included:** Selective Excavation, removal of OAEDL and a Cover/Capping system									Yes
2.Capping/ Cover System, with grouting of remaining OAEDL, draw pits									Yes
3. Hydraulic in ground barrier and cover system									No
4. Phytoextraction									No
5. Permeable Reactive Barrier and cover system									No
6. In situ stabilisation (Vitrification)									No
7. In situ stabilisation (Cement)									No
8. In situ electrokinetic remediation									No

4.4 Sustainability Assessment Process for Bradwell and Chapelcross Site

4.4.1 Objective of the Sustainability Assessments.

The objective of the sustainability assessments is to determine the most sustainable remediation option for Chapelcross and Bradwell Site. The remediation strategies brought forward for sustainability assessment are those capable of meeting the objectives, assumptions and constraints (table 7 and 8).

The remediation strategies for further assessment at Bradwell site are listed below and the key associated activities under each are summarised:

<u>Bradwell</u>

Option 1 - Original Remediation implemented: Selective Excavation, removal of OAEDL and a Cover/Capping system (Magnox, 2015).

- Selective excavation of >200Bq/g soils from the vicinity of the EDL, trench, South and West side of the trench.
- Monitoring of soils over Hi-ram technology in 1 tonne bags to determine disposal route. Soils which are <200Bq/g (VLLW) and geotechnically suitable are to be re-used as backfill. Soils >200Bq/g (LLW) are to be disposed of to the LLWR.
- Grouting and removal of remaining OAEDL structure by excavation and monitoring via 1 tonne bags over Hi-ram technology.
- A capping/cover system to be laid over remaining surface soils incorporating a low permeability geomembrane.
- Monitoring regime to be established for capped area and area outside the side boundary including the Borrow Dyke for throughout C&M.
- Maintenance regime will be required to inspect the cap system throughout C&M.

As Bradwell site has already undergone remediation with option 1, this allows for actual data already available from this remediation to be used within the sustainability assessment.

Option 2 - Capping/ Cover System, with grouting of remaining OAEDL, draw pits

- Grouting of remaining OAEDL line in situ.
- A capping/cover system to be laid over remaining surface soils incorporating a low permeability geomembrane.
- Monitoring regime to be established for capped area and area outside the side boundary including the Burrow Dyke for throughout C&M.
- Maintenance regime will be required to inspect the cap system throughout C&M.

Option 3- "Status Quo"
- As described in chapter 3.

<u>Chapelcross</u>

The remediation strategies brought forward from the Chapelcross screening process are listed below and the key associated activities under each are summarised:

Option 1 - In Situ Thermal Treatment, Soil Vapour Extraction, Enhanced Bioremediation & Monitored Natural Attenuation

- Mobilisation and set up of thermal treatment unit on the site.
- Installation of wells to apply thermal treatment.
- Installation of SVE units to wells.
- Demobilisation of plant off site.
- Monitoring of indicators to prove bioremediation is occurring.
- Monitoring regime to be established.

Option 2 – In Situ Chemical Reduction, Enhanced Bioremediation & Monitored Natural Attenuation

- Mobilisation of in situ soil mixing equipment to site.
- Application of ZVI and clay via in situ mixing to ATB soil area.
- Application of 3DMe via borehole wells spaced at 10m over dissolved plume area.

- Monitoring regime to be established to monitor parameters for MNA.

Chapelcross site has undertaken trials with 3DMe, so this strategy has a slight advantage as it has shown to have a positive effect from monitoring data. The other short listed options will rely on literature and case studies to score them.

Option 3- Permeable Reactive Barrier

- Mobilisation of equipment to site.
- Pneumatic or hydrofracturing/injection and installation of split winged casing to control the direction and pathway of the PRB wall (ITRC, 2011)
- Application of ZVI pumped slurry into boreholes (slurry pumped through the split winged casing makes the soil separate creating an iron treatment zone) (ITRC, 2011)
- Monitoring boreholes to be installed to monitor PRB performance.

Option 4- "Status Quo"

- As described in chapter 3

4.4.2 Bradwell Stakeholders and Engagement

The stakeholders that have been involved in the Bradwell "North End" remediation are the ONR, EA, Magnox Lead Team and Technical Specialists. All of these parties were involved in the remediation development proposals through to implementation. The remediation of the "North End" involved many technical meetings so as stakeholders agreed the remediation approach. Wider stakeholders such as the local community were not directly involved in the decision process but communications were made via regular Site Stakeholder Group Meetings that Bradwell puts on locally to let local people and neighbours know what is occurring and so they can air their concerns and ask questions.

This sustainability assessment will not involve any direct discussions with stakeholders but will take into account their views and opinions as summarised below. This will also be accounted for by applying different weightings to the chosen SuRF UK indicators to show how this could affect the sensitivity of the remediation strategy.

ONR:

To ensure that the site is compliant with its LC's for going into C&M and throughout the period until FSC. Substantiation and documentation as to how the remediation has met the Safety Case requirements and Independent Nuclear Safety Assessment must be undertaken to confirm this (Magnox, 2013).

EA:

To ensure that the local environment and receptors are protected from any pollution on the site (Magnox, 2013). To ensure the site is compliant with EPR2010 and if radiological waste is excavated and re-used in situ as an accumulation this must be with the intention to take further action and removal at FSC. The ONR have joint involvement with the EA in terms of agreeing stakeholder interests as the ONR will want to ensure that possible burdens on future generations are reduced as well as the existing liabilities at the site (ONR, 2006).

Magnox:

To ensure a remediation strategy is chosen that keeps the site compliant with regulations throughout C&M into FSC with minimal intervention required during the C&M period at value for money.

Local Community:

The Local Community would want a remediation strategy to be protective of the local environment but not cause unnecessary disturbance or inconvenience to the surrounding community and visitors.

4.4.3 Chapelcross Stakeholders and Engagement

The stakeholders that have been involved in the Chapelcross solvent plume remediation are SEPA, Dumfries and Galloway Council and Magnox.

SEPA:

To ensure that the water environment is being protected from any pollution on the site and ensure the site is compliant with regulatory requirements under Part IIA (SEPA, 2009).

Dumfries and Galloway Council:

Dumfries and Galloway Council are the lead regulator in terms of Part IIA and will have interest in contaminated land within the area for non special sites. They will want timely implementation of the remediation strategy to agreed remedial standards.

Magnox:

To ensure a remediation is chosen that keeps the site compliant with regulations throughout C&M with minimal intervention required during the C&M period at value for money.

Local Community:

The remediation should not be detrimental, cause disturbance or inconvenience to the surrounding fields, owners, local community and visitors to the area.

4.4.4 Sustainability Assessment Boundaries for Bradwell "North End"

This section will establish the boundaries for the assessment of space, time and component lifecycle as defined below (CL:AIRE, 2010).

Spatial Boundary: This assessment will look at the benefits/ impacts to the Bradwell site and surrounding area of the site, including the Borrow Dyke, neighbouring land and residents. It will consider the extent of wider impacts/benefits to LLWR and landfills where remediation involves excavation.

Time: This has been limited to the timescales of meeting the C&M date of 2015, acknowledging that monitoring will go beyond this (Magnox, 2013).

Each remediation strategy will have different durations of monitoring, which will affect the overall costs. Cost estimates for each option will include any long term monitoring costs, which will be reflected within the NPV and included under the economic pillar of the sustainability assessment. The same will apply for Chapelcross Site.

Component Lifecycle: The assessment will need to include the manufacture, mobilisation of plant and equipment to site and any demobilisation of equipment and facilities prior to C&M entry.

Equipment will remain within the radiological controlled area until it is not required, to avoid unnecessary decontaminaton and recontamination of items. Only plant or equipment which is explicitly required for the works can enter the radiological area, so as to avoid un necessary decontamination and radiological disposal costs if decontamination is unsuccessful.

Where equipment is coming in direct contact with radioactive soil, such as digger buckets then some assumptions will be made within the cost estimate to purchase certain pieces of equipment. This will avoid an upfront hire cost and then a full purchase cost at the end if decontamination is not successful on certain pieces of hired equipment and they have to be disposed of as radiological waste. Items of plant like the HIRAM are more easily protected by raising off the ground and soil is contained within suitable bags to prevent contamination.

4.4.5 Sustainability Assessment Boundaries for Chapelcross Solvent Plume.

This section will establish the boundaries for the assessment of space, time and component lifecycle as defined below (CL:AIRE, 2010).

Spatial Boundary: This assessment will look at the benefits/ impacts to Chapelcross site and the surrounding area of the site, including the Gullielands Burn, neighbouring fields, land and residents. It will consider the impacts for on site works due to the proximity of the remediation located on the main entrance to the site.

Time: This has been limited to the timescales of meeting the Interim C&M date of 2017, acknowledging that monitoring will go beyond this (Magnox, 2013).

Component Lifecycle: The assessment will need to include the manufacture, mobilisation of plant and equipment to site and any demobilisation of equipment and facilities prior to Interim C&M date.

4.4.6 Bradwell and Chapelcross Site Sustainability Assessment

In order to undertake the sustainability assessment a developed version of the URS spreadsheet was used for both sites (table 10 & 11). The table will include the SuRF UK categories and chosen indicators with justifications for their inclusion or exclusion from the assessment process. SuRF UK categories have only been excluded where there is a clear reason that options would score similarly or certain categories may already be covered under others, so as to avoid double accounting of scores against options.

Weights were applied taking account of stakeholder views and options were then scored against a scale of 0-100. The direct economic cost indicator within each sustainability table has used the NPV for each option. The NPV was calculated from cost estimates generated, which are presented in section 4.4.7 & 4.4.8. For Bradwell site additional quantitative data was available for the indicators of Environmental 1- Emissions to air, Environmental 5 – Minimisation of waste generation and Social 3- Disturbance from increased traffic movements. This was due to actual data available from the implemented option 1 at the site.

The qualitative scores, quantitative data and weights were modelled within the Hiview MCDA software to obtain an overall weighted score for each option, these results are shown in section 5.1 & 5.2.

Table 10 Sustainability Assessment for Bradwell Site "North End"

SuRF Category		Justification for inclusion/ Exclusion of category	Weight	Indicator to evaluate options	Qualitative Scores 0= Very Poor/ 25= Poor/ 50= Good/ 75= Very Good/ 100= Excellent Quantitative figures Those with * (see note *1)			Justification for Score	Uncertainties/ Assumptions
					Option 1	Option 2	Option 3		
Environmental									
ENV1	Air	Included, different remedial options will have differing impacts on emissions to air. The DEFRA Greenhouse Gas conversion factors will be utilised for this indicator (DEFRA, 2014). Weighted 60 as other categories within the Environmental pillar are considered of higher importance. Other activities at the site will also contribute to emissions to air so the "North End" remediation would not solely be responsible for this indicator.	60	Emission of pollutants to air from vehicular moves to and from the site (CO2e measurement of carbon dioxide equivalent)	14.82*	1.75*	0*	Appendix 13 shows the emissions to air (co2e) from vehicles coming to and from the site for waste disposals and capping materials. Option 1 is has the worst total emissions at 14.82 tonnes of CO2e being generated from remediation. Option 2 is better in terms of CO2e emissions as it does not involve the waste disposal that option 1 does and would create 1.75 tonnes of CO2e. Option 3 would score the best as no movements for waste or remediation materials would be required for the near /short term however if intervention was required during C&M this would change (Defra, 2014). (Figures account for co2e generated from vehicles coming to and from site for waste disposal and capping materials, does not include other machinery such as excavators and fork lift trucks as difficult to get an accurate measurement on the amount of co2e generated from these).	
ENV 2	Soil and ground conditions	Not included as the condition of the soil and its geotechnical properties will automatically be included in any remedial design so as to be protective of constraint no 1 & 2.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ENV 3	Groundwater & Surface Water	Included, some of the processes in the different remediation strategies could temporarily mobilise contaminants affecting sub surface and surface waters (constraint no 1) Weighted 100 because the main aims of the key stakeholders EA, ONR and Magnox is that the local environment and receptors are protected going forward into C&M. The local community would also want to know that local habitats and environment are being protected for their own recreational use and enjoyment.	100	Local environment - Prevention or reduction of contaminants to surface water and sub surface water now and in the future Limit mobilisation of contaminants during remediation	65	70	0	Option 2 scores the highest with a score of 70 as it would involve minimal mobilisation of contaminants during remediation with only anchor trenches being dug and minimal removal of legacy waste from the surface of the area. Installing a cap will remove the primary pathway of surface run off and reduce sub surface flow (figure 10, pathway 1 & 2). Grouting the OAEDL will remove any preferential pathways (figure 10, pathway 3) protecting the Borrow Dyke going. Option 1 scores slightly lower at 65 as during excavation works there was an increased chance for contaminants to become mobilised at the surface and sub surface of the area. This could lead to a temporary flux in future monitoring data until conditions stabilise. This is likely to be only minimal and short term. The cap would be protective of the local surface and sub surface waters as described for option 2. Option 3 has been scored poorly at 0 as although no mobilisation would be created by remediation the main pathway of surface contamination would still remain for throughout C&M. Future erosion and periods of heavy rain could lead to more contamination entering the Borrow Dyke. The infiltration rate of water to the sub surface would not reduce the risk of Sr-90 entering sub surface waters (Figure 10).	
ENV 4	Ecology	Not included, the remedial options (except option 3 "status quo") will all be intrusive of the area with installing a cap. All flora and fauna within the area will need removing prior to any of the options being initiated and a reptile survey will be undertaken prior to any vegetation removal. This will automatically be included within any remediation choice.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ENV 5	Natural resources and waste	Included, remediation options differ in use of resources and creation of waste and disposal routes (constraints no.3) Weighted 90 because Magnox has an overall responsibility to minimise creation of high activity wastes in line with BAT and so as to limit pressures on the LLWR. EA will also have an interest in ensuring that all wastes have a permitted disposal route and that use of natural resources within the remediation is sustainable.	90	Minimisation of waste generation and impacts on VLLW/ LLW and conventional disposal sites.	449.52*	28.01*	0*	Option 3 "Status Quo" scores the best in terms of having little impact on waste generation and resource use. There would be no creation of LLW/ VLLLW or conventional wastes if nothing was done in the short term and no impacts on resources such as aggregate having to be brought to site for capping works. Option 2 does not involve a large generation of waste, just from anchor trenches for the cap which totalled 22.98 tonnes and removal of legacy waste from the area which totalled 10.7 tonnes = 28.01 tonnes total (Figures taken from excavation of just anchor trenches for option 1 - Appendix 10 & 12 for VLLW and conventional waste). Option 1 totalled 449.52 tonnes of waste generated (Appendix 10, 11 & 12- VLLW/ LLW/Conventional waste). A total of 476 x 1 tonne bags were geotechnically unsuitable VLLW which could not be re-used as an accumulation in situ on site and had to be sent to Augean, East Northants Facility for direct burial (LLW Repository, 2012).	

Notes
***1 - Quantitative data will be used for category Env 1, Env 5**
Figures with a * have an inverse score, so the lower the figure the better the option

Options
Option 1 - Automatically included: Original Remediation implemented: Selective Excavation, removal of OAEDL and a Cover/Capping system
Option 2 - Capping/ Cover System, with grouting of remaining OAEDL, draw pits
Option 3- "Status Quo"

Table 10 (continued) Sustainability Assessment for Bradwell Site "North End"

SuRF Category		Justification for inclusion/ Exclusion of category	Weight	Indicator to evaluate options	Qualitative Scores 0= Very Poor/ 25= Poor/ 50= Good/ 75= Very Good/ 100= Excellent Quantitative figures Those with * (see note *1)			Justification for Score	Uncertainties/ Assumptions
					Option 1	Option 2	Option 3		
Economic									
ECON 1	Direct economic costs and benefits	Included as remediation strategies will have varying costs. Objective 4 cost effective monitoring will be included in the NPV by estimating the number of out years monitoring required. Weighted 100 as Magnox will want to ensure the remediation is value for money but also protective of the receptors identified in the CSM.	100	NPV Costs- Total Discounted cost over the continuing life of the remediation	£2,034,156*	£1,136,736*	£659,793*	Calculation for NPV shown in Table 20 and Appendix 7	
ECON 2	Indirect economic costs and benefits	The land will not be able to be sold on after remediation as there are no plans to reduce the license site boundary until FSC so no economical benefits would be directly dependent on the strategy employed.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ECON 3	Employment and employment capital	Included, different remediation options provide different degrees of innovation and opportunities for education/ training. Development of new skill sets can help make people employable in similar remediation roles at other sites in the future (Bradwell objective no. 5- TRL). Weighted 40 as although it helps to have resources developing new skills it is not the main aim of the remediation strategy but enables future works of a similar nature to be accepted more readily if already proven at another site and the skilled/ experienced people at available.	40	Opportunities for new skills and training development	65	50	0	Option 1 scored 65 as the remediation of radioactive contaminated land using Nuvia Hiram monitoring equipment has not been undertaken at many nuclear sites in the UK and enabled staff and contractors to gain valuable skills and knowledge required in order to remediate radioactive land on an accelerated decommissioning site. These skills will be transferable to other nuclear decommissioning sites which may have similar contamination to remediate. Option 2 scored 50 as although it would be good at providing experience in remediating radioactive land it is less than option 1 as installation of a capping system would only involve anchor trenches being installed which would not require the Nuvia Hi-ram as smaller volumes would be generated and these would largely be outside of areas where LLW was identified. A capping contractor would undertake a large proportion of the works in a short time frame limiting job opportunities.	
ECON 4	Induced economic costs and benefits	Not included as the land will not be able to be sold on even once remediated as further work will be required at FSC before the land can be delicensed. The induced economic costs and benefits are not dependent on the type of remediation.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ECON 5	Project lifespan and flexibility	This category has been included because the remediation will need a degree of flexibility within the constrained timeframe if difficulties arise so as to meet Bradwell objective 2 of reducing the need for further intervention during C&M. Weighted 60 as not the main aim for stakeholders but it gives them the confidence that possible contingency measures have been considered prior to implementing the scheme.	60	Ability of remediation to change to circumstances, increasing scope of works.	30	10	15	None of the options perform particularly well for this indicator, option 1 had the greatest ability to be flexible with excavating, however with the constraints at the North End of the slope, excavation of all the hot spot areas was not possible so not being as flexible as anticipated. The total excavation of the OAEDL line also showed that only two 1 tonne bags of LLW (0.95 tonnes) (Appendix 11) were removed in total so the project could have been more flexible if more upfront site investigation of the OAEDL line had been undertaken. Investigative holes could have been drilled through the OAEDL to the base underneath to confirm if this needed to be fully excavated and could have been grouted instead. Option 2 would not be very flexible and has scored 10 as just installing a cap means that when digging the anchor trenches for the cap if any abnormalities are found then an alternative plan would not be in place for excavating areas and may delay the remediation if different waste routes need to be looked at and set up. Option 3 scored slightly better with 15, still poor but by doing nothing means if suddenly during C&M further intervention was needed (objective 2) then at least the area would still be a blank canvas and not have a cap to contend with prior to undertaking any other works.	

Notes
***1 - Quantitative data will be used for category Econ 1**
Figures with a * have an inverse score, so the lower the figure the better the option

Options
Option 1 - Automatically included: Original Remediation implemented: Selective Excavation, removal of OAEDL and a Cover/Capping system
Option 2 - Capping/ Cover System, with grouting of remaining OAEDL, draw pits
Option 3- "Status Quo"

Table 10 (continued) Sustainability Assessment for Bradwell Site "North End"

SuRF Category		Justification for inclusion/ Exclusion of category	Weight	Indicator to evaluate options	Qualitative Scores 0= Very Poor/ 25= Poor/ 50= Good/ 75= Very Good/ 100= Excellent Quantitative figures Those with * (see note *1)			Justification for Score	Uncertainties/ Assumptions
					Option 1	Option 2	Option 3		
Social									
SOC 1	Human health and safety	Included, remediation options all have varying degrees of radiological and conventional safety especially where excavation and heavy duty machinery is involved in tight spaces. The long term impacts and protection of risk to the public is important and will need to be protective through C&M to FSC (objective 2) which is why the category has been weighted 100.	100	Worker Safety (radiological) Worker Safety (other conventional safety issues) Public Safety (long term risk)	45	75	25	Option 2 scores the highest at 75 as the remediation strategy would not involve any excavation of hot spots so would limit radiological exposure to workers. It would reduce the amount of heavy machinery being used in a tight area as only anchor trenches would need digging. No large open excavations would occur reducing the conventional safety risks for workers. The long term risk to public safety from surface mobilisation of contamination (figure 10, source 2 & pathway 2) would be removed with the cap being installed . Option 1 scored 45 as this strategy involved incredibly tight working spaces during its implementation in wet periods of weather where workers were near moving vehicles and excavations. Worker dose would have been higher from the hot spot removal than for option 2 although waste soil bags were removed as quickly as possible from the area. Option 3 "Status Quo" scores 25, conventional worker safety would be good and the worker safety radiologically would be minimal. it would still require workers to access and maintain the area putting them at risk to surface contamination over a longer period. The risk of spreading surface contamination to the public long term if nothing was done could also increase especially from erosion and heavy periods of rain.	
SOC 2	Ethics and equality	Included, options differ in their approaches to what will be left for future generations to deal with. Weighted 90 as the need to ensure what will be passed onto future generations is managed, controlled and well documented until FSC (68 years time). The ONR will want to reduce liabilities as much as possible. No new problems should be created from poor management now for future generations to have to resolve. (Bradwell constraint no.5, assumption no. 3 and objective no.4).	90	Avoid transfer of issues to future generations	40	25	0	Option 1 scored the highest at 40 as the selective excavation undertaken at the site removed higher activity LLW from the ground which will reduce the amount of legacy until FSC. A total of 22.08 tonnes of LLW was removed equating to 34 x 1 tonne builder bags (Appendix 11). The initial estimates that had been predicted for removal of LLW from the area was 286 tonne of LLW equating to 159m3 (Appendix 11). This is a lot less than the original estimate so a score of 40 was given as although its reduced the inventory of LLW in the ground and would go towards the interests of the ONR wanting to reduce burdens on future generations it has not removed as much as it could have. This is down to one area adjacent to the Forebay shafts (figure 8), not being fully excavated due to it being a narrow area on the very steep slope that was dangerous during wet periods when works were undertaken. Option 2 scored 25 as it would not reduce any of the legacy to be left until FSC as no excavation would be undertaken, only a cap. Option 3 scored 0 as "Status Quo" approach would actually increase the long term care and legacy if surface contamination was further spread during C&M this could lead to a larger area affected by contaminants at FSC to be remediated.	
SOC 3	Neighbourhoods and locality	Included as there will be differences between the remediations in lorry moves to and from the site for waste and raw materials. Weighted 70 as although important does not sit as highly as worker and public safety.	70	Disturbance from increased traffic movements (lorries) within the local area during the remediation strategy (short term)	486*	366*	0*	Option 1 scored the worst because selective excavation created geotechnically unsuitable VLLW, LLW and conventional waste for off site disposal. Appendix 10, 11 & 12 show that there was a total of 48 vehicular moves for VLLW, 68 vehicular moves for conventional waste and 4 vehicular moves for LLW, the importing of the capping material involved 366 moves, totalling 486 increased traffic movements for the local area (Appendix 14). Option 2 would be marginally better in terms of vehicular moves as it would only involve the moves associated with capping materials (366) and possibly a few extra moves for materials to grout the OAEDL. Option 3 "Status Quo" would be the best overall in the short term as no vehicular moves would be required with no remediation taking place.	
SOC 4	Communities and community involvement	Not included as any effects or changes to the local community would automatically be communicated through regular Bradwell community meetings.	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SOC 5	Uncertainty and evidence	Included as the different options provide a different degree of validation/ verification of what is being left in the ground until FSC. Weighted 80 as this evidence and data will be important for FSC.	80	Requirements for validation/ verification of contamination being left until FSC	75	50	40	Option 1 scored the best as the information from the site investigation and selective excavation of hot spots has given more data in terms of what has been removed and what will be left in situ until FSC. This has been supported by the production of a verification report confirming where all LLW was removed and where VLLW or conventional waste has been used as an accumulation within geotextile markers so as this can be easily identified at FSC along with the surveyed details of locations in the verification report. The continual C&M monitoring regime will also monitor the cap and how its performing throughout C&M providing useful information for FSC (Golder Associates, 2015). Option 2 still scores a good score as the information from the initial site investigation was very detailed so will provide a useful record for FSC clearance. The C&M monitoring regime for the cap will provide useful information for FSC as well. Option 3 has scored the lowest score although not very poor as there will still be the original site investigation data which can be kept for FSC and there will be continued routine monitoring regime up to FSC.	

Notes
***1 - Quantitative data will be used for category Soc 3**
Figures with a * have an inverse score, so the lower the figure the better the option

Options
Option 1 - Automatically included: Original Remediation implemented: Selective Excavation, removal of OAEDL and a Cover/Capping system
Option 2 - Capping/ Cover System, with grouting of remaining OAEDL, draw pits
Option 3- "Status Quo"

Table 11. Sustainability Assessment for Chapelcross Site Chlorinated Solvent Plume

SuRF Category		Justification for inclusion/ Exclusion of category	Weight	Indicator to evaluate options	Qualitative Scores 0= Very Poor/ 25= Poor/ 50= Good/ 75= Very Good/ 100= Excellent				Justification for Score	Uncertainties/ Assumptions
					Option 1	Option 2	Option 3	Option 4		
Environmental										
ENV1	Emissions to air	Included, different remedial options use different techniques/ equipment which have differing impacts on emissions. Weighted 60, not as high as the other two categories under Environment as there are other activities on the site which will contribute to emissions as well.	60	Emission of pollutants to air	25	50	60	70	Option 1 scores the lowest as the supply of electricity to run a thermal treatment and SVE unit would increase emissions to the environment the most out of all the options. As well as the high energy requirements for heating the soil, the manufacture, mobilisation and demobilisation of plant to site would produce emissions as well. If the remediation did not need to be undertaken in short timescales then lower temperatures of 30C - 40C may be able to be applied to the soil to gradually enhance the onset of bioremediation reducing energy requirements (Kueper et al, 2014). Due to the short timeframes the soil would be heated quicker to remove the source zone and help mobilise DNAPL at depth, as the soil is cooling down this would allow for enhancement of dehalogenating bacteria to establish (Provectus Group, 2009). Option 2 scores 50 as in situ ZVI mixing would be undertaken in the source zone shallower depths down to around 6m bgl in line with the higher concentrations of chlorinated solvents found in these depths for BH 55/ BH56A and WS9 (Figure 5 & Appendix 1). This would require energy for the ZVI mixing equipment and emissions would also be created bringing the clay and ZVI to site. Option 3 scores 60, only slightly better than option 2 as the drilling of the 20 boreholes at depths of ~25m would be slightly less energy intensive than option 2 where the ISCR in situ soil mixing would be required over a larger area. Option 4 “Status Quo” scores the best in terms of emissions as no machinery/ equipment or materials would be used, just mobilising people to monitor existing boreholes at the site, over a longer period until FSC.	Uncertainty over energy differences between installation of a PRB and ISCR ZVI soil mixing. Uncertainty over amount of energy required for thermal treatment and how timescales would affect emissions to air.
ENV 2	Soil and ground conditions	Not included as the options to be taken forward for assessment would score similarly for effects on soil. The area of soil to be treated on site will not need to support any future services to be provided from it.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ENV 3	Groundwater & Surface Water	Included, remediation technologies employed will use different techniques/ chemicals to treat the groundwater plume which will affect the release and mobilisation of the contaminants to the groundwater (Assumption 3 & 4, Objective 1 & 2). Weighted 100 as this is a key requirement of SEPA and Dumfries and Galloway Council that the remediation strategy breaks the linkages in order to protect the water environment as identified in figure 6	100	Local environment Groundwater chemistry Mobilisation of contaminants	50	65	55	0	Option 4 scores the lowest as “Status Quo” would result in source zone contaminants continuing to add to the plume and making the local groundwater chemistry worse and possible future effects on the Gullielands Burn and 3rd Party Receptors. Option 1 scores 50 as care needs to be taken when thermally treating the source zone as it will cause greater mobility of the contaminants which can remain for several months to a year after shutdown of a thermal unit allowing continued contaminant solubility (EPA, 2004). It is important that parameters for enhanced bioremediation to occur in this period are maintained so as contaminants are continuously biodegraded and harmful daughter products do not persist for long durations (Kueper et al, 2014). Option 2 scores 65 as ZVI and clay in situ soil mixing will stabilise the source contaminants and limit water infiltration whilst the ZVI will react and destroy the TCE (Kueper et al. 2014). By applying 3DMe to the groundwater plume will ensure the groundwater chemistry and DNAPL at depth are remediated and 3DMe has shown to be effective for up to five years after use (Desrosiers et al, 2013). Option 3 has scored slightly lower then Option 2 due to not having being trialled like the 3DMe at the site. A ZVI PRB installed before the 50m assessment point would be able to intercept the plume and at depth through using pneumatic fracturing/ injection to install at a suitable depth (ITRC, 2011).	
ENV 4	Ecology	Not included as the surrounding area is neighbouring fields and disturbances to flora, fauna or wildlife in the area would not differ enough between the options.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ENV 5	Natural resources and waste	Included, remediation options have differing impacts in energy and resource use. Creation of waste from all of the options being assessed is limited but will still differ due to the different techniques and resources being utilised. Weighted 70 as it is slightly less important than groundwater and surface water protection as this category is the main aim of the remediation strategy.	70	Energy use during remediation Material Resources used in remediation Waste Generation	40	50	60	70	Option 1 has scored the lowest as a thermal treatment plant may need to be built specifically for the site which will use raw materials and energy within its making and will require energy for the life of its operation at the site. Once remediation is completed it will need to be demobilised and waste such as GAC filters from the SVE unit will also be generated. Energy to power the thermal plant for up to two years prior to going into C&M will be required. Option 2 scores 50 as natural resources of clay and ZVI will be required for the in situ mixing and 3DMe for the plume. Option 3 PRB scores 60 as it would not require as much energy use as option 1 but would require pneumatic fracturing/ injection of 20 boreholes for injecting the ZVI. However the requirement on natural resources would be less than option 2 where larger quantities of clay and ZVI would be required for in situ mixing. Option 4 “Status Quo” performs the best as no natural resources or energy are required.	Uncertainty over operational period of the thermal treatment plant and the amount of electricity which will be required for its operational life.

Options:
Option 1 - In Situ Thermal Treatment, Soil Vapour Extraction, Enhanced Bioremediation & Monitored Natural Attenuation
Option 2 - In Situ Chemical Reduction, Enhanced Bioremediation & Monitored Natural Attenuation
Option 3- Permeable Reactive Barrier
Option 4- “Status Quo”

Table 11. (continued) Sustainability Assessment for Chapelcross Site Chlorinated Solvent Plume

SuRF Category		Justification for inclusion/ Exclusion of category	Weight	Indicator to evaluate options	Qualitative Scores 0= Very Poor/ 25= Poor/ 50= Good/ 75= Very Good/ 100= Excellent. Quantitative figures for those with * (see *1)				Justification for Score	Uncertainties/ Assumptions
					Option 1	Option 2	Option 3	Option 4		
Economic										
ECON 1	Direct economic costs and benefits	Included, remediation strategies will have varying costs. Weighted 100 as the remediation should be value for money for Magnox and the tax payer and also needs to account for the continued costs throughout the life of the remediation such as monitoring which is equally important for future generations.	100	NPV Costs- Total Discounted cost over the life of the remediation	£1,695,086*	£1,328,092*	£924,767*	£312,390*	Table 19 - NPV and Appendix 6	
ECON 2	Indirect economic costs and benefits	Not included as all the remediation options have been chosen on the basis of being undertaken in a timely manner (objective 1 & 2). The land will not be able to be sold on after remediation as there is no plans to reduce the license site boundary until FSC so no economical benefits would be directly dependent on the strategy employed.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ECON 3	Employment and employment capital	Not included as all options would provide short term employment for the duration of the works and there is not a large enough distinction between the options to score them differently.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ECON 4	Induced economic costs and benefits	The induced economic costs or benefits are not dependent on the type of remediation installed. Due to the location of the land on site being remediated it would not be sold off prior to FSC as its the main entrance point to the site so will not incur any costs/ benefits for the site or surrounding local economy.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ECON 5	Project lifespan and flexibility	Flexibility of the remediation has been included as each option differs with the techniques used and ability to respond. Weighted 80 as the remediation needs to have an element of flexibility to change if problems occur.	80	Flexibility to cope with changing circumstances	50	60	10	15	Option 4 scores the worst at 15 as "Status Quo" will not have considered any remedial approach and the changing circumstances that may arise where remedial intervention is required, however it still leaves an element of flexibility if intervention is required. Option 2 scores the best as the variety of approaches being applied enable more flexibility between the different techniques and if one technique should not be as successful due to problems there is capability within the other techniques being applied. Option 1 scores 50 as although the initial investment in thermal equipment and energy prices are expensive, by monitoring parameters of the soil and groundwater means that throughout the treatment less or more heat can be applied responding to changes that may be occurring which could help reduce energy costs. Option 3 scores 10 as the only way to install the PRB at the depth in the required location is by pneumatic fracturing/ injection which may encounter difficulties such as adequate coverage by the installation, if this is so then the flexibility to move to other installation techniques such as trenching or excavating are limited due the depths required making this strategy inflexible compared to the others.	Uncertainty over energy required, may be able to be reduced if lower temperatures can suitably remediate the source zone and maintain conditions for bioremediation.

Notes
***1- Quantitative data will be used for category Econ 1**
Options:
Option 1 - In Situ Thermal Treatment, Soil Vapour Extraction, Enhanced Bioremediation & Monitored Natural Attenuation
Option 2 - In Situ Chemical Reduction, Enhanced Bioremediation & Monitored Natural Attenuation
Option 3- Permeable Reactive Barrier
Option 4- "Status Quo"

Table 11 (continued). Sustainability Assessment for Chapelcross Site Chlorinated Solvent Plume

SuRF Category		Justification for inclusion/ Exclusion of category	Weight	Indicator to evaluate options	Qualitative Scores 0= Very Poor/ 25= Poor/ 50= Good/ 75= Very Good/ 100= Excellent				Justification for Score	Uncertainties/ Assumptions
					Option 1	Option 2	Option 3	Option 4		
Social										
SOC 1	Human health and safety	Included, remediation options to be assessed will use different techniques/ equipment and chemicals which have their own safety concerns. Weighted 80, lower than ethics and equality and uncertainty and evidence because these two categories encompass three of the main objectives 1,2 & 3 that the remediation strategy must meet.	80	Worker Safety (conventional safety issues)	55	40	45	70	Option 4 would score the best as "Status Quo" would mean the usual yearly monitoring which would involve no machinery, no use of chemicals or drilling would significantly reduce the safety risks. Option 2 scores the lowest score of 40 due to the combination of in situ soil mixing involving larger machinery working at depth and the use of ZVI and 3DMe which have their own risks which need to be considered when workers are applying them. Option 3 PRB scores 45 as most PRB's installed under conventional methods of trenching and excavation would be considered to score lower for conventional safety, but by using pneumatic fracturing/ injection in order to install the PRB reduces the degree of conventional safety risk. Option 1 scores 55 due to the thermal treatment plant being likely to have less conventional safety risks than the previous options due to monitoring systems included within the equipment to check temperatures and parameters.	
SOC 2	Ethics and equality	Included, options differ in their approaches and will deal with DNAPL at depth by different techniques which need to ensure that concentrations are on a continual decline after initial remediation to avoid possible future intervention being required (objective 3/ constraint 3 so has been weighted 95).	95	Avoid transfer of issues to future generations	50	65	40	0	Option 4 scores the worst for this indicator with 0 as "Status Quo" would mean the solvent plume would be left for future generations to deal with and could spread further in time affecting the Gullielands Burn and third party abstractions, making remediation even more costly in the future (Figure 6 Receptors 1 & 3). Option 2 scores 65, the best score due to the success of 3DMe having already been trialled at the site (Regenesis, 2015). Applying ZVI mixing in the source area would also reduce the infiltration of water to the area and ZVI will react and destroy the TCE (Kueper et al. 2014). This strategy should deal with the source and the DNAPL at depth in order to remediate the area so as no burdens on future generations. Option 1 scores 50 as thermal treatment would be able to destroy the source zone contaminants in minimal time and would also increase the diffusion rate and solubility of the DNAPL at depth (EPA, 2004). Coupled with enhanced bioremediation and ensuring conditions are kept favourable for this through regular monitoring it would reduce the future risks of contaminants being left at depth for future generations to deal with. Option 3 PRB scores 40 because it would be able to tackle the source plume as well as the DNAPL at depth but has not had the trials and investigation that the 3DMe has had already. A PRB would take longer to remediate the source zone as it would still be continually adding to the plume over time compared to options 1 and 2. There would be longer term maintenance, re injection and monitoring costs for future generations to ensure the barrier continues to work effectively.	Uncertainty over length of time the PRB will be required for and maintenance burden on future generations.
SOC 3	Neighbourhoods and locality	Included, remediation options differ in intrusiveness and disturbance that will be caused to the grounds and machinery used. Permissions required and access would cause disturbance in neighbouring fields. Weighted 60 as previous access has been gained to local fields for the site investigation works, which has not been badly received from the adjacent land owner. However a remediation strategy that limits this would reduce the disturbance caused to the locality.	60	Disturbance/ Intrusiveness in neighbouring fields to the site.	70	25	35	50	Option 4 "Status Quo" scored 50 as although limited access and disturbance would be required for undertaking yearly monitoring it would still be required up until FSC. Option 1 scored 70 because thermal treatment and enhanced bioremediation will cause very little impacts on the surrounding neighbouring fields as the thermal treatment will be applied to the source zone area on site, not affecting neighbouring fields. Existing boreholes within the neighbouring fields and vicinity will require regular monitoring however the monitoring period would be over fewer years than option 4, meaning less intrusion in the future. Option 2 scores 25 as 309 injection points would be required which will be intrusive to neighbouring fields as installation will be on a 10 x 10m area which will cause some disturbance and noise whilst the injection is being undertaken. Option 3 scores 35 as the PRB would be installed in the car park so 6 additional boreholes would be required on adjacent land so limited intrusion. The pneumatic fracturing/ injection would cause some noise and disturbance to neighbouring fields during its installation and if it requires re injection in the future as assumed in 5 years time (ITRC, 2011) the same disturbance would be created again.	Assumption that the 3DMe for option 2 will be injected on a 10m x 10m area. Assumption that reinjection of the PRB will be required in 5 years time based on longevity ZVI being installed by pneumatic fracturing/injection (ITRC, 2011).
SOC 4	Communities and community involvement	Not included as any effects or changes to the local community would automatically be communicated through regular community meetings, keeping involvement.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SOC 5	Uncertainty and evidence	Included, different strategies will need to deal with the uncertainty surrounding removing DNAPL at depth and reducing risk of rebound after initial remediation. Weighted 100 as this category addresses three of the main objectives 1,2 & 3 and needs to be robust so as it can deal with DNAPL at depth.	100	Compliance with remedial criteria (To be determined) Long term robustness/ validation of remediation.	50	70	55	0	Option 4 "Status Quo" scores the worst at 0 as it would keep putting receptors identified in the CSM (figure 6) at risk which could result in regulatory action being taken. There is no long term robustness with the approach and this could make impacts worse in the future to remediate if the plume spreads. Option 2 scores the best at 70 due to the trial of 3DMe showing success in a short time period (Appendix 1). Combining this with in situ ZVI soil mixing will further reduce the spread from the source zone. Option 3 scores 55 because a PRB would fully intercept the plume and deal with DNAPL at depth which would make this a robust solution and validation and effectiveness of the ZVI would be confirmed by monitoring boreholes. Option 1 scores 50, only slightly less than option 3 due to the application of thermal treatment being over a shorter timescale and having to maintain favourable and consistent bioremediation parameters for future years. Option 1 and 3 have assumed a re application of media in the future to maintain enhanced bioremediation if required. For option 1 once the thermal treatment plant has been removed then bioremediation parameters need to be maintained for the future to ensure that if future DNAPL at depth in fractures was to diffuse out after treatment still then the correct bioremediation parameters would ensure concentrations of chlorinated solvents remain within compliance criteria (EPA 2004). Re mobilisation of thermal treatment plant would make this option very expensive if the sources did not have enough heat applied on the first treatment to ensure they were remediated.	

Options:
Option 1 - In Situ Thermal Treatment, Soil Vapour Extraction, Enhanced Bioremediation & Monitored Natural Attenuation
Option 2 - In Situ Chemical Reduction, Enhanced Bioremediation & Monitored Natural Attenuation
Option 3- Permeable Reactive Barrier
Option 4- "Status Quo"

4.4.7 Cost Breakdowns for Chapelcross Site

The remediation cost estimates for Chapelcross site are shown in tables 12-15. Appendix 4 shows the detailed breakdown behind how the individual cost estimates were calculated. The cost breakdowns were used to calculate the NPV's for each site which are shown in section 4.4.9.

Table 12 Cost estimate for Option 1- In Situ Thermal Treatment (ISTT)/SVE & Enhanced Bioremediation & MNA

Option 1		
Costings have been taken from ISTT case studies for DNAPL contamination from Kueper et al, 2014 and from a remediation undertaken by Provectus Group using TCH for chlorinated solvent contamination.		
Capital Costs	**Cost (£)**	**References**
Design & Procurement	165,929	Kueper et al, 2014
Mobilisation and Demobilisation	137,298	
Drilling & Installation of heater borings to install heating element and SVE wells	161,894	
Thermal and SVE Equipment Installation	51,954	Provectus Group, 2009.
Operation and Maintenance	34,636	
Variable Costs		
Waste GAC- off gas treatment	35,625	Provectus Group, 2009.
Waste GAC condensate treatment	17,812	
Energy Consumption	1,033,302	Kueper et al, 2014. Department of energy and Climate Change, 2015.
TOTAL CAPITAL COSTS (£)	1,638,450	
Operations & Maintenance (O&M) Costs		
Soil Sampling (1st Year)	7,808	Kueper et al, 2014.

Validation & Monitoring of Enhanced Bioremediation Indicators (Year 1)	14,431	Provectus Group, 2009.
Year 2	14,431	
Yearly monitoring Year 3-7 (Total for 5 years)	18,035	Kueper et al, 2014. Provectus Group, 2009.
TOTAL O&M COSTS (£)	54,705	

NOTES/ ASSUMPTIONS

Based on a 2-year operation, comprising 4 months' mobilisation, setup, drilling of heater borings and system installation. Active treatment time of 3 months and 1-month demobilisation, 6 month cooling period so as enhanced bioremediation indicators can then be monitored (Provectus, 2009).

Variable cost of the electricity has been priced based on recommendations for TCH energy use from Kueper et al, 2014 and priced on March 2015 quarterly energy prices from the Department of Energy and Climate Change.

Table 13 Cost estimate for Option 2 - In Situ Chemical Reduction (ISCR), Enhanced Bioremediation & MNA

Option 2		
Costings have been taken from remedial case studies for DNAPL contamination in a low permeability source area, from Kueper et al, 2014. Regenesis 3DMe case study has been used from an example site.		
Capital Costs	**Cost (£)**	**References**
Injection of 3DMe at 10m intervals (Based on 3DMe trial)	260,410	Regenesis, 2010. Serco, 2008
Design & Procurement in situ ZVI mixing	72,228	Kueper et al, 2014.
Mobilisation and Demobilisation in situ ZVI mixing	97,605	
Removal of top 1m of soil, mixed with iron and bentonite clay for re-use	22,384	
Soil Mixing	249,868	
Materials (ZVI/ bentonite clay)	193,258	
Air Monitoring during excavation and mixing of soil ex situ	6,507	
TOTAL CAPITAL COSTS (£)	902,260	
O&M Costs		
Soil Sampling (1st Year)	7,808	Kueper et al, 2014.
Validation/ Enhanced Bioremediation Monitoring Costs Year 1	29,802	
Year 2	29,802	
Year 3	29,802	
Year 4	7,450	
Year 5 - Maintenance Activity- Addition of 3DMe	260,410	Regenesis, 2010.
Yearly Monitoring for 4 years after re-addition of 3DMe	29,800	
TOTAL O&M COSTS (£)	394,874	

NOTES/ ASSUMPTIONS

3DMe has shown to be effective for periods of 3-4 years therefore consideration needs to be given that future injection may be required if remedial concentrations have not been met. In order for 3DMe to last 4 years' optimal conditions are required such as low permeability and low consumption environments (Kueper et al, 2014).

An assumption has been made that Chapelcross Site will require one further future round of 3DMe injections in 4 years' time based on the area being of low permeability and the 3DMe trial undertaken showing optimum conditions. If the first 3-4 years monitoring shows concentrations meeting remedial targets then this cost may then become a saving.

Table 14 Cost estimate for Option 3- Permeable Reactive Barrier (PRB)

Option 3		
Based on costings taken from the Naval Facilities Engineering Command (NAVFAC) PRB cost and performance report. A case study of Hunters Point Naval Yard, San Francisco, California, USA, where pneumatic fracturing/ injection was used to inject ZVI as a PRB in 2008.		
Capital Costs	**Cost (£)**	**References**
Design & Procurement	232,413	NAVFAC, 2012.
Mobilisation and Demobilisation	18,408	
Drilling & application of ZVI into boreholes to create PRB	224,313	ITRC, 2011. NAVFAC, 2012. Appendix 9
Installation of monitoring boreholes	30,365	
Verification Monitoring	7,032	NAVFAC, 2012.
TOTAL CAPITAL COSTS (£)	512,531	
O&M Costs		
Monitoring Costs Year 1 (Quarterly)	28,128	ITRC, 2011. NAVFAC, 2012.
Monitoring costs year 2-4 (6 monthly)	42,192	
Maintenance Activities - Addition of new media (year 5)	242,721	
Monitoring costs year 6-10 (6 monthly)	70,320	
TOTAL O&M COSTS (£)	383,361	
NOTES/ ASSUMPTIONS		
An assumption has been made that the reactive media will have to be re-injected every 5 years (ITRC, 2011) if the remedial concentrations in samples have not been met, this is likely with the highest concentrations being identified in the source zone which will still be adding to the plume (section 4.3.3). The mobilisation and application of ZVI costs previously used under capital costs have been applied (NAVFAC, 2012).		

6 monthly monitoring would continue after addition of new media if required up until year 10 at which point if the PRB is still required an assessment of future viability will need to be made.

Table 15 Cost estimate for Option 4 "Status Quo"

Option 4	Cost (£)	References
O&M Costs	Based on yearly monitoring continuing.	
68 years of annual monitor-ing	486,064	Magnox, 2015 Appendix 8
TOTAL O&M COSTS (£)	486,064	
NOTES/ ASSUMPTIONS Is based on estimated monitoring costs for just solvent plume area at the site from contractor's bill of quantities for one monitoring event per year. Does not take into account if further intervention/ remedial action is required within this period of monitoring. Yearly monitoring will be assumed to cover a period of 68 years throughout C&M to FSC.		

4.4.8 Cost Breakdowns for Bradwell Site

The remediation cost estimates for Bradwell site are shown in tables 16-18. Appendix 5 shows the detailed breakdown behind how the individual cost estimates were calculated for Bradwell site.

Table 16 Cost Estimate for Option 1- Selective Excavation, removal of OAEDL and cover/capping system

Option 1		
Actual costs were taken from the contractors cost estimate who undertook the selective excavation and capping of the "North End" based on a 28-week programme. Items of equipment which would have direct contact with the soil were purchased outright due to the likelihood of them becoming radio-actively contaminated, so as to avoid hire charges and then a purchase price. Where comment is given to a "platform for excavating" having to be created this was required due to surface contamination in the area needing to be covered in advance of any movement over it. This was required so as personnel and equipment were protected and to reduce the further spread within the area and mobilisation of it outside the area through machinery, people and weather.		
Capital Cost	**Cost (£)**	**Reference**
Design & Procurement	200,000	Magnox, 2013
Mobilisation and Demobilisation	224,718	
Management Cost	305,444	
Preparation of Area/ Set up for selective excavation (platform for excavating)	89,029	
Earthworks- Selective excavation	52,788	
OAEDL- Preparation works	42,736	
Earthworks-Removal of OAEDL/ EDL	101,319	
Capping- Excavation of anchor trenches	52,322	
Capping system- Liner	103,511	

Capping system - Soil	73,950	
Capping system -Gravel	125,345	
Reinstating reptile fencing	6,834	
Reporting phase	9,952	
Waste Disposal- LLW	115,140	LLW Repository Ltd, 2015. Appendix 11 (Magnox, 2013)
Waste Disposal- VLLW	248,478	LLW Repository Ltd, 2014 & 2012. Appendix 10 (Magnox, 2013)
Waste Disposal-Conventional	24,547	Appendix 12 (Magnox, 2013) Green Recycling, 2015.
TOTAL COST (£)	1,776,113	
O&M Costs		
Yearly Monitoring/ Inspection and maintenance costs for 10 years	175,000	Golder, 2015 Magnox, 2013
Yearly Inspection costs of cap up until FSC (58 years) including maintenance on cap. (Assumed every 10 years)	137,000	
TOTAL O&M COSTS (£)	312,000	

Table 17 Cost estimate for Option 2- Capping/ Cover System, with grouting of remaining OAEDL, draw pits

Option 2		
Actual costs were taken from the contractors cost estimate for selective excavation and then capping. Therefore it has been assumed for just a capping strategy that the time frame would be reduced from the original estimate of a 28 week duration to a 10 week duration (4 weeks for preparation of anchor trenches/ removal of legacy waste, 4 weeks to install the cap and 2 weeks spare if required).		
Capital Costs	**Cost (£)**	**References**
Design & Procurement	200,000	Magnox, 2013
Mobilisation and Demobilisation	105,247	
Management Costs	97,286	
Preparation of Area	52,066	
Preparation works	42,736	
Grouting of OAEDL/ EDL	25,990	
Capping- Excavation of anchor trenches	29,868	
Capping system- Liner	103,511	
Capping system - Soil	73,950	
Capping system -Gravel	125,345	
Reinstating reptile fencing	6,834	
Reporting phase	5,000	
Waste Disposal-Conventional	4,308	Appendix 12 (Magnox, 2013) Green Recycling, 2015
Waste Disposal- Anchor Trenches - VLLW	6,550	LLW Repository Ltd, 2014 & 2012 Appendix 10
TOTAL COST (£)	878,691	
O&M Costs		
Yearly Monitoring/ Inspection and maintenance costs for 10 years	175,000	Golder, 2015

Yearly Inspection costs of cap up until FSC (58 years) including maintenance on cap. (Assumed every 10 years)	137,000	Magnox, 2013
TOTAL O&M COSTS (£)	312,000	

Table 18 Cost estimate for Option 3 - "Status Quo"

Option 3	**Cost (£)**	**References**
O&M Costs	Based on yearly monitoring continuing.	
68 years of annual monitoring	450,000	Golder, 2015 Magnox, 2013
TOTAL O&M COSTS (£)	450,000	
NOTES/ ASSUMPTIONS Is based on estimated monitoring costs for just "North End" area at the site. Does not take into account if further intervention/ remedial action is required within this period of monitoring. Yearly monitoring will be assumed to cover a period of 68 years throughout C&M to FSC.		

4.4.9 Net Present Value (NPV) for Chapelcross & Bradwell Site

This section presents the NPV for each site which were calculated using the cost estimates developed in section 4.4.7 & 4.4.8. The estimates enabled the capital cost of each option to be determined. The timeframe required for future operation, maintenance and monitoring enabled future yearly costs to be assigned. The appropriate nuclear discount rate could then be applied to the years to calculate the NPV for each option.

Table 19 NPV for Chapelcross Site Remediation Strategies

	NPV (£) of Remediation Strategy			
Discount Rate	**Option 1**	**Option 2**	**Option 3**	**Option 4**
HM Treasury Nuclear Discount rates (NDA, 2014) 0-5 yrs -1.95% 5-10 yrs -0.65% 10+ yrs 2.20%	£1,695,086	£1,328,092	£924,767	£312,390
Sensitivity applied 0-5 yrs -0.9% 5-10 yrs -0.35% 10+ yrs 3.20%	£1,582,843	£1,311,417	£909,277	£266,274

Option 1 - In Situ Thermal Treatment, Soil Vapour Extraction, Enhanced Bioremediation & Monitored Natural Attenuation
Option 2 – In Situ Chemical Reduction, Enhanced Bioremediation & Monitored Natural Attenuation

Option 3- Permeable Reactive Barrier

Option 4- "Status Quo"

Table 20 NPV for Bradwell Site Remediation Strategies

	NPV (£) of Remediation Strategy		
Discount Rate	**Option1**	**Option 2**	**Option 3**
HM Treasury Nuclear Discount rates (NDA, 2014) 0-5 yrs -1.95% 5-10 yrs -0.65% 10+ yrs 2.20%	£2,034,156	£1,136,736	£659,793
Sensitivity applied 0-5 yrs -0.9% 5-10 yrs -0.35% 10+ yrs 3.20%	£2,015,187	£1,117,767	£561,187

Option 1 - Original Remediation implemented: Selective Excavation, removal of OAEDL and a Cover/Capping system
Option 2 - Capping/ Cover System, with grouting of remaining OAEDL, draw pits
Option 3- "Status Quo"

Table 19 and 20 show the calculated NPV for each remediation option at each site. A sensitivity analysis has been applied to the rates by slightly increasing them if interest rates were to go up. This shows that the NPV improves as the negative discount rates being applied become smaller.

Appendix 6 & 7 shows the underpinning calculations behind each of the NPV's. Option 1 for both sites has the highest NPV of all the remediation strategy options. For Chapelcross site option 3 has the lowest NPV after option 4 of "Status Quo". At Bradwell site option 2 has the lowest NPV after option 4 of "Status Quo".

Chapter 5 Data analysis

This section presents the Hiview MCDA assessment results for both sites. Each site was modelled separately through Hiview. Firstly, the description of the SuRF UK indicators were input into the Hiview software to build the "value tree". The "value tree" represents the three pillars of sustainability as nodes and from these nodes branch the indicators chosen under the environmental, economic and social categories. The options for the site being modelled were entered into Hiview.

The qualitative scores, quantitative data and weights from the sustainability assessment spreadsheet for the particular site being modelled were input into the software against each option. The weighted score for each option are represented in a series of tables that show what indicators contributed most to the scores for options. A breakdown of data under each of the three pillars of sustainability and the sensitivity analysis are provided.

A further assessment of altering the weights applied to each criteria has been undertaken in section 5.3 to see what impact this has on the overall preferred option. This has been undertaken by increasing and decreasing weights on certain criteria to see what effect this has on the weighted score of each option.

5.1 Hiview MCDA Assessment Results - Chapelcross Solvent Plume Remediation Strategies

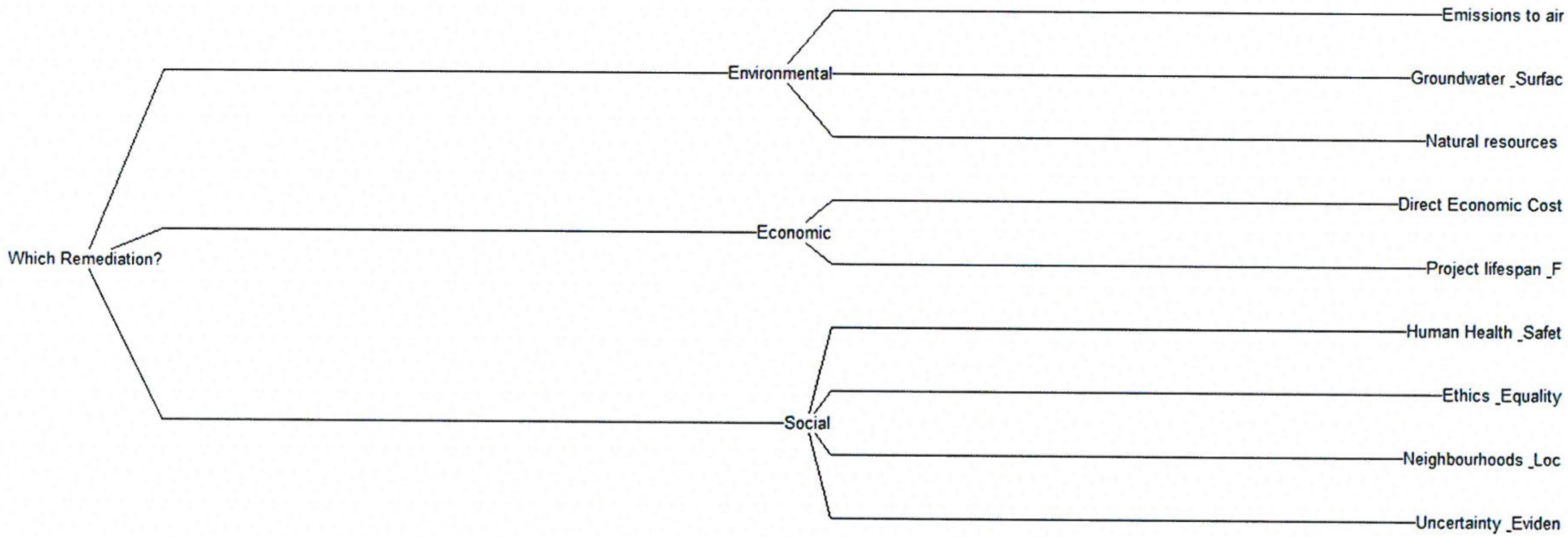


Figure 11 Chapelcross Site Hiview Value Tree of Nodes and SuRF UK indicators

Figure 11 shows the first stage in building the Hiview model, the "value tree" of the criteria (SuRF UK Categories). It shows for Chapelcross site that three SuRF UK indicators have been chosen under the environmental pillar, two under the economic and four under the social pillar.

Table 21 Chapelcross Site Remediation Criteria Contribution

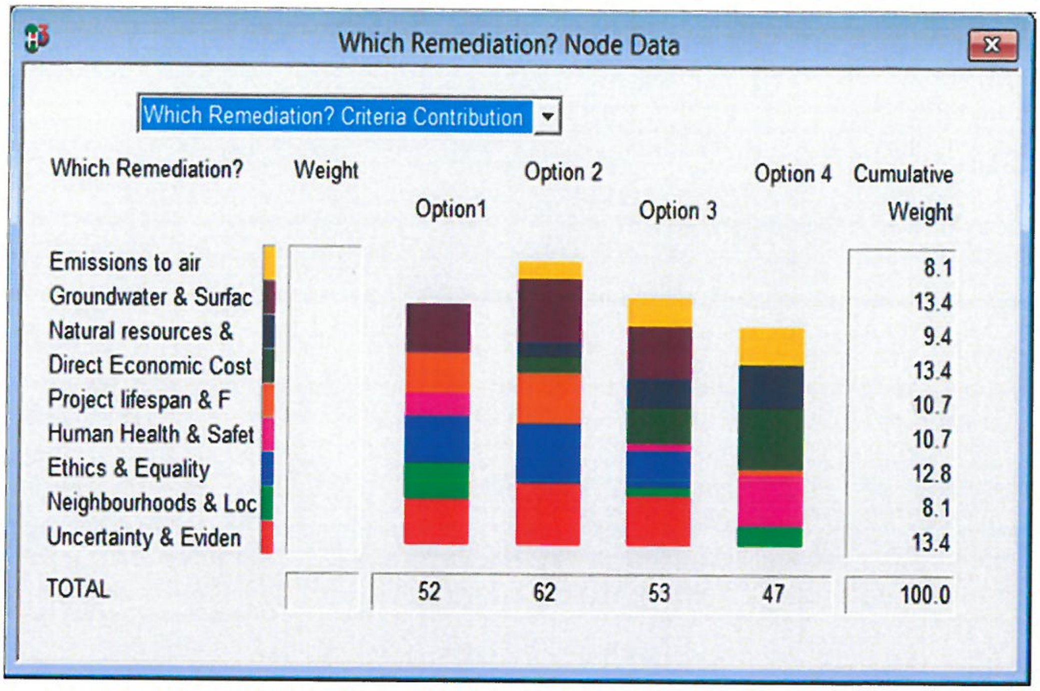


Table 21 shows the results from the Hiview modelling and the overall weighted score for each option. Option 2, ISCR, enhanced bioremediation & MNA scored the highest at 62. Option 3 PRB was second with option 1, ISTT and enhanced bioremediation a very close third, with only 1 point between second and third position.

Table 21a shows the Hiview Scores for Chapelcross site. An example is shown below and overleaf on how the preference score, cumulative weight and weighted score are calculated in Hiview.

Appendix 15 shows an example of the Hiview calculations for Chapelcross Site.

Formulae:

$$\frac{\text{Weight given to individual indicator}}{\text{Total of indicator weights}} = \text{Cumulative Weight}$$

Cumulative Weight X Preference score = Weighted Score.

Example:

ENV 1 - Emissions to Air Weight = 60

Total of Indicator Weights = 745

$$\frac{60}{745} = 0.0805 \text{ (cumulative weight)}$$

0.0805 (cumulative weight) x 55.56 (preference score from table 21a) = 4.47 weighted score

Table 21a Example of Hiview Scores from Chapelcross Site.

SuRF UK Category	Weight (from Table 11- Sustainability Assessment)	Option	Input Score	Preference Score	Weighted Score
ENV 1 - Air- Emissions of pollutants to air	60	Option1	25.0	0.00	0.00
		Option 2	50.0	55.56	4.47
		Option 3	60.0	77.78	6.26
		Option 4	70.0	100.00	8.05
ENV 3 - Groundwater & Surface Water Local groundwater chemistry. Mobilisation of contaminants.	100	Option1	50.0	76.92	10.33
		Option 2	65.0	100.00	13.42
		Option 3	55.0	84.62	11.36
		Option 4	0.0	0.00	0.00
ENV 5 - Natural resources & Waste- Energy use during remediation. Material resources used remediation. Waste Generation.	70	Option1	40.0	0.00	0.00
		Option 2	50.0	33.33	3.13
		Option 3	60.0	66.67	6.26
		Option 4	70.0	100.00	9.40
ECON 1 - Direct Economic Cost- NPV	100	Option1	£1,695,085.5	0.00	0.00
		Option 2	£1,328,092.2	24.48	3.29
		Option 3	£924,767.3	51.39	6.90
		Option 4	£312,390.0	100.00	13.42
ECON 5 - Project Lifespan & Flexibility		Option1	50.0	80.00	8.59

Flexibility to cope with changing circumstances	80	Option 2	60.0	100.00	10.74
		Option 3	10.0	0.00	0.00
		Option 4	15.0	10.00	1.07
SOC 1 - Human Health & Safety Worker Safety	80	Option1	55	50.00	5.37
		Option 2	40	0.00	0.00
		Option 3	45	16.67	1.79
		Option 4	70	100.00	10.74
SOC 2 - Ethics & Equality Avoid transfer of issues to future generations	95	Option1	50	76.92	9.81
		Option 2	65	100.00	12.75
		Option 3	40	61.54	7.85
		Option 4	0	0.00	0.00
SOC 3 - Neighbourhoods & Locality Disturbance/ Intrusiveness in neighbouring fields to the site	60	Option1	70	100.00	8.05
		Option 2	25	0.00	0.00
		Option 3	35	22.22	1.79
		Option 4	50	55.56	4.47
SOC 5 Uncertainty & Evidence Compliance with remedial criteria (TBD) Long term robustness/ validation of remediation	100	Option1	50	71.43	9.59
		Option 2	70	100.00	13.42
		Option 3	55	78.57	10.55
		Option 4	0	0.00	0.00

Table 22 Chapelcross Site Remediation Sensitivity

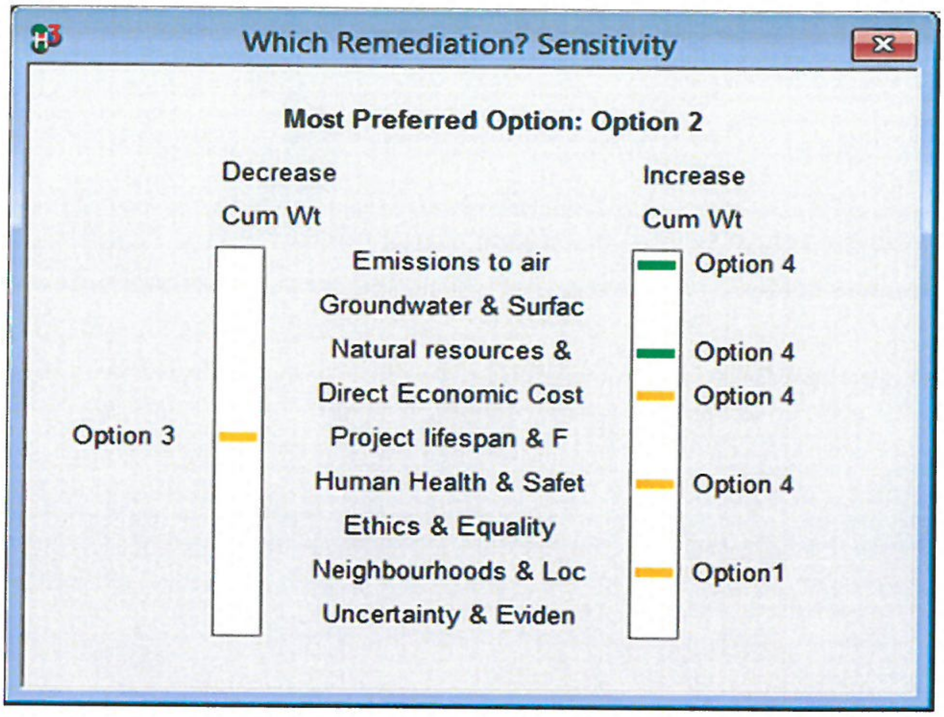


Table 22 shows the sensitivity analysis of the most preferred option 2. The sensitivity table from Hiview displays the sensitivity of the SuRF UK indicators by representing them with coloured bars. A green bar means the cumulative weight would have to increase by more than 15 points in order for the preferred option to change. A 15-point increase in cumulative weight would be required under emissions to air & natural resources in order for option 2 to change to option 4. A yellow bar means the cumulative weight would have to change by >5 to 15 points in order for the preferred option to change. A >5 to 15-point increase in cumulative weight would be required under direct economic cost and human health & safety to change to option 4. A >5 to 15-point increase in cumulative weight would be required under neighbourhoods & locality to change to option 1. A decrease of >5 to 15 points would be required under project lifespan & flexibility to change option 2 to option 3.

Table 23 Chapelcross Site Economic Node Data

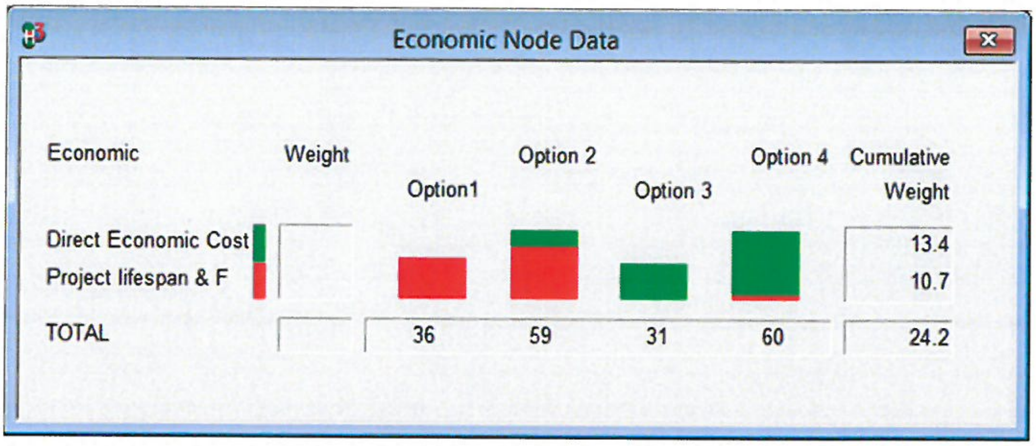


Table 23 shows that option 4 "Status Quo" scored the highest weighted score under the economic node, with the direct economic cost category contributing most to the weighted score. Option 2 came a close second place with project lifespan & flexibility being the largest contributing category to the weighted score.

Table 24 Chapelcross Site Environmental Node Data

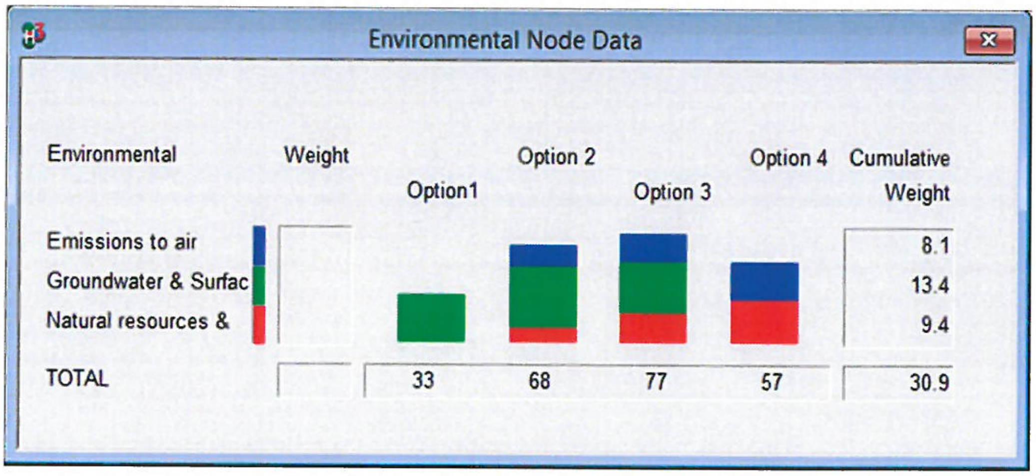


Table 24 shows that option 3, PRB was the most preferred option under the environmental node, with the category of groundwater & surface water contributing most to the weighted score. Option 2 came second place with groundwater & surface water contributing most to the weighted score.

Table 25 Chapelcross Site Social Node Data

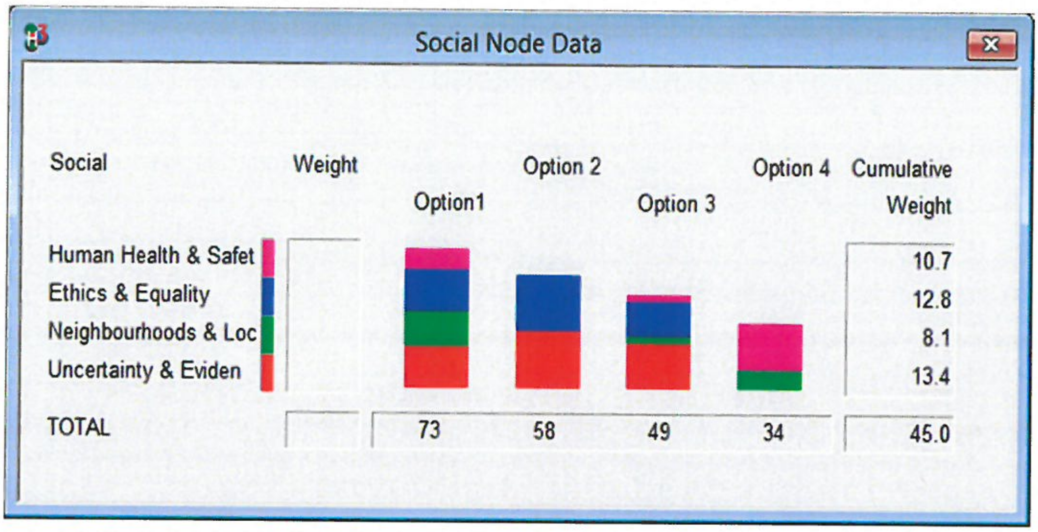


Table 25 shows that option 1 ISTT, enhanced bioremediation and MNA scored the highest under the social node, with all four categories contributing fairly evenly to the overall weighted score. Option 2 came second with ethics & equality and uncertainty & evidence contributing most to the overall weighted score.

5.2 Hiview MCDA Assessment Results - Bradwell "North End" Remediation Strategies

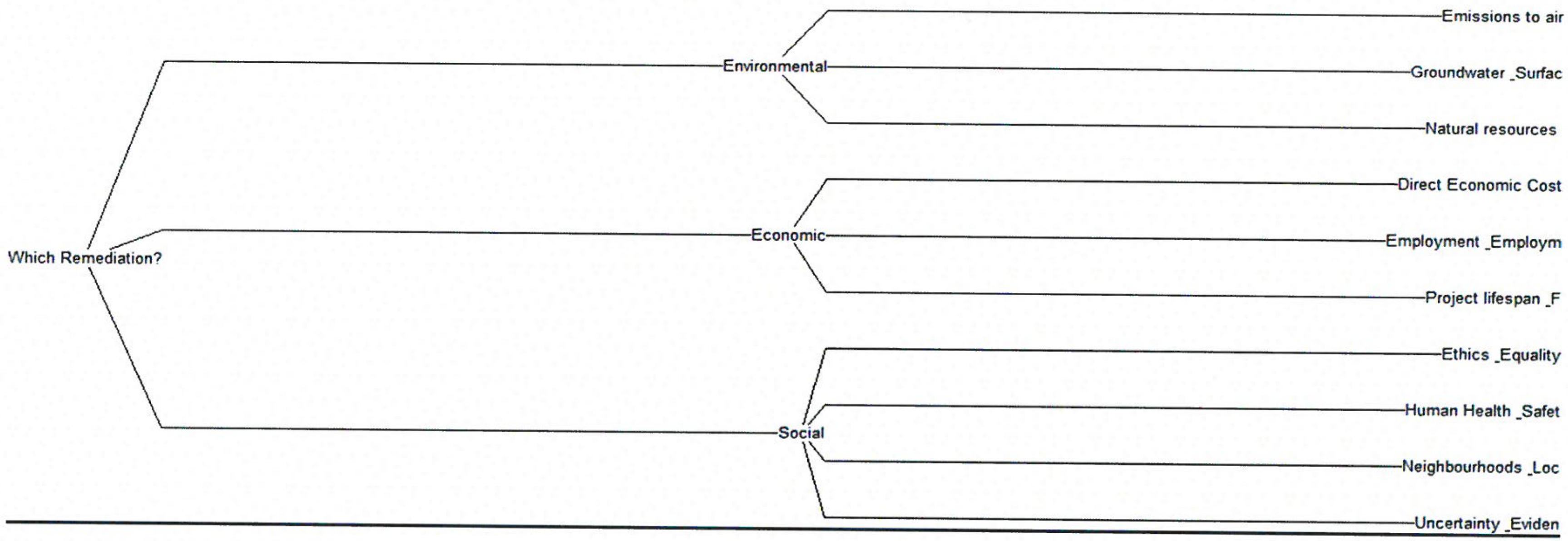


Figure 12 Bradwell Site Hiview Value Tree of Nodes and SuRF UK indicators

Figure 12 shows the first stage in the Hiview model procedure of building the "value tree" of the criteria. It shows that three SuRF UK indicators have been chosen under the environmental pillar, three under the economic and four under the social pillar

Table 26 Bradwell Site Remediation Criteria Contribution

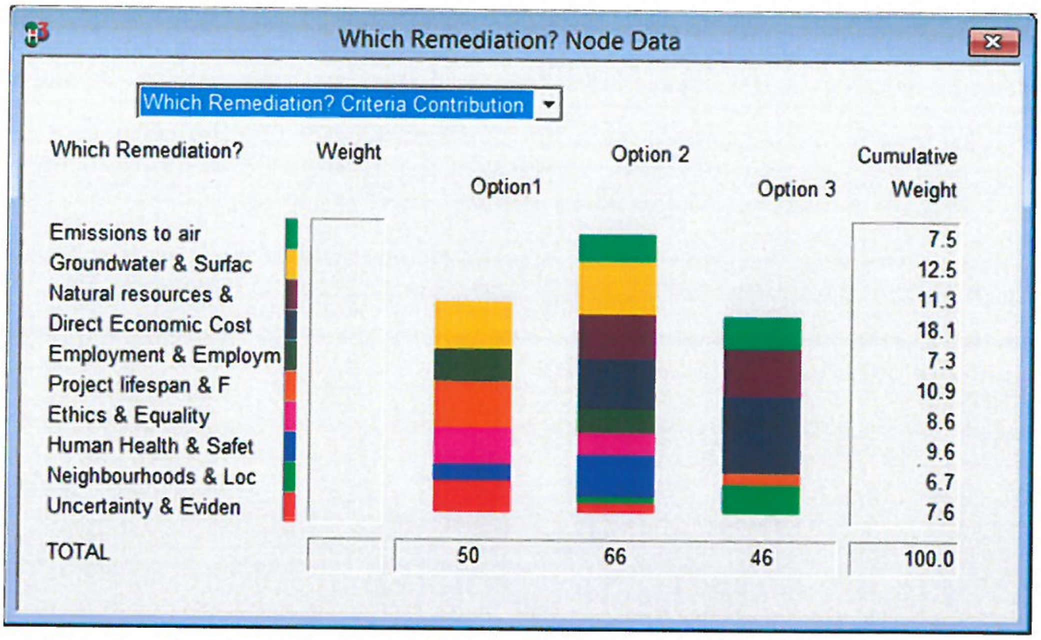


Table 26 shows the results from the Hiview modelling and the overall weighted score for each option. Option 2, capping/ cover system, with grouting of remaining OAEDL and draw pits scored the highest at 66. Option 1, selective excavation, removal of the OAEDL and cover/capping system came second with option 3 "Status Quo" coming last.

Table 27 Bradwell Site Remediation Sensitivity

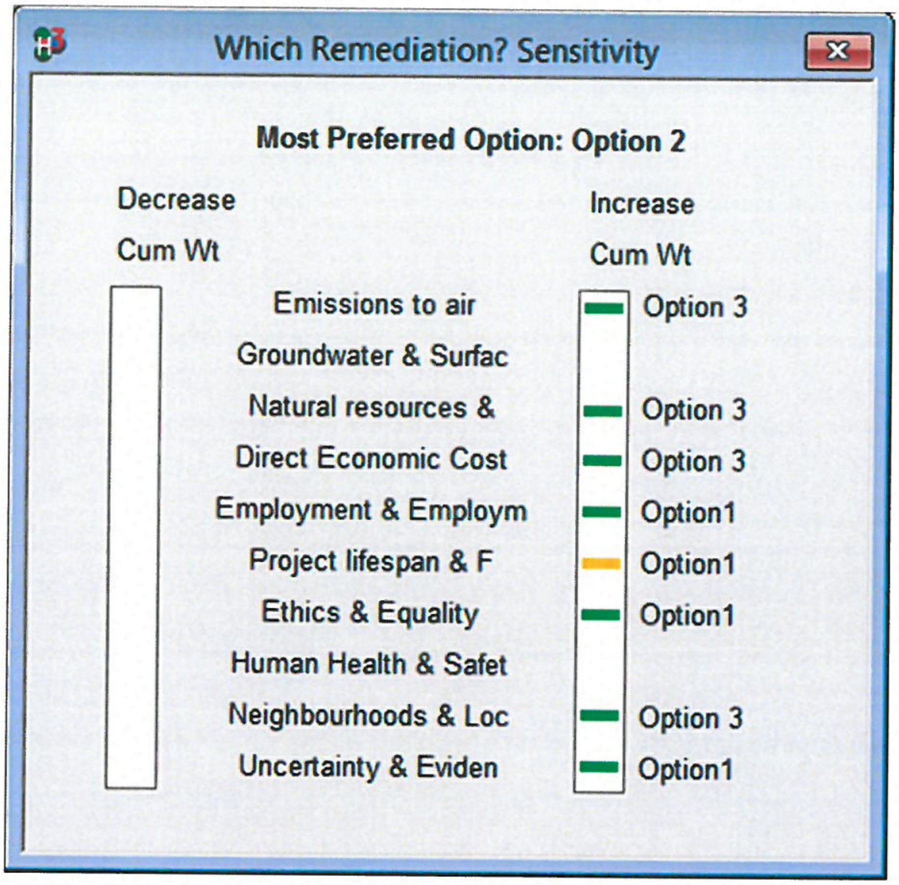


Table 27 shows the sensitivity analysis of the most preferred option 2. The sensitivity table shows that there are seven green bars which would require a cumulative weight increase of more than 15 points in order for the preferred option to change. In order for option 2 to change to option 3 an increase of more than 15 points (green line) would be required under emissions to air, natural resources & waste, direct economic cost and neighbourhoods & locality.

In order for option 2 to change to option 1, an increase of 15 or more points in cumulative weight would be required under employment & employment capital, ethics & equality and uncertainty & evidence. The yellow bar under project lifespan & flexibility means the cumulative weight would have to increase by >5 to 15 points in order for option 2 to change to option 1.

Table 28 Bradwell Site Economic Node Data

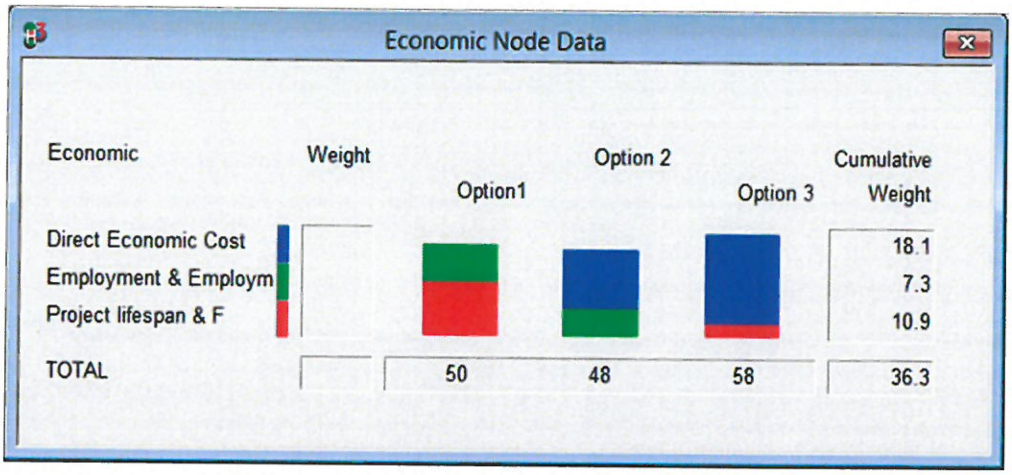


Table 28 shows that option 3 "Status Quo" scored the highest under the economic node, with direct economic cost contributing significantly towards the overall weighted score. Option 1 came second with project lifespan & flexibility contributing the most to the weighted score with option 2 in third position.

Table 29 Bradwell Site Environmental Node Data

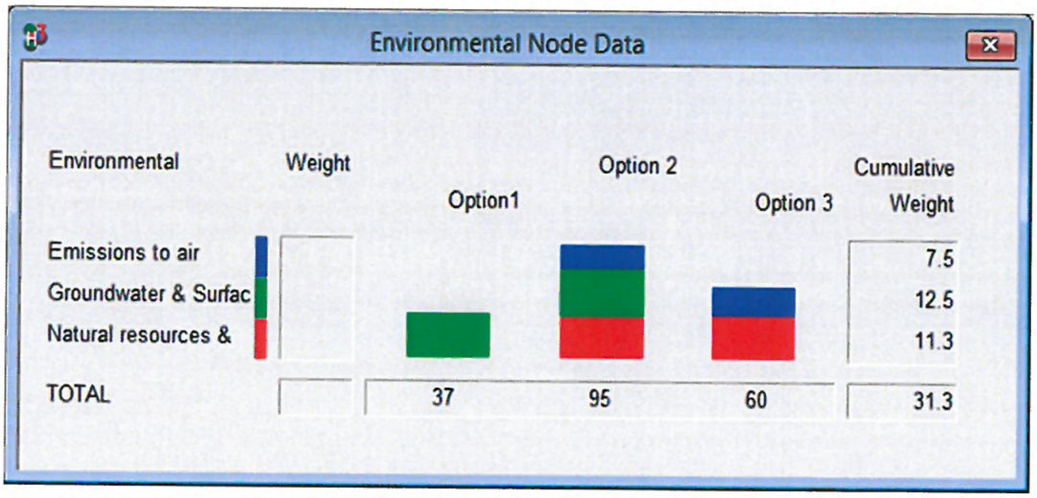


Table 29 shows that option 2 capping/ cover system, with grouting of the remaining OAEDL and draw pits scored the highest under the environmental node. The categories of groundwater & surface water and natural resources & waste contributing most towards the weighted score.

Table 30 Bradwell Site Social Node Data

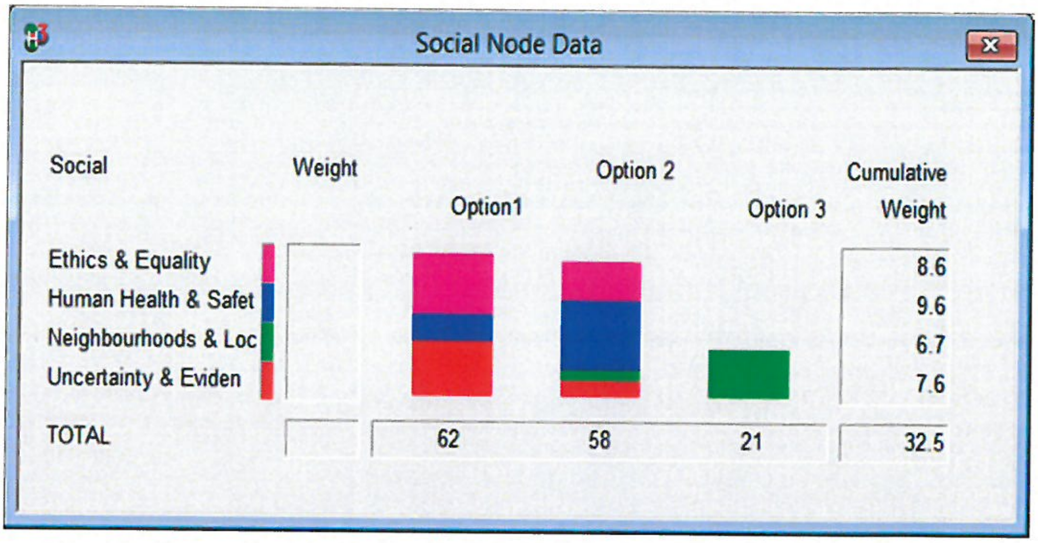


Table 30 shows that option 1 selective excavation, removal of the OAEDL and cover/capping system scored the highest under the social category, with ethics & equality and uncertainty & evidence contributing most to the weighted score. Option 2 came second with the human health & safety category contributing most to the weighted score.

5.3 Hiview- Analysis of Different Weightings on the Preferred Option

A further analysis was undertaken within Hiview by altering the weights entered on certain indicators under the three pillars to see what effect this would have on the overall preferred option and if it changed.

In previously assigning the weights to the indicators I had tried to take account of all stakeholder views. In order to analyse what effect altering the weights would have, I have altered them in this instance from a local community perspective.

Table 31 & 32 show the initial assessment weights and new weights from 1-100 entered into Hiview, which will then calculate the cumulative weight against each indicator.

Table 31 Chapelcross Site Criteria Weights

Pillar	Criteria	Initial Weight	New Weight
Environmental	Emissions to air	**60**	**80**
	Groundwater chemistry/ mobilisation of contaminants	100	100
	Energy use, material resources, waste generation	**70**	**60**
Economic	Direct economic costs and benefits	100	100
	Project lifespan & flexibility	**80**	**60**
Social	Worker safety	**80**	**70**
	Ethics & equality	95	95
	Neighbourhoods & locality	**60**	**100**
	Uncertainty & evidence	**100**	**80**

Table 32 Bradwell site Criteria Weights

Pillar	Criteria	Initial Weight	New Weight
Environmental	Emissions to air	**60**	**80**
	Groundwater chemistry/ mobilisation of contaminants	100	100
	Energy use, material resources, waste generation	**90**	**60**
Economic	Direct economic costs and benefits	100	100
	Employment & employment capital	**40**	**70**
	Project lifespan & flexibility	**60**	**40**
Social	Worker safety	**100**	**70**
	Ethics & equality	**90**	**95**
	Neighbourhoods & locality	**70**	**100**
	Uncertainty & evidence	**80**	**60**

I have increased the weighting under criteria for neighbourhoods and locality and emissions to air as the local community is likely to consider these criteria of more importance to affecting them and their surrounding environment. For Bradwell site I have increased the weighting under employment & employment capital as I believe local residents would consider the opportunity for new skills and training of people employed at the site especially if local important.

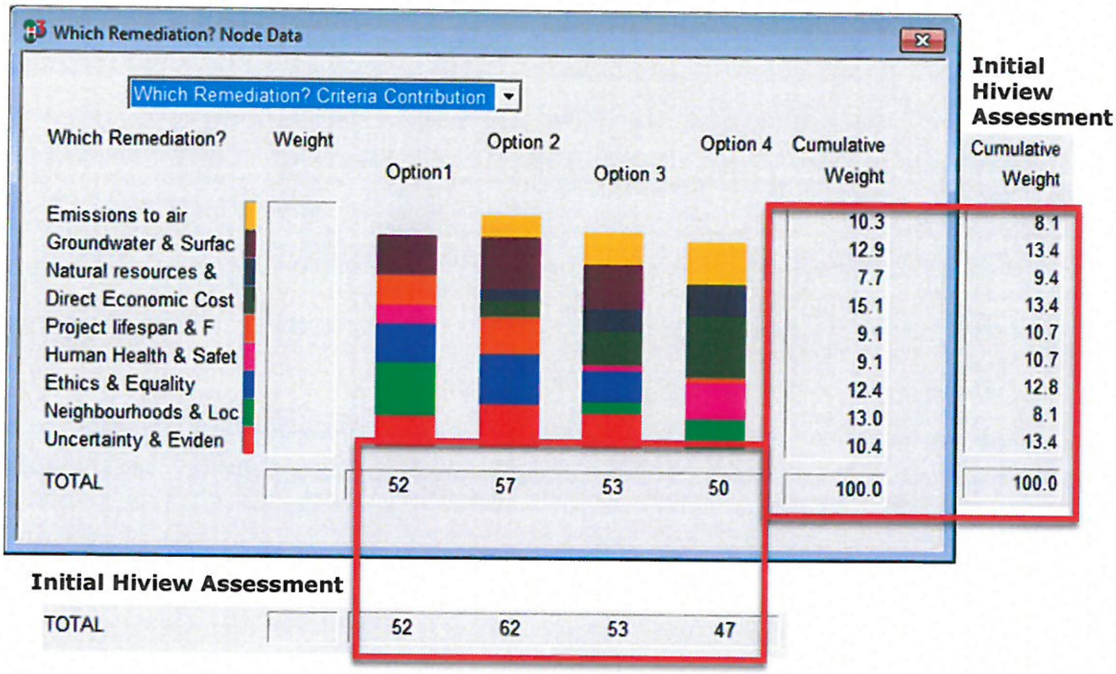
I have kept the weight for groundwater chemistry and direct economic costs and benefits the same as it was already 100. I believe the Local Community would consider tax payer's money being spent effectively as an important issue and that their local groundwater and environment is being protected.

I have reduced the weights on other indicators which are more important to regulators such as project lifespan & flexibility and uncertainty & evidence.

Table 33 & 34 show Hiview outputs from altering weights on each criterion to a local community perspective and the effect this has on the cumulative weight of each criteria and the overall scores of options.

The cumulative weights and scores of options from the initial Hiview remediation options assessment have been included to the right and beneath the tables for comparison.

Table 33 Chapelcross Site - Effects of changes in weighting on scores of remediation options.



Which Remediation? Node Data

Which Remediation? Criteria Contribution

Which Remediation?	Weight	Option1	Option 2	Option 3	Option 4	Cumulative Weight	Initial Hiview Assessment Cumulative Weight
Emissions to air						10.3	8.1
Groundwater & Surfac						12.9	13.4
Natural resources &						7.7	9.4
Direct Economic Cost						15.1	13.4
Project lifespan & F						9.1	10.7
Human Health & Safet						9.1	10.7
Ethics & Equality						12.4	12.8
Neighbourhoods & Loc						13.0	8.1
Uncertainty & Eviden						10.4	13.4
TOTAL		52	57	53	50	100.0	100.0
Initial Hiview Assessment TOTAL		52	62	53	47		

Table 33 shows an increase in cumulative weights under criteria such as neighbourhoods & locality. The changes in the weights show that the overall preferred option is still option 2, although the score of the option has reduced from 62 to 57. The difference between the most preferred option 2 and second place option 3, now has only 4 points difference. The scores for option 1 and 3 have not been altered by the changes in weight, but option 4 has improved.

Table 34 Bradwell Site – Effects of changes in weighting on scores of remediation options.

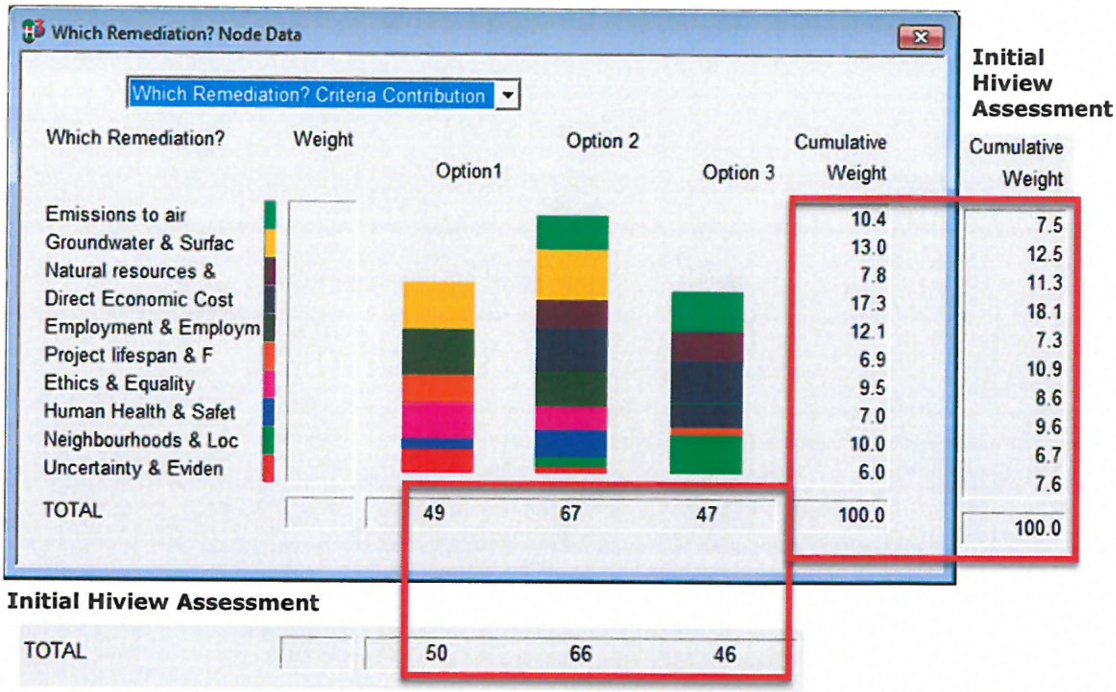


Table 34 shows an increase in cumulative weights under criteria such as neighbourhoods & locality and ethics and equality. The changes in the weights show that the overall preferred option is still option 2, and the overall score has increased from 66 to 67. The new weightings have given a marginally greater difference in scores between option 2 and second place option 1 than the initial assessment. The score for option 1 has only reduced by 1 and for option 3 increased by 1 from the initial assessment.

The analysis of the effect of different weightings on the preferred option has shown that a large difference is required between the indicator weightings entered into Hiview in order to affect the overall cumulative weight against each indicator.

Chapter 6 Discussion

6.1 Development of the Conceptual Site Model's

The CSM's (figures 5,6,9 & 10) were developed on the CLR 11 principles of the need to develop a CSM to support the decision making process (EA, 2004). The NIGLQ QLRA, Safegrounds guidance and ONR LC's were taken into account especially when developing Bradwell sites CSM. For Chapelcross site, non radiological contamination was present so the CLR 11 process for developing a CSM was followed taking into account Part 2A and SEPA regulatory guidance. The Safegrounds, NIGLQ QLRA and CLR 11 are good at guiding the developmental stages for a CSM and outline information that should be included such as geology, hydrogeology, exact areas of contamination concentrations and contaminant linkages (EA, 2004, CIRIA, 2009 & NIGLQ, 2012). However the guidance documents discussed do not provide any detailed examples of how a visual CSM should look.

The NIGLQ QLRA gives a very high level basic drawing of a CSM but this has no detail on it such as geology, contaminant concentrations or depth. In the guidance the sources, pathways, receptors and contaminant linkages are generally shown as being listed separately. This is good to have them clearly stated but I found it useful to have them listed in a table and presented alongside the visual CSM. This makes visualising the site easier, where the contaminants are present and the pathways they take to receptors. This was important when screening remediation techniques because being able to see the contaminant linkages enabled an improved understanding of how they could be broken by different techniques. This was especially important when developing Chapelcross sites CSM as I had never visited the site so creating the CSM helped paint a picture in my mind of what was occurring at the site.

In hindsight the process of developing the CSM for Chapelcross site and understanding the site in more detail would have been made easier if I had visited. The CSM for Chapelcross site took longer as I had to go over reports and monitoring data in more detail to establish a basic understanding of the site. I did not have this problem with Bradwell site as I had visited it before so had a better knowledge of the "North End" area. CLR 11, Safegrounds and NIGLQ QLRA guidance do not mention about undertaking a site visit before developing a CSM, as it is not necessary in all cases.

However, for complex sites like Chapelcross site where chlorinated solvent contamination is present, being able to visit the site enables a better understanding and see what every day activities and interfaces could affect remediation within the area. This gives an early indication of what decommissioning activities could affect investigation and future remediation objectives and screening. Recommendations on the importance of undertaking a site visit for more complex sites within guidance would help save time in developing a CSM. By being able to visually see the APC at a site and other activities occurring in the vicinity like at Bradwell site enabled better understanding of site investigation data and faster assimilation into the CSM.

I learnt through the process of developing the CMS's, that it took alot longer than I initially anticipated. The CLR 11 and Safegrounds guidance made no reference to how long a CSM can take to develop (EA, 2004 & CIRIA, 2009). The Bradwell CSM took around 15-20 days, as I had visited the site and had an understanding of the the APC and and reports available. The Chapelcross CSM took 25-30 days to assimilate the factual and monitoring reports and develop the CSM.

The CSM's were first developed as draft hand sketches which were drawn up using CAD software. Once the CSM's were drawn up in CAD this made the process of adding information to them easier instead of having to redraw sketches every time. Through developing the models, I realised early on that there was a lot of data that I wanted to incorporate, so I decided to develop two separate CSM's for each site. In line with NIGLQ QLRA I realised the importance of providing maps and diagrams of the sites and areas of contamination. An overview of the history that led to the contamination, previous investigations and regulatory drivers were all important elements to explain within the text to set the scene for the pictorial CSM's (NIGLQ, 2012).

A large proportion of time was spent upfront understanding each site and developing a CSM, this is an important step not to be taken for granted in the overall land quality management at a site. As there were no detailed cases studies or examples of developing CSM's in the literature for nuclear decommissioning sites, further case studies or examples for developing CSM's from easy to complex sites would prove useful for future users of the CLR 11 and Safegrounds guidance. Examples of remediating land at decommissioning NLS is limited so this would be useful, as a lot of these sites have complex land quality issues, which can sometimes involve radioactive and non radioactive contaminants.

Sharing examples of CSM's in the future via networks like Safegrounds would show what detail is expected for complex land contamination issues that can exist at some nuclear sites. I have learnt through this study that investing the appropriate amount of time in developing a CSM ensures that a good understanding is gained of the contaminant linkages. This makes screening of remediation techniques much easier and highlights the importance of taking time to ensure the CSM has the correct amount of detail before deciding on a management strategy to be taken.

The Safegrounds guidance and the NEA highlight the importance of information being fed back into evolving a more refined CSM. I found this was the case with both sites as I gradually gained a better understanding of the relationships between the sources, pathways and receptors, this helped reduce the uncertainties in the CSM. For example, the site investigation data from 2012 at Chapelcross site enabled a greater understanding of the depth and concentrations of contaminants (NIGLQ, 2012 & EA, 2004). This has helped support screening of remediation techniques as a better understanding of the sources and contaminant linkages was gained prior to undertaking the second stage in CLR 11 of Options Appraisal (EA, 2004).

The process of developing the CSM for each site was the same in identifying the sources, pathways and receptors and building these into a model. However different factors and regulations have to be considered at each site when deciding how the linkages in the CSM are to be broken due to Chapelcross having non radioactive land contamination and Bradwell having radiological land contamination. Bradwell sites radioactive land contamination falls outside of Part IIA and the Planning regime as it is regulated by the NIA65 and the LC's which govern the site. A safety case forms part of the requirements for radioactive land and ALARP demonstrations. Compliance with LC's such as LC34 require that the spread of radioactive contamination is minimised, monitored and demonstration of BAT is needed for minimising radioactive wastes (ONR, 2014).

Therefore, the ONR and EA were the main regulatory stakeholders throughout the process at the site and as not many Magnox decommissioning sites have undergone remediation of radioactive contaminated land, the ONR have limited experience in regulating and approving such remediation schemes. This will improve as more sites have to undergo remediation of radioactive contaminated land and experience, development and improvement of different techniques occurs.

At Chapelcross as the contamination was non radioactive meant that the ONR were not involved and the Local Authority and SEPA were the main stakeholders. The experience of Local Authorities and SEPA in regularly dealing with and approving remediation at non radiological contaminated sites means that guidance on requirements is more developed and clearer. Being aware of the regulations, stakeholder requirements and concerns are important when determining how the linkages within the CSM can be broken.

6.2 Site Characterisation and uncertainties in the Conceptual Site Model

The site investigations and monitoring data for each site provided a lot of information which enabled detailed CSM's to be developed, which has helped reduce the uncertainty for each sites CSM. Bradwell site had an advantage that it had already undergone remediation so further information was gained from the selective excavation and capping undertaken at the site to refine the CSM. If up front characterisation of the ground beneath the OAEDL at Bradwell site had been undertaken prior to remediation in 2013/14, this would have provided the data to confirm that the OAEDL did not need to be fully excavated. This supports the CLR 11 guidance which highlights the importance of identifying gaps and important uncertainties so that further information can be gained and integrated to refine the model early on so as to ensure the correct remediation strategy is chosen (EA, 2004).

The uncertainty surrounding the quantity and variety of buried materials at the "North End" could not have been improved with more site investigation as the distribution was so varied, therefore this uncertainty had to be managed through the screening process (section 4.3.4). Where techniques such as in situ electrokinetic remediation were screened, this uncertainty had to be taken into account as the technique is affected by metallic materials present in the ground (IAEA, 2014). The CSM's developed for each site have taken a lot of time and reiterations but through this process much understanding has been gained which has supported the remediation screening (NIGLQ, 2012).

The CSM developed for Chapelcross site took into account the more detailed 2012/13 site investigation data (section 4.1.2). This detail was added to the CSM on the depth and concentrations of chlorinated solvents so as a better understanding of the linkages was known for screening remediation strategies. Through reading the site investigation reports it was established that DNAPL had migrated at depth through fractures in the St Bees Sandstone. The DNAPL was then able to slowly dissolve back into the groundwater from the fractures. The time this will take is an important uncertainty and had to be addressed within the remediation options screening process.

The further detailed site investigation proved useful in establishing that DNAPL at depth is unlikely to have penetrated into the matrix of the sandstone (section 4.1.2) (EA, 2001 & Parker et al, 2012). The further site investigation and time taken developing the CSM has enabled better understanding of these linkages for remediation screening (EA, 2004). This supports CLR 11 and the importance of further site investigation and continuously updating the CSM so it helps feed the right information into the decision making process (EA, 2004).

6.3 Setting screening criteria for remediation strategies

The screening objectives, assumptions and constraints were set based on regulatory drivers, C&M dates and site specific requirements. Most of the objectives for each site were based on Magnox and NDA requirements for getting sites into a suitable condition for C&M and ensuring liabilities are reduced as much for FSC. The objectives for each site couldn't have been set without developing the CSM's and having a full understanding of the contaminant linkages. Assumptions and constraints were developed from site specific information gained through developing the CSM. For example, limited space at Chapelcross and restrictions at the Bradwell "North End" slope were all information gained through developing the CSM's and affected the screening of remediation options.

The detailed level of assumptions and constraints set for each site would not have been possible without the time taken to develop the detailed CSM's. For Bradwell site objectives existed from a previous options assessment which was undertaken. These objectives were reviewed to ensure those going forward were in line with recent guidance published and updated information in the CSM. Updated regulatory expectations issued by ONR, EA, NRW and SEPA in June 2014 (ONR, 2014) and the NDA's preference of trying to retain flexible final site end states (Magnox, 2013) all supported reasons to remove criteria on removing soils with radioactive contamination >200Bq/g (Magnox, 2013).

The Safegrounds guidance on comparison of contaminated land management options does not acknowledge that remediation options may need to retain some flexibility for the future. As discussed (section 4.3.6) technological advancements for remediating radioactive land could improve significantly within the 60-70 years of C&M until FSC. This can be seen with conventional remediation approaches moving from physical methods towards chemical and biological treatments (Kueper et al, 2014). Although physical approaches such as excavation seem to be the most commonly still used for radiologically contaminated land, advancements have occurred towards biological and chemical approaches (Tabak, 2005 & CIRIA, 2004). The USA have shown applications of zeolite PRB's for Sr-90 contaminated groundwater as effective long term solutions (VanderMeulen, 2012). In situ techniques such as electrokinetic remediation can permanently remove contamination by concentrating the contamination as a smaller waste mass to be removed on electrodes. Application of chemical techniques such as chelating agents to geologies where radioactive contaminants have become bound, like Cs-137 on clay shows an area where further development and advancement is needed (Tabak, 2005).

A TRL of 7 or above was one of the objectives for both sites, taking into account the technical effectiveness consideration under CLR 11 and Safegrounds (EA, 2004 & CIRIA, 2009). I believe incorporating a TRL at the screening stage supported the short time bound objective for each site. It upheld the Magnox requirements of reducing the need for further intervention during Interim C&M and C&M (Magnox, 2013). This showed how the time bound consideration influenced the level of technological readiness required for both sites. If the time was not so tight at both sites then the screening of options may have enabled less technologically developed options to progress to assessment, as time would have been available to undertake further developmental and demonstration trials (NDA, 2014).

This highlights the importance of not leaving remediation until the end stages of moving into C&M as it may limit certain techniques. The importance of sites encompassing the Safegrounds key principle of "immediate action" and making sure a programme of prioritised APC's for investigation is undertaken is important so as the appropriate management strategy or remediation is not rushed (CIRIA, 2009).

6.4 Screening of remediation techniques in developing remediation strategies

The screening of remediation techniques for each site took a long time initially as it involved establishing a basic level of understanding of a wide range of techniques. I first started with a high level overview of the supporting information section in CLR 11 and the "Remediation Options Applicability Matrix" (EA, 2004). This gave me a guide on what techniques were applicable to what contaminants at a high level. For a more in depth overview of radioactive remediation techniques, the Safegrounds guidance on technical options for managing contaminated land was reviewed. This gave more detail on shortlisting techniques for Bradwell site such as electro remediation, stabilisation and vitrification (CIRIA, 2004).

The development of the contaminant linkages in the CSM's required going back to basic principles and seeing how each linkage could be broken by the remediation technique or combination of techniques (EA, 2004). CLR 11 highlights the importance of having knowledge of the broad characteristics of remediation options when screening. But neither Safegrounds and CLR 11 highlight that in order to ensure contaminant linkages are broken in the CSM, further detail is required on what depth and geologies certain techniques are best suited to so as remediation is effective. Some of the constraints at the sites such as limited space meant that certain techniques which required a large footprint for equipment or waste were not viable. In order to understand the detail required in order to fulfil all the objectives, assumptions and constraints at each site meant a time consuming process of reviewing different publications, journals and case studies. This process would have been undertaking in less time if an experienced consultant in remediation techniques was undertaking the process.

Through the screening process I realised that a detailed CSM, objectives, assumptions and constraints ensures you can properly look at what remediation techniques are suitable. The screening process took around 35-40 days from setting criteria for each site through to selection of options. This highlights that for more complex sites, screening can be a timely task.

The length of time this took is also reflective of undertaking the task for the first time as a single assessor. Normally this process would involve a group of stakeholders discussing and agreeing screening requirements. The setting of screening criteria may take longer amongst a group of stakeholders due to a wide range of different perspectives and considerations to be taken into account. The different regulatory stakeholders involved in such a process at the Magnox sites would mean that when identifying suitable remediation techniques to screen against this stage is likely to be quicker due to a wider range of knowledge and experience to be shared. Whereas I experienced as a single assessor undertaking such an assessment for the first time with limited knowledge of different remediation techniques meant that further time was needed researching and developing my knowledge in order to determine which remediation techniques were best suited to each site.

The screening process has shown mean that more than a broad understanding of remediation techniques is required to ensure that the correct options are taken through for assessment. The evaluation of why options pass or fail needs to be clearly documented. I found developing an overarching visual colour coded table showing where options passed or failed gave a good high level summary. This would be particularly useful when communicating the screening process to stakeholders who may not fully understand the detailed documented evidence for why techniques passed or failed.

CLR 11 and Safegrounds guidance could provide more detail on the screening process particularly in the Safegrounds guidance for complex nuclear sites. Highlighting within the guidance that detailed CSM's enable easier setting of screening criteria and developing the right level of understanding of remediation techniques to ensure contaminant linkages are broken effectively needs are important areas to address within guidance. The use of summary tables for screening and examples of these within Safegrounds and CLR 11 would help give clearer ideas and guidance on different formats that can be applied to current practice to record the screening process.

As discussed Safegrounds options assessment guidance and CLR 11 are very limited on the detailed advice they give in regards to applying different remediation techniques or combining techniques. The "Remediation Options Applicability Matrix" in CLR 11 was a useful starting point but the high level nature of the matrix did not give enough detail (EA, 2004). Searching journals, publications and case studies to understand the detail of a technique and if it was valid to the site specific requirements had to be undertaken. CLR 11 guidance could be improved to help this process if a matrix was developed giving a more detailed breakdown than just the substance the remediation is applicable to. For example, detail on the different forms of thermal technique available under thermal treatment and what geologies they would be best suited to. A matrix which shows the applicability of techniques against factors such as geology, hydrogeology, space required and waste generated are all useful considerations at screening. Defra project SP1001 (Defra, 2010) has developed sheets on each remediation technique incorporating this sort of data, but it would be easier in a matrix, similar to those in CLR 11. An example of a few of the different in situ thermal techniques for chlorinated solvents and factors that could affect the choice are shown in an example matrix below.

Chlorinated solvents					
Remediation	Applicable Media (Soil=S Ground Water= GW)	Geology - Low permeability	Geology- High permeability	Space required for plant	Waste
In Situ Thermal Techniques					
Electrical Resistance Heating	S	✓		Can require a large foot print	Minimal
Thermal Conductive Heating	S	✓		Can require a large foot print	Minimal
Steam Enhanced Heating	S		✓	Can require a large foot print	Minimal

CLR 11 and Safegrounds guidance on technical options for managing contaminated land do not provide information on which remediation techniques are good to combine in different scenarios. CLR 11 mentions about combining techniques but no detail on how to do this. There is published literature on combining remediation techniques for conventional contaminated land but for radioactive contaminated land there is little mentioned.

Due to the C&M phase providing a period where techniques will evolve and emerge, the ability to have a combined technique gives the option for interchangeability when new developments occur. This could possibly make a site more flexible in the long term and keep in line with NDA preferences of making best use of technological advancements that may evolve. Although combining techniques is not as advanced for radioactive contaminated land, it is an area that requires further development. Combining techniques could benefit sites for the C&M and FSC stages and needs to be a future area for review and development in Safegrounds guidance in the coming years.

6.5 Discussion of the sustainability assessment process undertaken at Chapelcross site and Bradwell site.

The sustainability assessments undertaken worked well using the SuRF UK framework and briefcase (CL:AIRE, 2010 & 2013). The guidance documents gave a clear and structured format to follow which made the sustainability assessments fairly straight forward to undertake. The key boundary conditions of spatial, time and component lifecycle (Bardos et al. 2011) were easy to set as the majority of them had already been considered through following CLR 11 and Safegrounds guidance on setting objectives, assumptions and constraints (EA, 2004 & CIRIA, 2009). This highlights how closely related the steps in the SuRF UK framework and briefcase are to the "screening" and "identification of feasible remediation options" within CLR 11 and Safegrounds. The SuRF UK framework and process of sustainable remediation options assessment works well alongside CLR 11 and Safegrounds. Reference to using the SuRF UK framework within Safegrounds and CLR 11 would ensure greater emphasis on sustainability as part of the overall options assessment process in the future.

SuRF UK strongly recommends as one of its 6 key principles to involve stakeholders early on (CL:AIRE, 2010). For the purpose if this study this was not possible with either sites due to the permission, time required of stakeholders and resources to set up workshops. Instead a best account of stakeholder views and opinions were summarised (section 4.4.2 & 4.4.3) so as these could be considered when undertaking the sustainability assessment and scoring options. This is further supported by a case study under SuRF UK of a remediation options assessment where only limited stakeholder involvement was undertaken with representatives from key stakeholders (CL:AIRE, 2013). This shows that it is not always necessary to have all stakeholders involved in the process as long as all likely views are considered and taken into account to make as balanced assessment as possible.

With both sites, stakeholder interest forms a major part of the assessment especially for regulators such as the ONR, EA, SEPA, Magnox and the local community wanting to have input and agree with the best way forward. Their views and opinions were considered as best as possible but required trying to make sure bias was not introduced when weighting indicators. As a single assessor this was a difficult task and represented the same findings as the sustainability appraisal benchmarking exercise discussed in the literature on a tier 2 assessment being difficult to undertake as a single assessor (Smith & Kerrison, 2013). The SuRF UK framework, Safegrounds and CLR 11 highlight the importance of applying sensitivity analysis when undertaking an assessment. This was even more important as a single assessor to highlight any weaknesses in the assessments at each site. The application of Hiview software meant sensitivity analysis was part of the software output making this process much easier to undertake using an existing software application which highlighted where weaknesses existed.

The application of the SuRF UK indicators within the Hiview software were incorporated quite easily showing the flexibility of the SuRF UK framework into an existing software tool. The Hiview software had previously been used in options assessment of waste projects at nuclear sites on the basis of costs and benefits, but had never been used for a contaminated land remediation options assessment at a nuclear site (DCLG, 2009). Applying the SuRF UK framework within the Hiview software meant the environmental, economic and social pillars were considered in place of costs and benefits (Catalyze, 2003).

This was a fairly straight forward application to achieve in the software and after speaking to an advisor from Catalyze I was able to alter and incorporate the three pillars of sustainability under three nodes (figure 11 & 12). More examples of applications of existing tools like Hiview with the SuRF UK framework would give assessors more ideas on how to implement sustainable remediation options assessment more readily. As discussed in the literature, frameworks and metrics are seen as barriers to implementing sustainable remediation practices (Ellis & Hadley, 2009). Provision of further case studies on the application of different tools for sustainability assessment in SuRF UK, Safegrounds and CLR 11 guidance would help support the incorporation of sustainability within the remediation options assessment process more readily.

Before looking to undertake the sustainability options assessment, such tools as SRT REC and GoldSET (table 2) were further researched within the literature review. SRT and REC have far fewer indicators under the social pillar of sustainability than the SuRF UK indicators, with both tools more focused on the environmental and economic pillars. GoldSET has a wider range of indicators under all three pillars of sustainability but is only available commercially as part of Golder Associates Services so was discounted from being used.

The SuRF UK framework enabled an equal focus on all three pillars of sustainability due to the wide range of indicators to be considered under each pillar. The SuRF UK framework addressed indicators such as possible burdens on future generations which is especially important in options assessment for nuclear decommissioning sites due to the long C&M phase until FSC and intergenerational effects this can then have. The SuRF UK categories also took account of considerations mentioned under the nuclear specific literature on requirements for options assessment (ONR, 2006 & CIRIA, 2009).

Although the SuRF UK framework is not a tool or technique, it has shown through this study that it can be applied to an already existing tool like the Hiview software. It was noted through using Hiview that justifications cannot be recorded within the software for why a score was given. Clear and reproducible evidence based decision making, ensuring record keeping and transparency are two key principles of the SuRF UK framework (CL:AIRE, 2010). Undertaking the assessment in the URS spreadsheet first meant that instead of scores being put directly in Hiview, they were recorded in a spreadsheet and the justifications for the score also recorded. This meant that all the evidence was kept to support the output from Hiview.

The completion of URS sustainability spreadsheet for each site took 4 -5 days per site. The inputting of the sustainability assessment data into the Hiview software, modelling and generating the results took around 2 days per site. Around 5 days of reading, learning and understanding how the Hiview software worked prior to undertaking each of the assessments was done first. Smith & Kerrison benchmarked that a tier 2 assessment should take on average of 1-3 days. Having only undertaken a basic tier 1 sustainability assessment once previously I did not have any experience of a tier 2 assessment and completing it as a single assessor may have made it slightly slower.

The use of the Hiview software extended the time for the tier 2 assessment, but was a useful piece of software particularly when undertaking sensitivity analysis as it provides this as part of the model in an easily interpreted table. The study showed a tier 2 assessment took longer than the literature discussed and may have been down to incorporation of a software tool and being a single assessor. Hiview was unable to record the justifications for scoring and weighting but implementing the URS sustainability assessment spreadsheet ensured this was covered. This needs to be a consideration within future SuRF UK guidance and highlighting to assessors that dependent on the tool used and if the assessment is being undertaken as a group or individual will affect the time it takes.

6.5.1 Chapelcross Sustainability assessment and sensitivity analysis

At Chapelcross site the Hiview results (table 21) show that option 2 scored the highest of all 4 options in the sustainability assessment however it did not score the highest individually under any of the three pillars of sustainability (table 23, 24 & 25). Option 2 was still a strong performer in the economic and environmental pillars, although not as strong under the social pillar, but this did not affect the overall performance and weighted score of option 2.

The sensitivity analysis at Chapelcross site showed that option 2 is fairly robust (table 22). The sensitivity of option 2 under project lifespan and flexibility required a >5 to 15 cumulative weight decrease to change to option 3. Option 3 (PRB) would not have been improved under this indicator because the technique required more detailed research on how flexible it would be as a combined strategy and if this would increase the project duration. All of the other options except "Status Quo" involved combining at least two different physical, biological or chemical techniques in order to break the linkages. In most cases this helps speed up the project duration and gave the options greater flexibility due to utilising two techniques, which meant they performed better under the project lifespan and flexibility indicator.

This shows that in certain cases a combined strategy as discussed in the literature can give greater flexibility and reduce uncertainty as you are not then reliant on just one technique (Kueper et al, 2014). However, this would only be applicable to certain combined remediation techniques where one is not reliant on the other. For example, if surfactants are applied to leach contaminants from the soil then a secondary treatment such as biological or chemical would still be required in order to permanently remove the contaminants to ensure they are not spread even further. In the case of removing the uncertainty surrounding the project lifespan of a PRB at Chapelcross site, a more detailed design would be required. Incorporation of another treatment such as a source zone treatment like in situ ZVI soil mixing would reduce the uncertainty, as this would stabilise and reduce the source zone that may otherwise be adding to the plume.

If these improvements were made to option 3, it would mean that the economic direct cost would increase. It already scored the lowest on this indicator under the economic pillar so it would have performed even worse. More resources required for in situ soil mixing would mean that the environmental natural resources and waste indicator would not score as well. The score would improve under ethics and equality due to reducing the long term transfer to future generations.

In order to assess the above effects on option 3, I re-run the model through Hiview incorporating the source zone treatment of in situ ZVI soil mixing with the PRB. The direct economic costs were increased by adding the capital costs for in situ ZVI from table 13, along with altering the indicators of natural resources & waste, project lifespan & flexibility, ethics & equality and uncertainty & evidence. The altered scores and Hiview output are shown in appendix 16. The results show that the incorporation of a source zone treatment alongside the PRB were not enough to make option 3 the preferred option, although it did increase the score. Option 2 still remained the preferred option, although the score reduced making the difference between option 2 and 3 only four points.

The sensitivity analysis has highlighted that step 8 in the MCDA process is very important and has shown that creating and testing new possible options ensures that a robust decision is made. SuRF UK mentions testing alterations in data, assumptions and stakeholder views within a sensitivity analysis. The guidance does not go into the time and detail this process can take at the end of a sustainability assessment. If examples and case studies of sensitivity analysis were provided within the SuRF UK and Safegrounds guidance this would give assessors a better idea of how time consuming the process can be but the importance of undertaking it.

The sensitivity of option 2 under neighbourhoods & locality required a >5 to 15 cumulative weight increase to change to option 1. Option 1 scored well under this indicator as the strategy involved all on site remediation activities except for just routine monitoring of boreholes afterwards. The further analysis of the effect of different weightings in section 5.3 has shown that a large difference is required between the input weights in order to change the overall cumulative weight. Further assessment was undertaken in Hiview by altering the input weight against the neighbourhood & locality indicator. In order to change option 2 to 1 against neighbourhoods & locality, the weight against this indicator had to be increased by at least three times the inputted weight of 60. This has highlighted that the input weightings against indicators do not have large enough differences in order to affect a significant change in the cumulative weights. As some of the indicators have been weighted quite closely in the assessment, the difference between them is not great enough to affect the overall preferred option.

Option 2 involved more boreholes having to be drilled in neighbouring fields which would cause more disturbance than option 1. Although option 1 is a general good all rounder across all indicators under the social pillar, option 2 performs very strongly under uncertainty & evidence and ethics & equality (table 25), due to the confidence gained from the 3DMe trials. In line with the literature on MCDA, if the remediation option information is of greater maturity it will generally perform better against other options where factual information is only available (CIRIA, 2009).

Option 2 performs better than option 1 across all the environmental and economic indicators therefore the lower social indicator scores do not affect its overall weighted score. A qualitative feeling of local community was assessed on my own judgement for the social scores. Literature has shown that MCDA is better where a range of stakeholder views are taken into consideration (CIRIA, 2009). Although I tried to consider stakeholder views as best as possible, this assessment shows that the social pillar can be more difficult to undertake as a single assessor. It is more open to varied views and opinions which introduces bias to an assessment. This might support reasons why tools such as SRT and REC discussed in the literature measure only a limited number of indicators under the social pillar due to the uncertainty that could be introduced when trying to score social impacts (Beames et al, 2014).

The sensitivity table showed what cumulative weight changes were required to change the preferred option, further analysis was undertaken in section 5.3 to see what affects changing the weights would have on the preferred option. The weights were changed purely trying to take account of what a local community perspective might be to see how this would impact the overall preferred option.

In order to try best represent only a community perspective the weights were increased under criteria which would have the most effect on the local surroundings and people such as 'neighbourhoods & locality' and 'emissions to air'. I felt that some weights already given to some criteria such as 'groundwater chemistry & mobilisation of contaminants' were already relevant to the importance that a local stakeholder would place. Table 33 shows that altering the weights has not changed the overall preferred option 2, although the scores between all four options has become much closer. There are now only four points difference between option 2 and second place option 3.

6.5.2 Bradwell Sustainability assessment and sensitivity analysis

At Bradwell site the Hiview results (table 26) show that option 2, capping/ cover system, with grouting of remaining OAEDL and draw pits scored the highest of all 3 options. The assessment was made easier as actual data could be used from the option 1 remediation scheme which had already been implemented at the site. This provided figures on waste generation for the environmental pillar and costs for capping and waste removal under the economic pillar. These figures could also be applied to option 2 as the remediation technique was similar, just not involving the selective excavation elements. This gave the Bradwell sustainability assessment an advantage over the Chapelcross assessment as more mature data was available for the MCDA assessment (DCLG, 2009). The sensitivity analysis (table 27) supports this with the overall preferred option being less sensitive than Chapelcross sites. This supports the literature that a more robust assessment can be undertaken if the data is of greater maturity.

The sensitivity analysis (table 27) showed that 7 of the indicators required more than a 15-point cumulative weight change in order to change them from option 2. This shows that option 2 is not very sensitive to changes in cumulative weight under these indicators and is a robust assessment. A large difference in the inputted weights would be required as experienced in the case of Chapelcross site, in order to affect the cumulative weights against these indicators and change the preferred option. The only indicator where >5 to 15 cumulative weight increase to change from option 2 to option 1 was required was under project lifespan and flexibility. This is a limiting indicator under option 2, as option 1 involves excavation whereas option 2 does not have this ability. If excavation was included, then it would reduce the burden on future generations and reduce the uncertainty about what was being left but environmental indicators and direct economic cost would have suffered. Option 1 could have been improved if elements of option 2 were included such as concreting the OAEDL in situ instead of removing it completely, which would have reduced the overall waste disposal costs and duration of the project.

Looking at ways to improve option 1 supports the DCLG MCDA literature on sensitivity analysis and looking at the advantages and disadvantages of options to see where a new or improved option can be created (DCLG, 2009). If option 1 was improved by grouting and leaving the OAEDL in situ then it would have improved under the indicators of 'Emissions to air', 'Natural resources and waste', 'Direct economic costs' and 'Neighbourhoods and locality'. However, when looking at the sensitivity analysis and scores under each of the three pillars for these two options it would still not be enough to change the highest scoring option 2 to option 1.

In order to further analyse the sensitivity of the Bradwell assessment the same exercise was undertaken on the indicator weights as had been undertaken for Chapelcross site. This involved altering the weightings purely from a community perspective. Table 34 shows that altering the weights has not changed the overall preferred option, but increased the score of the most preferred option 2. It has also lowered the score of second place option 1, although only by 1 point, making the difference between the most preferred option 2 and second place option 1 greater. The example of sensitivity analysis at Bradwell site supports the SuRF UK framework and the importance of comparing differences and impacts between indicators at the end of the assessment so as a balanced robust decision can be made (CL:AIRE, 2011).

Safegrounds highlights the importance of the outcome of the sustainability assessment process not being a direct decision but through consultation with stakeholders a strategy is then developed. I did not have stakeholder involvement at the end of the assessment but through analysis of the sensitivity and further testing with altering input weights ensures that a robust process is undertaken. For more complex sites like Bradwell and Chapelcross stakeholder and regulatory input is important to ensure buy in to the overall strategy is agreed (CIRIA, 2009).

6.6 Status Quo Option and importance for comparison against options

At both sites the "Status Quo" option scored the lowest out of all options. Incorporating an option of "Status Quo" within both sites assessments has shown that the benefits brought from implementing remediation at both sites outweighs remaining with the option of "Status Quo" at both sites (CIRIA, 2009). It highlights the importance of only using "Status Quo" within an overall sustainability assessment because if the decision had been made on the economic pillar of NPV alone "Status Quo" would have come out on top.

The high weighting given to the economic indicator of NPV is appropriate as its important for the nuclear provision budgeting, but still needs to be balanced against the other indicators to determine a sustainable option. Implementation of most remediation techniques will involve impacts to emissions to air and natural resources & waste, whereas continuing with routine monitoring will score attractively under these indicators. This shows the importance of sustainability assessment overall and how status quo can be a good basis to compare the improvement other options give, but only for this purpose.

6.7 Cost estimates at Chapelcross and Bradwell Site

The cost estimates derived for Chapelcross site were the most time consuming element of section 4.0 and took around 15 days. They took longer to complete than the Bradwell cost estimates because the literature on examples of remediation costs was limited, hard to find and only applied to site specific scenarios. This study has observed the same as Kueper et al, 2014 which identified examples of remediation costs as a weakness and developed case scenarios for sites affected by chlorinated solvent contamination. These examples were used along with cost data taken from real life scenario case studies by the USA Naval Facilities Engineering Command, Provectus Group and Regenesis in supporting my high level cost estimates.

It was hard to find examples of cost data on remediation strategies as a lot of it is commercially sensitive for remediation contractors so there are limited published case studies. Due to the date when the cost data was published some costs had to be indexed up to current day prices. The Kueper et al, 2014 case study costs were in US dollars so an exchange rate had to be applied to convert them into British pounds. Therefore I had to apply the rate from the day I undertook the cost estimates.

Site specific considerations were used where possible such as area and depth in calculating costs. Option 1 at Chapelcross site used TCH which had the biggest variable cost (table 12) because the amount of electricity required could change significantly depending on the TCH plant, operational period and temperatures required. This will also depend on what the remedial targets are set at, which are yet to be determined for Chapelcross site (section 4.1.3). This will affect the length of application required and the cost. This is where the detail for the cost estimate is lacking and can show how this has a knock on effect to the NPV if not detailed enough.

The Bradwell site cost estimates were much easier in comparison as most of the data was available and could be readily applied to the alternative options under the assessment, making the cost estimate faster to undertake. Actual cost data was available from contractors cost estimates and I was also able to establish the waste disposal costs through quotations given for disposal of radioactive waste. This made the cost estimates for Bradwell site more accurate than those at Chapelcross site and a lot quicker to undertake as less research was required. However, this would be very unlikely in a scenario where you were developing a remediation strategy from scratch, as the quantity and quality of data would not necessarily be available. The process has highlighted that there can be a lot of assumptions that have to be drawn at the lower level of cost estimating especially where data is limited and not as detailed and this can in turn affect the accuracy of the NPV calculated.

6.8 Discount rates and calculation of NPV at Chapelcross and Bradwell site

The calculation of the NPV at each site was not a time consuming task once the cost estimates were completed and the years the costs were being spread over set. Excel has a function which can calculate NPV as long as capital and yearly future costs are known. This took around 5 hours per site to check and enter the cost data to calculate the NPV. The calculation of the NPV for each site showed that setting a clear time line for a remediation strategy is important to ensure that the costs are accounted for in the nuclear provision, especially if monitoring is required for outer years (NDA, 2015).

I found setting the timeframe for remediation strategies easier at Chapelcross site because the techniques screened had been previously applied more readily and were more advanced (table 8). Whereas at Bradwell site there was uncertainty surrounding the technological readiness of some techniques (table 9) and being able to meet the tight C&M date. The strategies which made it through screening were capable of being effective for the C&M period until FSC and had some flexibility if technology evolved and a new technique could be applied in this period. The process highlighted time and technological advancement being uncertainties particularly for Bradwell site, which is line with the literature and the reflection of these uncertainties within the nuclear discount rates set (NDA, 2014).

The sensitivity applied to the nuclear rates was to reflect the possibility of interest rates increasing and potentially improving the rates under the nuclear provision. Technological developments would improve uncertainties over time and have the potential to reduce the rates (NDA, 2013/14). Therefore, the original HM Treasury Nuclear Discount rates used in table 19 and 20 were improved to see what affects this would have on the NPV of each option. The sensitivity applied to the rates can also be seen in table 19 and 20, with 0-5 years applying -0.9%; 5-10 years applying -0.35% and 10+ years applying 3.20%.

At Bradwell site the sensitivity analysis on the NPV (table 20) showed that option 3 "Status Quo" would improve by £98,606 if the discount rates were improved. This was the largest difference between the sensitivity analysis applied to the NPV of all three options, showing that the 68-year term until FSC for continued monitoring was the largest contributor to the difference.

At Chapelcross site option 1 was calculated over a seven-year period, which meant that only negative discount rates were applied (NDA, 2014). The sensitivity applied (table 19) showed that the NPV for option 1 for Chapelcross site would improve by £112,243, if the rates improved. This is because option 1 has the largest capital cost therefore any improvement in the discount rates within the earlier years where negative rates are applied will mean the saving for the nuclear provision will be larger.

For option 2 and 3 (table 19) the sensitivity analysis applied showed the improvement was a lot smaller as the capital costs were less. The assumptions drawn for re application of media in line with literature reviewed on 3DMe and injection methods for ZVI (Regenesis, 2015 & ITRC, 2011) would have been better determined if the remedial targets were known for the site. This may have given a better indication as to whether these assumptions could have been removed or kept and may have improved the NPV for each of these options. Option 4 "Status Quo" was calculated until FSC (68 years) therefore the sensitivity applied showed a greater improvement in the NPV compared to option 2 and 3 but not as large as for option 1. This was due to smaller yearly costs being spread over a longer period so were not affected as much by the negative rates in year 0-10.

I realised through undertaking the sensitivity analysis on the NPV for each site that if I had more time further alterations in sensitivity could have been applied to give further comparison. The sensitivity analysis applied gives a good comparison between what an NPV would be if the interest rates improved, but additionally sensitivity could have been applied to show what affect would have occurred if they got worse. Many factors will affect the nuclear discount rate applied over time from interest rates, regulatory and governmental changes, alterations to end states of sites and even a significant nuclear safety incident could lead to increased liabilities which could make the rates worse.

The application of the nuclear discount rates shows that if you can try and refine your uncertainties in the first ten years then this could reduce the NPV (NDA, 2014). Ensuring remediation works fit in with proposed C&M dates for a site is important so that the site can enter this period with reduced intervention but suitable control over land quality issues until FSC (Magnox, 2013). If sites do not meet C&M dates this puts increased pressure on the nuclear provision and amending plans, budgets and ultimately more tax payer's money to support this (NDA, 2014). This process has shown that the time boundary for calculation of an NPV is equally important as it is for a sustainability assessment (Bardos et al, 2011). Therefore, the quality of the data and the level of detail used within costs estimates for an NPV must be considered in the overall result of a sustainability assessment.

Chapter 7 Conclusion

In conclusion:

- Feasible soil and groundwater remediation strategies have been chosen for both sites based on sustainable remediation options assessment incorporating NPV. This thesis shows that the SuRF UK framework can be readily applied to remediation options assessment and radiologically contaminated land and groundwater at nuclear decommissioning sites;
- The sustainability assessment has shown it is important for the decommissioning nuclear industry to consider the social, environmental and economic perspectives to ensure a robust remediation strategy. The SuRF UK framework addresses long term liability issues within its indicators and has shown it can be flexible by incorporating an NPV under the economic pillar. This is crucial for ensuring intergenerational sustainability at decommissioning nuclear sites;
- The assessment has shown that Hiview an MCDA software tool works well within the SuRF UK framework and highlights the importance of undertaking a sensitivity analysis to achieve a robust strategy. Weaknesses identified under indicators for certain options can be tested by changing scores, weights or identifying areas for improvement, which can be re-assessed through Hiview to see the affect on the overall preferred remediation. Through testing identified weaknesses this makes the assessment more transparent to stakeholders;
- Combined strategies need to be thought about carefully to ensure that where techniques are interdependent on one another that they both work in conjunction to ensure overall success of a remediation strategy;
- The research into remediation techniques for radioactive contaminated land has highlighted the need for more development in this area. Trials for techniques such as electrokinetic remediation and chelating agents to remove and concentrate radioactive waste into smaller waste quantities require further pilot trials and development. These techniques could reduce the focus from large excavations of radioactive contaminated soils and disposal at facilities like the LLWR;
- This thesis has shown the importance of utilising a framework like SuRF UK and how it could be applied to other industries which will have similar long term liabilities. For example, some of the long term

issues which are highlighted from 'Fracking' such as water pollution, waste disposal and methane leaks will need to be managed from the outset to get stakeholder buy in. Implementing techniques like sustainability options assessment from the start of such projects and not just when remediation is required will help ensure future energy developments are sustainable in the long term as well.

The SuRF UK framework has shown it can support remediation options assessment by identifying options which balance all three pillars of sustainability. At Chapelcross site the sensitivity analysis has shown that option 2, ISCR, enhanced bioremediation and monitored natural attenuation was the preferred option (section 6.5.1). The sustainability assessment for Bradwell site has shown option 2, capping/cover system with grouting of remaining OAEDL and draw pits was the preferred option (section 6.5.2).

The sensitivity analysis was robust for Bradwell site due to quantitative data available from the implemented remediation at the site. Option 2 was more sustainable than the original option 1 of selective excavation, removal of OAEDL and a capping system. The sensitivity analysis at Chapelcross site highlighted where possible improvements could be made to options. These were tested for option 3 by adding a source zone treatment and altering the scores to accommodate this. These were then re-run through Hiview to see what affect this had on the overall preferred option. Altering the weights from a local community perspective also enabled the assessment at each site to be tested further to see how different stakeholder perspectives could influence the preferred option.

The sensitivity analysis has shown that through analysing where improvements can be made to options, developing new options and the effect this has on indicators has not changed the overall preferred option in this assessment. It shows that sensitivity analysis is an important task to make an assessment transparent and testing different theories can be time consuming, but is required to ensure a robust well justified and balanced remediation strategy.

The CSM for each site has shown that a clear understanding is required of the area where contamination is present in order to understand the contaminant linkages thoroughly to support the screening process. The process of developing the CSM can be very time consuming especially for complex nuclear decommissioning sites and therefore a site visit is essential. In conclusion developing a CSM to a very detailed level can provide more confidence in the screening and identification of remediation strategies.

The identification of suitable remediation strategies has shown that a basic level of understanding of remediation techniques is required. In order to ensure contaminant linkages are effectively broken in the CSM further detailed understanding of techniques is needed, which can be time consuming. A detailed CSM made the process of setting screening objectives, assumptions and constraints much quicker and enabled a smoother screening process. Where radioactive land contamination exists and the need for long term intergenerational sustainability is required, remediation techniques that have the capability to be interchangeable with new evolving technologies will be more sustainable long term.

The calculation of the NPV has shown that an understanding of developing a cost estimate is needed and appreciation of the quality of data being used. The limited examples of cost estimates in literature for remediation strategies has highlighted that assumptions have to be drawn at this level and this affects the accuracy of the NPV. Having access to actual site specific cost data makes a cost estimate more accurate and faster to undertake and therefore the NPV is of a better quality. Undertaking a cost estimate from only examples in literature has proven to take longer than undertaking a sustainability assessment.

In order to reduce uncertainties within nuclear decommissioning and improve the nuclear discount rates there will need to be innovations, efficiencies and shared learning from experiences of remediating land at decommissioning nuclear sites. The long period of time through C&M to FSC means new techniques will evolve and emerge. Those sites which have developed remediation strategies with the ability to be flexible and interchangeable will be best placed to ensure they remain sustainable up to FSC.

7.1 Areas for improvements

Due to the nature of the assessment there was no direct stakeholder involvement, although this is not necessary, it would have made the weighting and scoring of options easier. The views and opinions of stakeholders were included and reflected in the assessment as best as possible, but this was particularly hard and some bias may have been introduced through undertaking the assessment as a single assessor. If the sustainability assessments were to be undertaken again, stakeholder involvement would be recommended, to ensure the inclusion of a wide range of perspectives.

More time could have been assigned to the weighting of indicators and ensuring they were representative of the stakeholders. This could have been undertaken by engaging with different departments at Magnox but also outside of the industry and recording the weights different groups would assign to the indicators. This would have made the assessment more inclusive of a broader range of stakeholder opinions. A more reliable weight for each indicator could have then been established by taking the average of the range of weights.

The sensitivity analysis identified where there were weaknesses under indicators, so as further testing of these could be undertaken to see how robust the preferred option was. It also highlighted where possible improvements could be made to options to make them score better. The further testing of sensitivity was limited and could have been extended to re-run the Hiview models from a variety of stakeholder views to see how this affected the overall remediation option.

The inclusion of TRL's within this options assessment for nuclear Decommissioning sites has shown that they can be open to interpretation. Where techniques need to be combined this can make assessing the TRL difficult. If undertaking this study again I would consider input from specialists when deciding an appropriate TRL's for a technique, especially where there is more than one technique and combinations. This would give a more thorough consensus when assigning a TRL level.

7.2 Recommendations for future work.

Recommendations for future work include additions to CLR 11, Safegrounds and NIGLQ QLRA guidance. Further guidance within these documents is needed for where complex sites exist and the importance of taking time to develop a detailed CSM in these cases. The inclusion of a site visit within guidance should be recommended for complex sites as it could reduce the timeframe required to develop the detail in the CSM. More case studies within guidance on CSM's for contaminated land at complex sites would help guide such sites when undertaking remediation.

The Safegrounds options guidance should highlight that some sites will be best placed to keep their options open and flexible. This would make them better placed to take advantage of technological change and innovation which may occur throughout C&M to FSC. The development of a high level summary table when screening remediation techniques proved useful. Examples of such formats within the CLR 11 and Safegrounds guidance may prove useful in giving assessors ideas for communicating screening results to stakeholders easier. More case studies on the application of sustainability frameworks such as SuRF UK within Safegrounds and CLR 11 will ensure that sustainability is considered more readily as part of remediation options assessment in the future.

Further development of the "Remediation matrix" in CLR 11 to include the applicability of techniques against factors such as geology, hydrogeology, space required and waste would be particularly helpful at the screening stage. The development of a matrix to show what remediation techniques have been successfully combined would also help sites where one technique is not enough to demonstrably break the contaminant linkages in the CSM.

The further development of a table or additions to the Beames et al, 2014 table (table 2) for tools and techniques for sustainability assessment would be beneficial, so as other techniques such as Hiview could be added. A recommendation for the Hiview software would be that an area should be added within the software to record justifications for scoring and weighting options, so as all evidence is kept together. Compilation of this data into a suitable output from the software showing the process, results and justifications would be useful. Future application of sustainable remediation options assessment at other nuclear decommissioning sites would give more examples of the process for sites to follow.

Applying other sustainability frameworks other than SuRF UK would enable comparisons to be made to determine if any others are better suited to remediation options assessment for nuclear decommissioning sites. As well as the different frameworks which could be tested, different options assessment tools such as REC, SRT and GoldSET could be compared against Hiview. By testing the same site scenarios and remediation options through the different tools would enable a comparison of the different tools to see how this impacts the remediation option outcome.

The sustainability options assessment has shown that sensitivity analysis is an important element within the choice of a remediation strategy. It has shown that a sustainability options assessment can be subjective and depends on the inclusion of a wide range of considerations across different stakeholder perspectives. Therefore, further work could be undertaken by getting a wide range of stakeholders from different sectors and professions to weight the indicators chosen at each site and reasons why. The range of stakeholder weights could then be consolidated in a table and an average weight gained for each indicator. This could be run through Hiview to see what impact this has on the remediation option. This process would be more pragmatic and representative of a broader range of stakeholders rather than trying to gauge as a single assessor the likely weight against each indicator.

The mix of radioactive and non radioactive contaminated land and development of remediation strategies to deal with these combinations is not available within a framework or guidance and is an area that could do with improving. There are APC's present at Magnox sites which have mixed radiological and non radiological land contamination, although none of these cases have required remediation so far. This could be an emerging area where further research into combining remediation techniques for such cases would prove beneficial in the future. Further research and development of in situ remediation techniques particularly for radioactive contaminated land are required. This will make sites more flexible and reduce the future burdens on waste disposal facilities such as the LLWR, as well as the large economic costs associated with the excavation and disposal of radioactive contaminated land.

The USA have established a more flexible approach to site end states with a "restricted release" criteria, which still enables the site to be delicensed but restrictions are applied for future use of the land (Safegrounds, 2012). This may prove useful for some decommissioning NLS in the UK where remediating radioactive land to delicensing risk criterion could be grossly disproportionate and therefore not the most sustainable choice. The IAEA guidance on utilising the "restricted release" criteria could be useful in the future if the ONR and EA were to agree to its use. This would mean more sustainable use of tax payers money by doing some remediation in order to achieve the criteria with conditions still remaining on the land. This gives flexibility for future technological developments to evolve in the next 60-70 years through the C&M phase. The Safegrounds options assessment guidance needs to value that in the case of some sites keeping options open and flexible until FSC and even long term stewardship has to be considered within options assessment.

Historically short term gains usually triumph over long term consequence, this is where sustainability options assessment ensures that long term issues are not forgotten. This is a key requirement for nuclear decommissioning sites like Magnox which need to ensure long term sustainability for its long term liabilities.

Glossary of Terms

AETP	Active Effluent Treatment Plant
ALARP	As Low As Reasonably Practicable
APC	Area of Potential Concern
ATB	Armature Treatment Bay
BAT	Best Available Techniques
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CBA	Cost Benefit Analysis
CIRIA	Construction Industry Research and Information Association
CL:AIRE	Contaminated Land: Applications in Real Environments
CLU-IN	The Contaminated Site Clean-Up Information
C&M	Care & Maintenance
C&MP	Care and Maintenance Preparations
CSM	Conceptual Site Model
DCE	Cis 1,2 Dichloroethene
DCLG	Department for Communities and Local Government
Defra	Department for Environment, Food and Rural Affairs
DNAPL	Dense Non Aqueous Phase Liquid
DQRA	Detailed Quantitative Risk assessment
EA	Environment Agency
EDL	Effluent Discharge Line
ERH	Electrical Resistance Heating
FSC	Final Site Clearance
GEM	Gamma Excavation Monitor
GoldSET	Golders Sustainability Evaluation Tool
GQRA	Generic Quantitative Risk assessment
HIRAM	High Resolution Assay Monitor
HRC	Hydrogen Release Compound
IAEA	International Atomic Energy Agency
ISCO	In Situ Chemical Oxidation
ISCR	In Situ Chemical Reduction
ITRC	Interstate Technology & Regulatory Council
ISTT	In Situ Thermal Treatment
KoC	Partition Co-efficient
LC	Licence Condition

LLW	Low Level Waste
LLWR	Low Level Waste Repository
MCDA	Multi Criteria Decision Analysis
MCLA	Maintained Contaminated Land Area
MNA	Monitored Natural Attenuation
NAVFAC	Naval Facilities Engineering Command
NDA	Nuclear Decommissioning Authority
NEA	Nuclear Energy Agency
NIGLQ	Nuclear Industry Group for Land Quality Guidance
NLS	Nuclear Licensed Site
NPV	Net Present Value
NRW	EA & Natural Resources Wales
OAEDL	Original Active Effluent Discharge Line
O&M	Operations & Maintenance
ONR	Office of Nuclear Regulation
PCE	Tetrachloroethene/ Perchloroethene
PRB	Permeable Reactive Barrier
QLRA	Qualitative Land Risk Assessment
RCLA	Recorded Contaminated Land Area
REC	Risk Reduction, Environmental Merit and Costs
RIFE	Radioactivity In Food and the Environment
RPV	Resource Protection Value
SAP's	Safety Assessment Principles
SEPA	Scottish Environment Protection Agency
SRT	Sustainable Remediation Tool
SuRF UK	Sustainable Remediation Forum UK
SVE	Soil Vapour Extraction
TCE	Trichloroethene
TCH	Thermal Conductive Heating
TESVE	Thermally Enhanced Soil Vapour Extraction
TRL	Technological Readiness Level
US EPA	United States Environmental Protection Agency
VC	Vinyl Chloride
VOCs	Volatile Organic Compounds
VLLW	Very Low Level Waste
WHO	World Health Organisation
ZVI	Zero Valent Iron

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APPENDICES

Appendix 1- Chapelcross Site chlorinated solvent concentrations in boreholes from 2002 to 2014 & Examples of Borehole Logs.

BH1 - 2.25-5.45m slotted section installed (7.15m bgl. deep)

Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Nov-02	690	10	228	10	3382	50	1	7	53	0.5
Dec-03	445	10	465	10	3062	50		7	57	0.5
Feb-05	231	10	370	10	1632	50		7	32	0.5
Aug-05	465	10	628	10	2960	50	147	7	53	0.5
Nov-05	444	10	395	10	2419	50	113	7	48	0.5
Feb-06	223	10	223	10	1712	50	70	7	26	0.5
Jun-06	445	10	506	10	2399	50	103	7	31	0.5
Aug-06	530	10	538	10	3101	50	120	7	34	0.5
Nov-06	356	10	371	10	2074	50	89	7	26	0.5
Mar-07	54	10	59	10	1100	50	31	7	18	0.5
May-07	190	10	370	10	2900	50	110	7	40	0.5
Sep-07	75	10	120	10	1700	50	56	7	15	0.5
Nov-07	77	10	170	10	1700	50	65	7	29	0.5
Feb-08	94	10	290	10	160	50	10	7	4	0.5
May-08	740	10	300	10	1000	50	64	7	15	0.5
Aug-08	1600	10	450	10	870	50	75	7	14	0.5
Nov-08	850	10	430	10	870	50	35	7	6	0.5
Mar-09	450	10	270	10	1000	50	33	7	13	0.5
Jul-09	560	10	430	10	1200	50	40	7	24	0.5
Oct-09	580	10	570	10	1500	50	110	7	34	0.5
Feb-10	360	10	350	10	1400	50	57	7	27	0.5
Apr-10	540	10	390	10	1700	50	43	7	25	0.5
Jun-10	570	10	460	10	2100	50	39	7	26	0.5
Oct-10	390	10	450	10	1900	50	47	7	28	0.5
Jan-11	7	10	16	10	250	50	1	7	2	0.5
May-11	210	10	230	10	1400	50	29	7	12	0.5

Aug-11	110	10	190	10	3000	50	63	7	62	0.5
Nov-11	104	10	44	10	987	50	15	7	6	0.5
Feb-12	150	10	72	10	947	50	20	7	10	0.5
Jun-12	368	10	142	10	1180	50	28	7	11	0.5
Sep-12	214	10	50	10	753	50	13	7	4	0.5
Dec-12	1250	10	190	10	866	50	37	7	21	0.5
Mar-13	339	10	184	10	1550	50	21	7	19	0.5
Mar-13	1290	10	184	10	1330	50	38	7	15	0.5
May-13	16	10	6	10	25	50	0	7	0	0.5
Jul-13	201	10	236	10	1430	50	24	7	27	0.5
Oct-13	221	10	262	10	1000	50	25	7	18	0.5
Dec-13	75	10	115	10	1200	50	20	7	8	0.5
Feb-14	730	10	183	10	678	50	23	7	6	0.5

BH26 (9.20m bgl. Deep)										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Jan-04	15	10	46	10	321	50		7	1	0.5
Feb-05	9	10	41	10	246	50	1	7	1	0.5
Aug-05	9	10	45	10	279	50	12	7	1	0.5
Nov-05	1	10	44	10	231	50	8	7	1	0.5
Feb-06	8	10	33	10	249	50	1	7	1	0.5
Jun-06	8	10	41	10	233	50	7	7	2	0.5
Aug-06	5	10	27	10	219	50	6	7	1	0.5
Nov-06	4	10	25	10	196	50	6	7	1	0.5
Mar-07	5	10	34	10	230	50	7	7	1	0.5
May-07	5	10	31	10	300	50	6	7	1	0.5
Sep-07	3	10	21	10	200	50	5	7	1	0.5
Nov-07	3	10	19	10	170	50	4	7	1	0.5
Feb-08	6	10	40	10	350	50	9	7	1	0.5
May-08	4	10	22	10	270	50	6	7	2	0.5
Aug-08	7	10	19	10	200	50	9	7	1	0.5
Nov-08	2	10	23	10	280	50	2	7		0.5
Mar-09	5	10	25	10	310	50	8	7	2	0.5
Jul-09	2	10	21	10	210	50	4	7	2	0.5
Oct-09	2	10	23	10	260	50	6	7	1	0.5
Feb-10	3	10	27	10	300	50	7	7	4	0.5
Apr-10	2	10	26	10	300	50	6	7	2	0.5
Jun-10	2	10	23	10	270	50	6	7	1	0.5
Oct-10	1	10	24	10	280	50	6	7	3	0.5
Jan-11	1	10	3	10	77	50	1	7	1	0.5
May-11	1	10	23	10	300	50	6	7	4	0.5
Aug-11	1	10	18	10	270	50	5	7	2	0.5

Nov-11	5	10	16	10	259	50	5	7	3	0.5
Feb-12	5	10	17	10	288	50	6	7	5	0.5
Jun-12	5	10	16	10	280	50	6	7	4	0.5
Sep-12	5	10	13	10	258	50	6	7	4	0.5
Dec-12	5	10	13	10	204	50	5	7	6	0.5
Mar-13	5	10	11	10	244	50	5	7	4	0.5
Jul-13	0	10	11	10	263	50	6	7	4	0.5
Oct-13	0	10	12	10	287	50	6	7	8	0.5
Dec-13	0	10	11	10	302	50	6	7	5	0.5
Feb-14	0	10	14	10	289	50	5	7	7	0.5

BH43 8.0m-10.4m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Jun-10	4	10	8	10	43	50	2	7	1	0.5
Oct-10	8	10	16	10	66	50	5	7	1	0.5
Jan-11	1	10	2	10	22	50	1	7	1	0.5
May-11	10	10	19	10	85	50	6	7	2	0.5
Aug-11	6	10	13	10	54	50	4	7	2	0.5
Nov-11	9	10	12	10	64	50	5	7	1	0.5
Feb-12	8	10	12	10	68	50	5	7	1	0.5
Jun-12	8	10	12	10	64	50	4	7	1	0.5
Sep-12	9	10	16	10	72	50	6	7	1	0.5
Dec-12	8	10	16	10	60	50	5	7	2	0.5
Mar-13	9	10	16	10	75	50	6	7	1	0.5
Jul-13	7	10	11	10	63	50	5	7	1	0.5
Oct-13	13	10	17	10	60	50	4	7	0	0.5
Dec-13	14	10	18	10	57	50	5	7	0	0.5
Feb-14	13	10	20	10	73	50	5	7	1	0.5

BH55 Deep 23.6-26.65m bgl. Response Zone.										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Jun-12	22	10	71	10	6190	50	67	7	144	0.5
Feb-13	11	10	35	10	4810	50	40	7	58	0.5
Mar-13	0	10	0	10	4410	50	38	7	57	0.5
May-13	60	10	47	10	1000	50	7	7	8	0.5
Jul-13	90	10	164	10	8050	50	57	7	75	0.5
Oct-13	21	10	46	10	12000	50	104	7	225	0.5
Dec-13	0	10	26	10	5610	50	51	7	106	0.5
Feb-14	5	10	17	10	10400	50	87	7	620	0.5

BH55 Shallow 5.0-6.8m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Jun-12	48	10	87	10	6070	50	79	7	147	0.5
Feb-13	64	10	118	10	6880	50	92	7	106	0.5
Mar-13	3440	10	1060	10	9270	50	106	7	151	0.5
May-13	98	10	43	10	1120	50	8	7	9	0.5
Jul-13	212	10	136	10	5550	50	42	7	53	0.5
Oct-13	86	10	24	10	9650	50	88	7	179	0.5
Dec-13	55	10	13	10	8490	50	74	7	178	0.5
Feb-14	34	10	7	10	8950	50	72	7	499	0.5

BH56A Deep 17.30-18.30m bgl. Response Zone

Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Feb-13	0	10	0	10	218	50	3	7	6	0.5
Mar-13	0	10	0	10	248	50	2	7	4	0.5
May-13	0	10	0	10	18	50	0	7	0	0.5
Jul-13	0	10	0	10	255	50	3	7	4	0.5
Oct-13	0	10	0	10	179	50	2	7	6	0.5
Dec-13	0	10	0	10	77	50	0	7	2	0.5
Feb-14	0	10	0	10	19	50	0	7	0	0.5

BH56A Shallow 6.0-6.8m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Feb-13	0	10	15	10	993	50	16	7	26	0.5
Mar-13	0	10	0	10	1090	50	16	7	25	0.5
May-13	0	10	0	10	59	50	0	7	0	0.5
Jul-13	0	10	8	10	1380	50	20	7	44	0.5
Oct-13	0	10	9	10	1260	50	19	7	60	0.5
Dec-13	0	10	7	10	1100	50	15	7	44	0.5
Feb-14	0	10	6	10	877	50	8	7	94	0.5

BH56B Deep 40.70-41.70m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Feb-13	0	10	0	10	24	50	0	7	0	0.5
Mar-13	0	10	0	10	17	50	0	7	0	0.5
May-13	0	10	0	10	13	50	0	7	0	0.5
Jul-13	0	10	5	10	18	50	0	7	0	0.5
Oct-13	0	10	0	10	14	50	0	7	0	0.5
Dec-13	0	10	0	10	9	50	0	7	0	0.5
Feb-14	0	10	0	10	15	50	0	7	0	0.5

BH56B Shallow 29.40-30.40m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Feb-13	0	10	9	10	222	50	3	7	7	0.5
Mar-13	6	10	13	10	87	50	1	7	2	0.5
May-13	9	10	15	10	18	50	0	7	0	0.5
Jul-13	5	10	8	10	15	50	0	7	0	0.5
Oct-13	6	10	9	10	16	50	0	7	0	0.5
Dec-13	7	10	10	10	16	50	0	7	0	0.5
Feb-14	5	10	7	10	21	50	0	7	0	0.5

BH59 Deep 12-15m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Oct-13	0	10	0	10	0	50	0	7	0	0.5
Dec-13	0	10	0	10	0	50	0	7	0	0.5
Feb-14	0	10	0	10	0	50	0	7	0	0.5

BH59 Shallow 4-6m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Oct-13	6	10	0	10	2	50	0	7	0	0.5
Dec-13	0	10	0	10	0	50	0	7	0	0.5
Feb-14	6	10	0	10	4	50	0	7	0	0.5

BH60 Deep 18-20m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV[*2] (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV[*1] (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV[*1] (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV[*1] (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV[*1] (µg/l)
Oct-13	0	10	0	10	0	50	0	7	0	0.5
Dec-13	0	10	0	10	0	50	0	7	0	0.5
Feb-14	0	10	0	10	0	50	0	7	0	0.5

BH60 Shallow 10-12m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Oct-13	19	10	24	10	42	50	4	7	0	0.5
Dec-13	18	10	21	10	39	50	4	7	0	0.5
Feb-14	21	10	27	10	50	50	4	7	0	0.5

BH61 Deep 21.90-22.90m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Oct-13	0	10	0	10	0	50	0	7	0	0.5
Dec-13	0	10	0	10	0	50	0	7	0	0.5
Feb-14	0	10	0	10	0	50	0	7	0	0.5

BH61 Shallow 8.50-9.50m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Oct-13	0	10	0	10	4	50	0	7	0	0.5
Dec-13	0	10	0	10	5	50	0	7	0	0.5
Feb-14	0	10	0	10	3	50	0	7	0	0.5

BH64 Deep 18.45-20.0m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Dec-12	0	10	0	10	7	50	0	7	0	0.5
Feb-13	0	10	0	10	9	50	0	7	0	0.5
Jul-13	0	10	5	10	46	50	4	7	0	0.5
Oct-13	0	10	0	10	38	50	2	7	0	0.5
Dec-13	0	10	0	10	67	50	2	7	0	0.5
Feb-14	0	10	6	10	103	50	3	7	0	0.5

BH64 Shallow 14.0-15.5m bgl. Response Zone										
Date	Tetrachloroethene (µg/l)	Tetrachloroethene RPV*2 (µg/l)	Trichloroethene (µg/l)	Trichloroethene RPV*1 (µg/l)	cis 1,2-Dichloroethene (µg/l)	cis 1,2-Dichloroethene RPV*1 (µg/l)	1,1-Dichloroethene (µg/l)	1,1-Dichloroethene RPV*1 (µg/l)	Vinyl Chloride (µg/l)	Vinyl Chloride RPV*1 (µg/l)
Dec-12	0	10	0	10	71	50	4	7	2	0.5
Feb-13	0	10	0	10	15	50	0	7	0	0.5
Jul-13	0	10	0	10	12	50	0	7	0	0.5
Oct-13	0	10	0	10	46	50	5	7	0	0.5
Dec-13	0	10	0	10	44	50	3	7	0	0.5
Feb-14	0	10	0	10	18	50	0	7	0	0.5

References:

*1- SEPA (2014) Position Statement (WAT-PS-1-01) Assigning Groundwater Assessment Criteria for Pollutant inputs. Version 3.0.

*2-European Commission (2013). Review of the Annexes I and II of the Groundwater Directive:Report on the results of the public consultation

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RPS Group (2012) Groundwater and Surface Water Monitoring Factual Report: Q4. Land Quality File Document No: CHX-LQF-091

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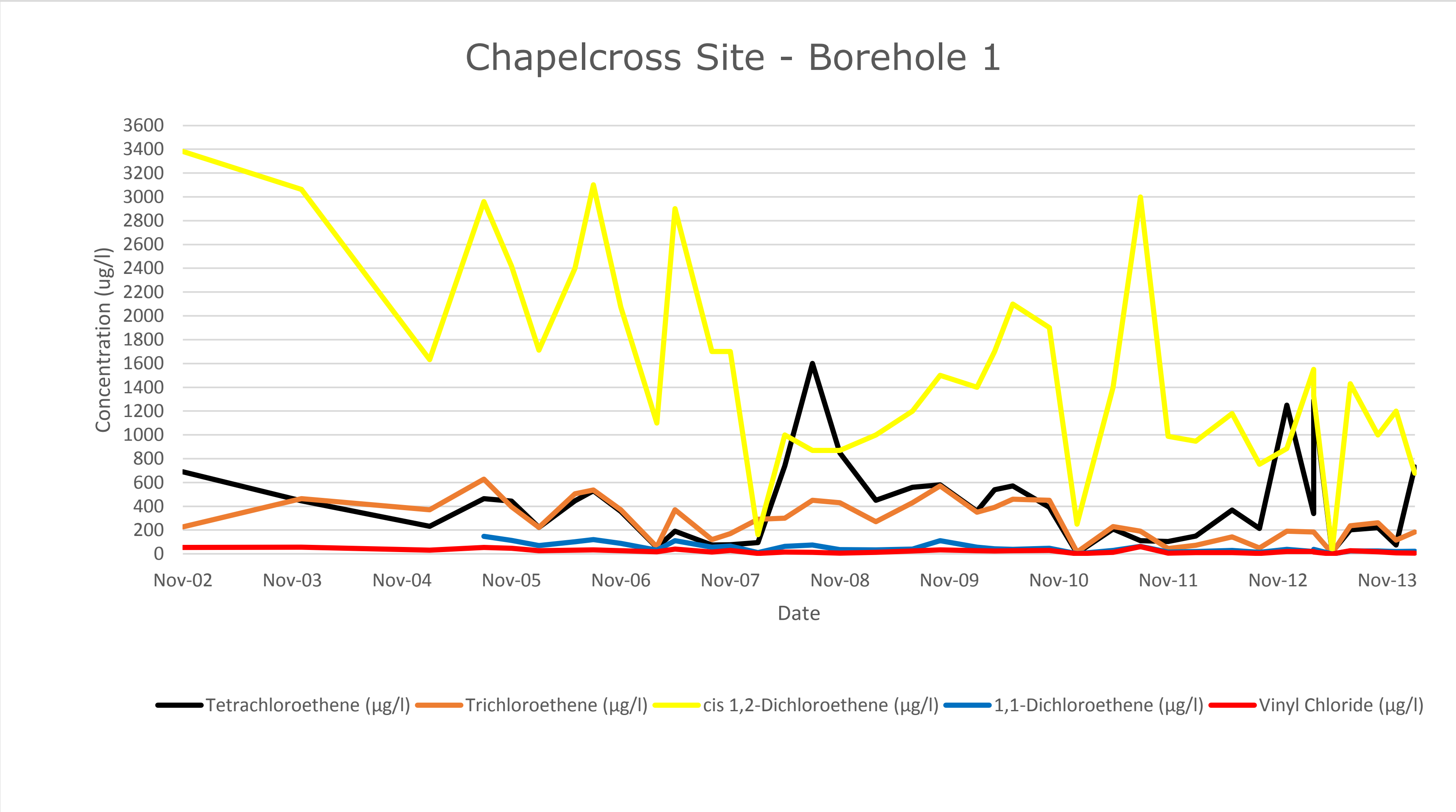
RPS Group (2013) Groundwater and Surface Water Monitoring, Factual Report Q2. Land Quality File Document No:CHX-LQF-105

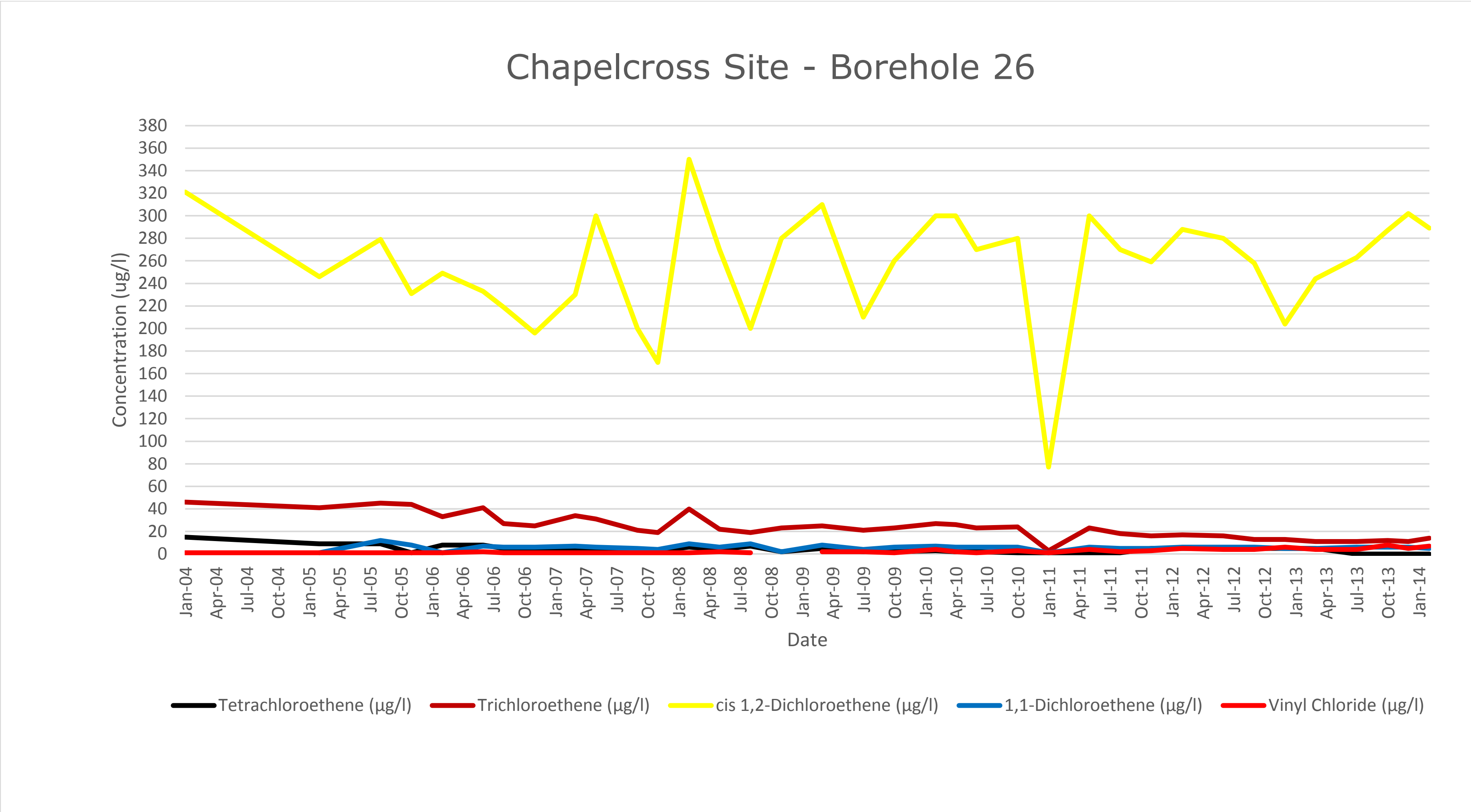
RPS Group (2013) Groundwater and Surface Water Monitoring, Factual Report Q3. Land Quality File Document No:CHX-LQF-098

RPS Group (2013) Groundwater and Surface Water Monitoring, Factual Report Q4. Land Quality File Document No:CHX-LQF-103

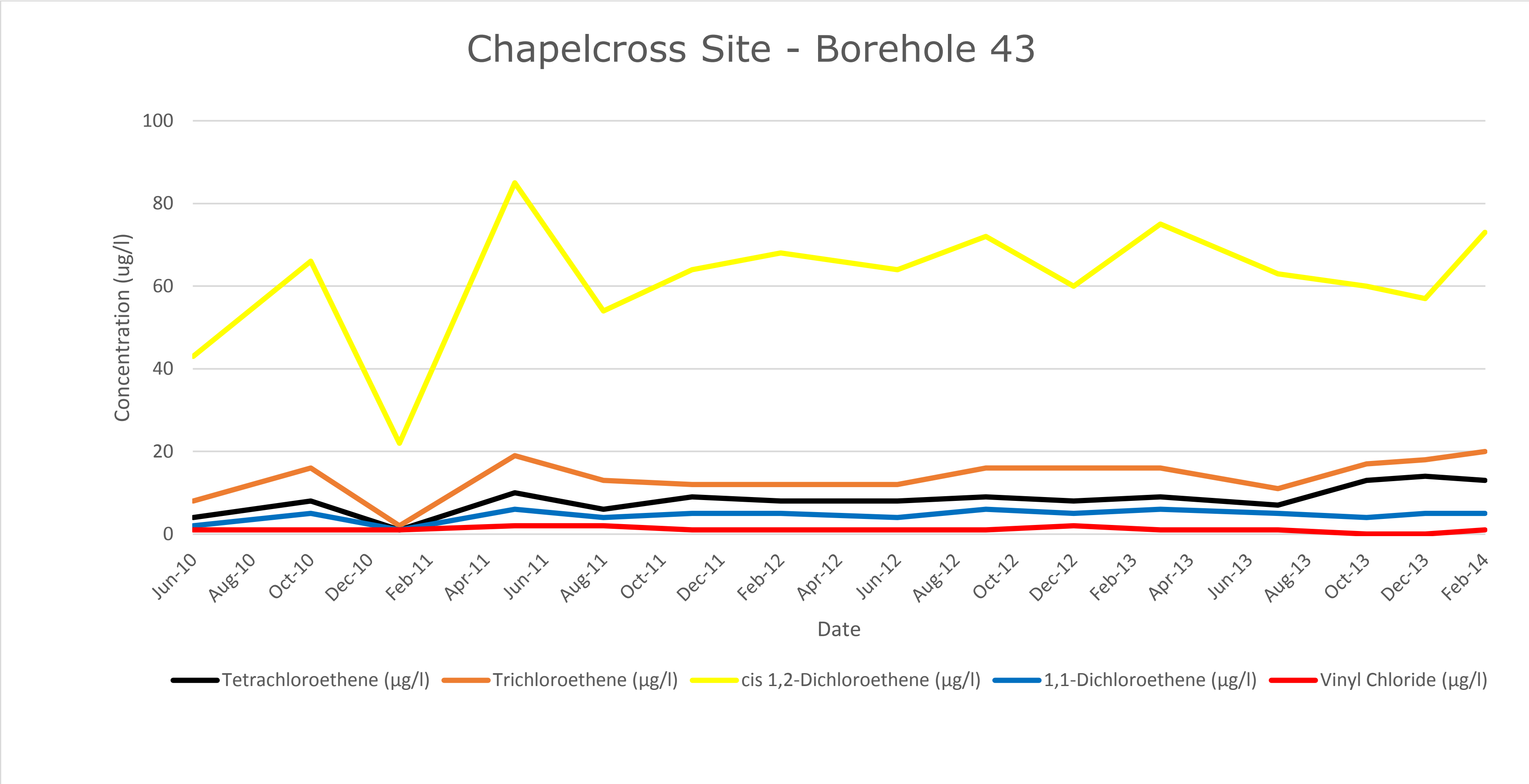
RPS Group (2014) Groundwater and Surface Water Monitoring, Factual Report Q3. Land Quality File Document No:CHX-LQF-109

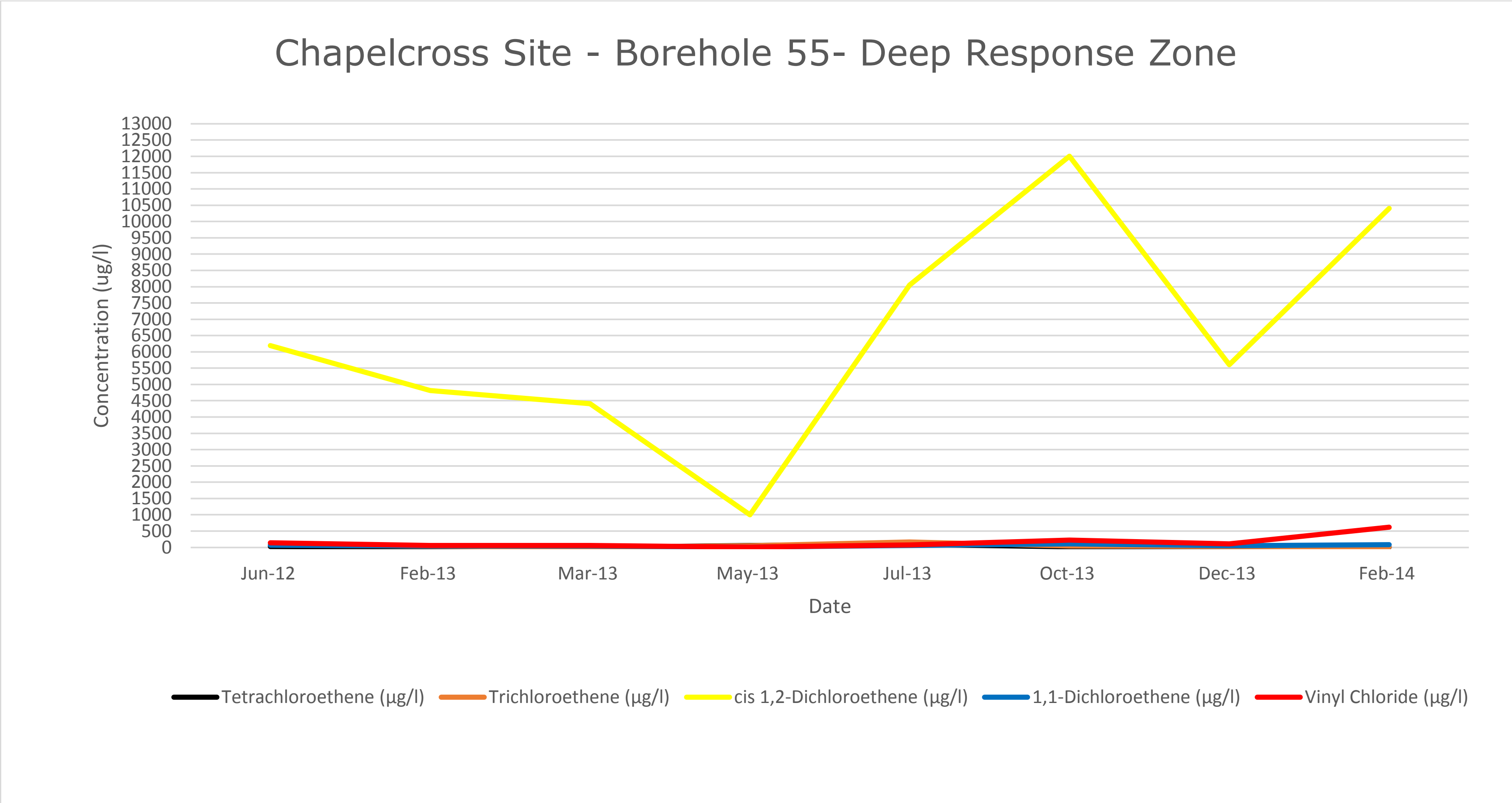
Time Series Data Graphs

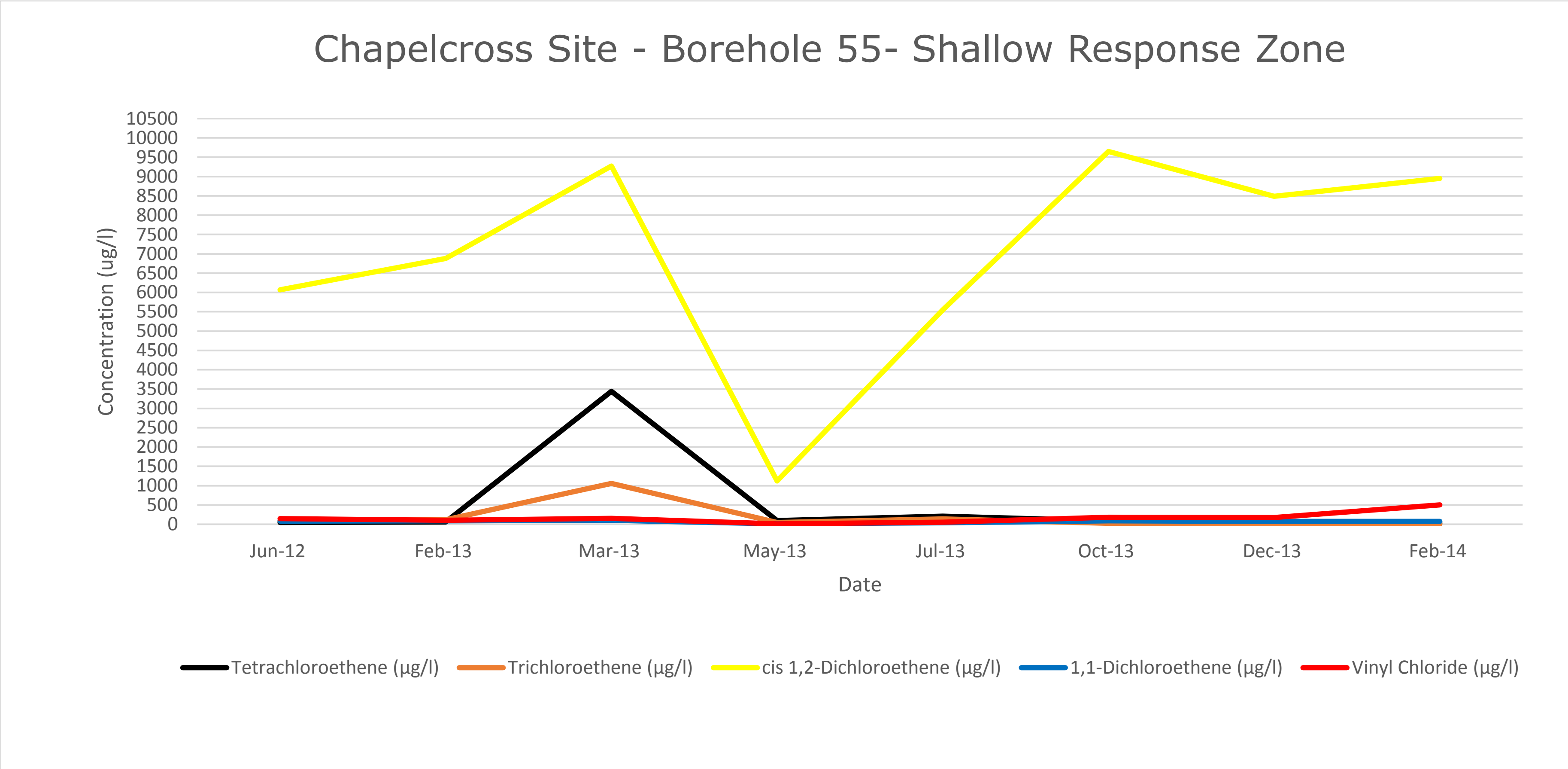


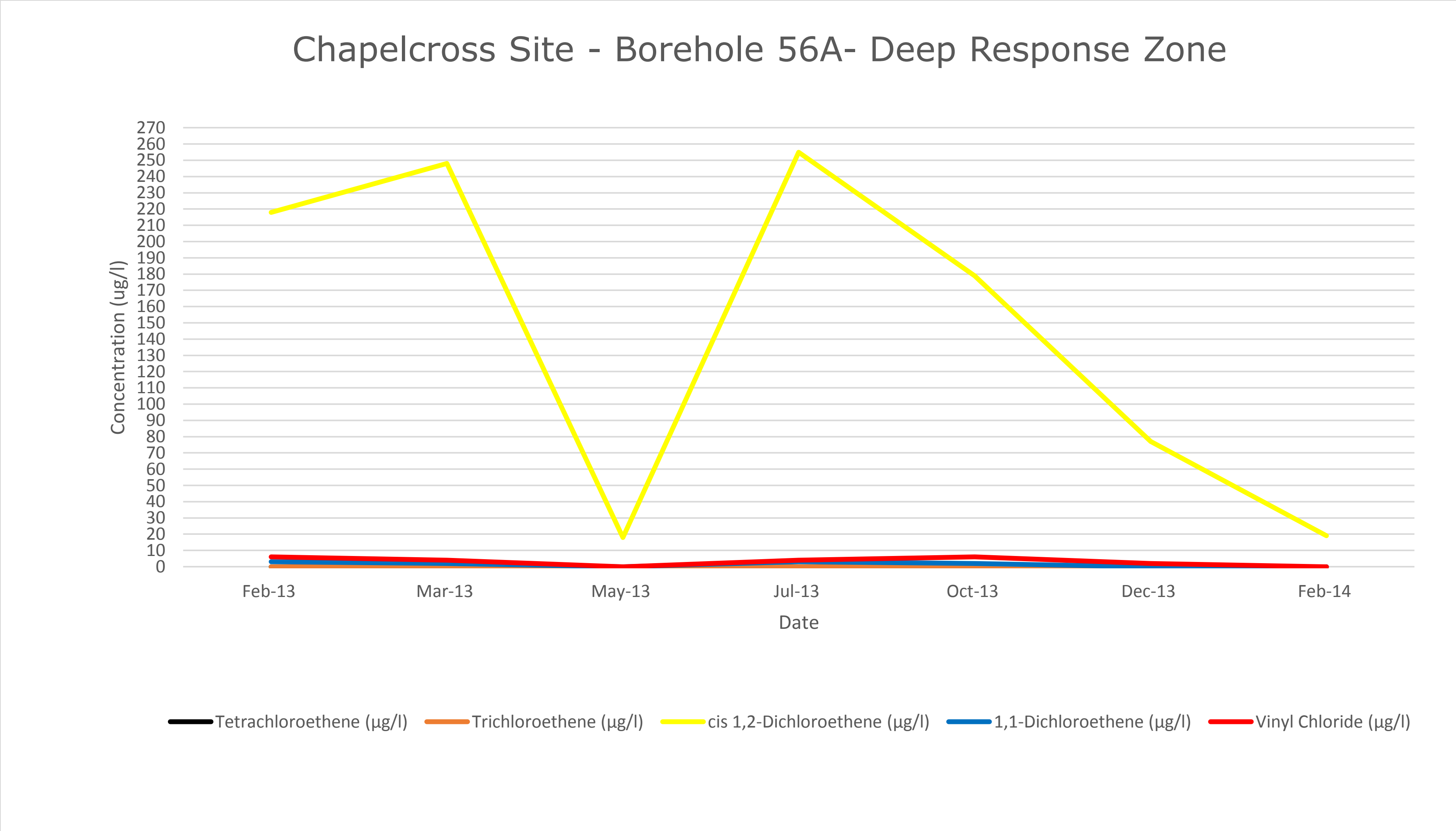


Chapelcross Site - Borehole 26
Concentration (ug/l)
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
Oct-06
Jan-07
Apr-07
Jul-07
Oct-07
Jan-08
Apr-08
Jul-08
Oct-08
Jan-09
Apr-09
Jul-09
Oct-09
Jan-10
Apr-10
Jul-10
Oct-10
Jan-11
Apr-11
Jul-11
Oct-11
Jan-12
Apr-12
Jul-12
Oct-12
Jan-13
Apr-13
Jul-13
Oct-13
Jan-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)

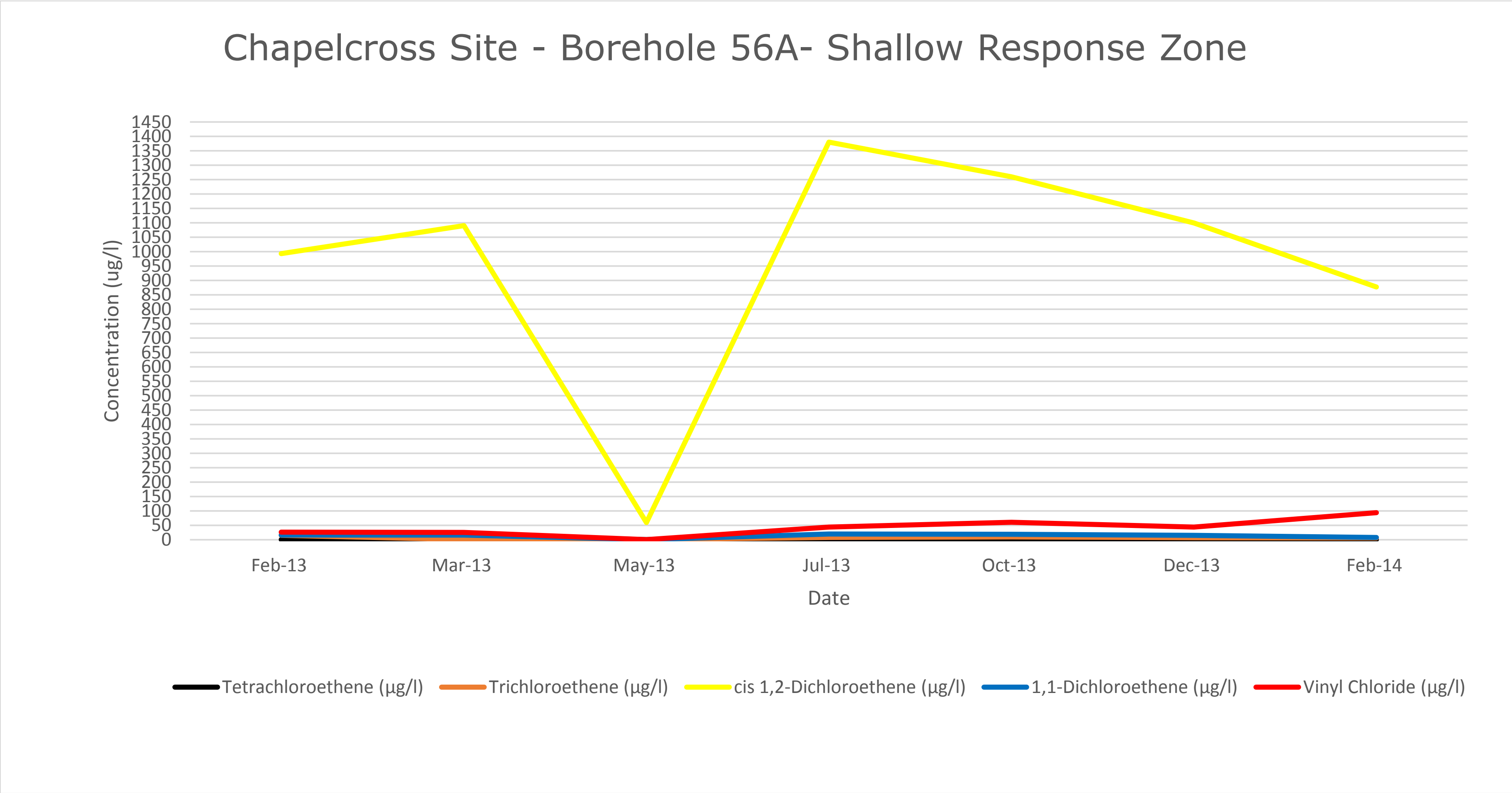

Chapelcross Site - Borehole 43
Concentration (ug/l)
100
80
60
40
20
0
Jun-10
Aug-10
Oct-10
Dec-10
Feb-11
Apr-11
Jun-11
Aug-11
Oct-11
Dec-11
Feb-12
Apr-12
Jun-12
Aug-12
Oct-12
Dec-12
Feb-13
Apr-13
Jun-13
Aug-13
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)


Chapelcross Site - Borehole 55- Deep Response Zone
Concentration (ug/l)
13000
12500
12000
11500
11000
10500
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Jun-12
Feb-13
Mar-13
May-13
Jul-13
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)

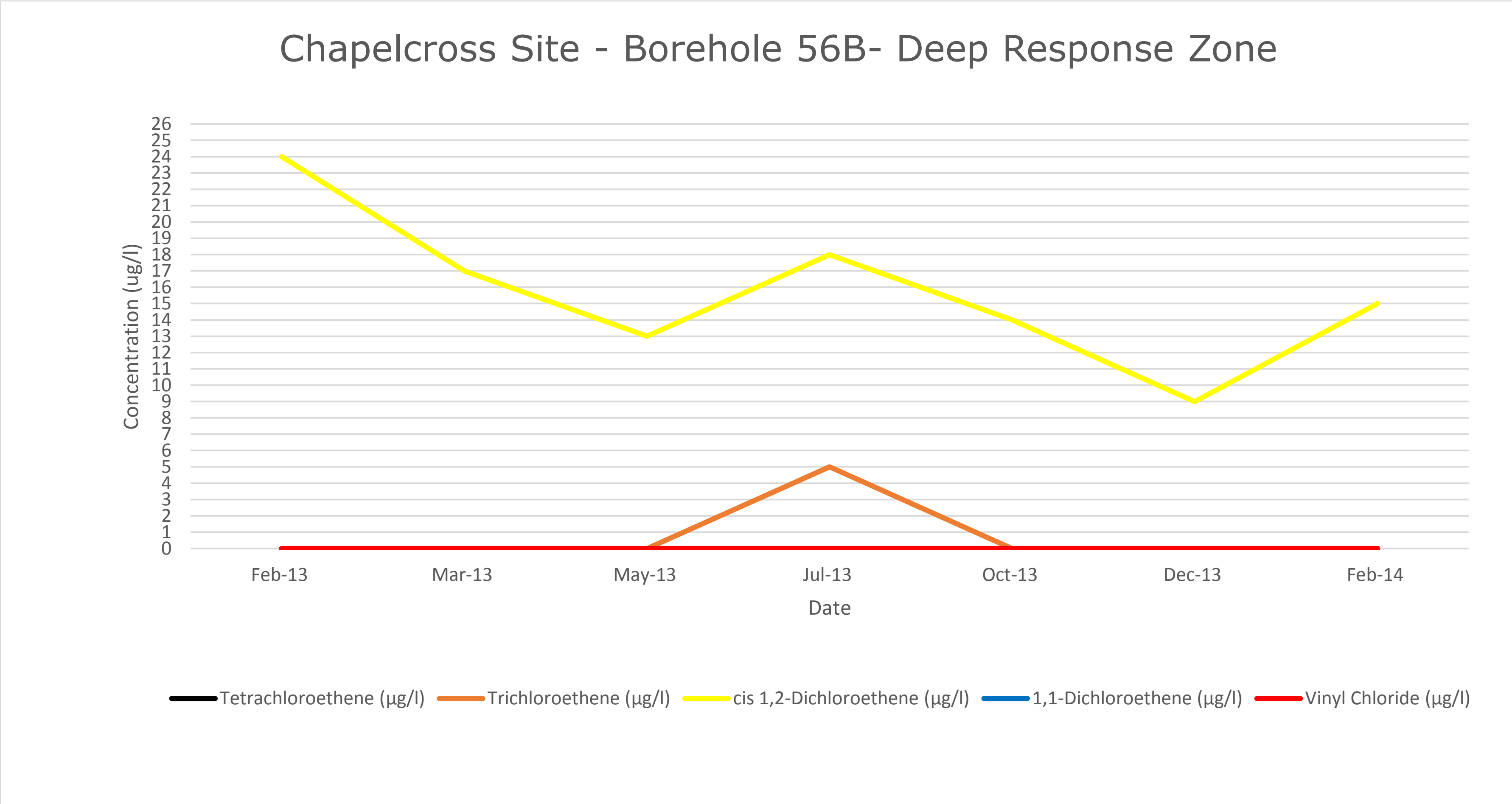

Chapelcross Site - Borehole 55- Shallow Response Zone
Concentration (ug/l)
10500
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Jun-12
Feb-13
Mar-13
May-13
Jul-13
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)

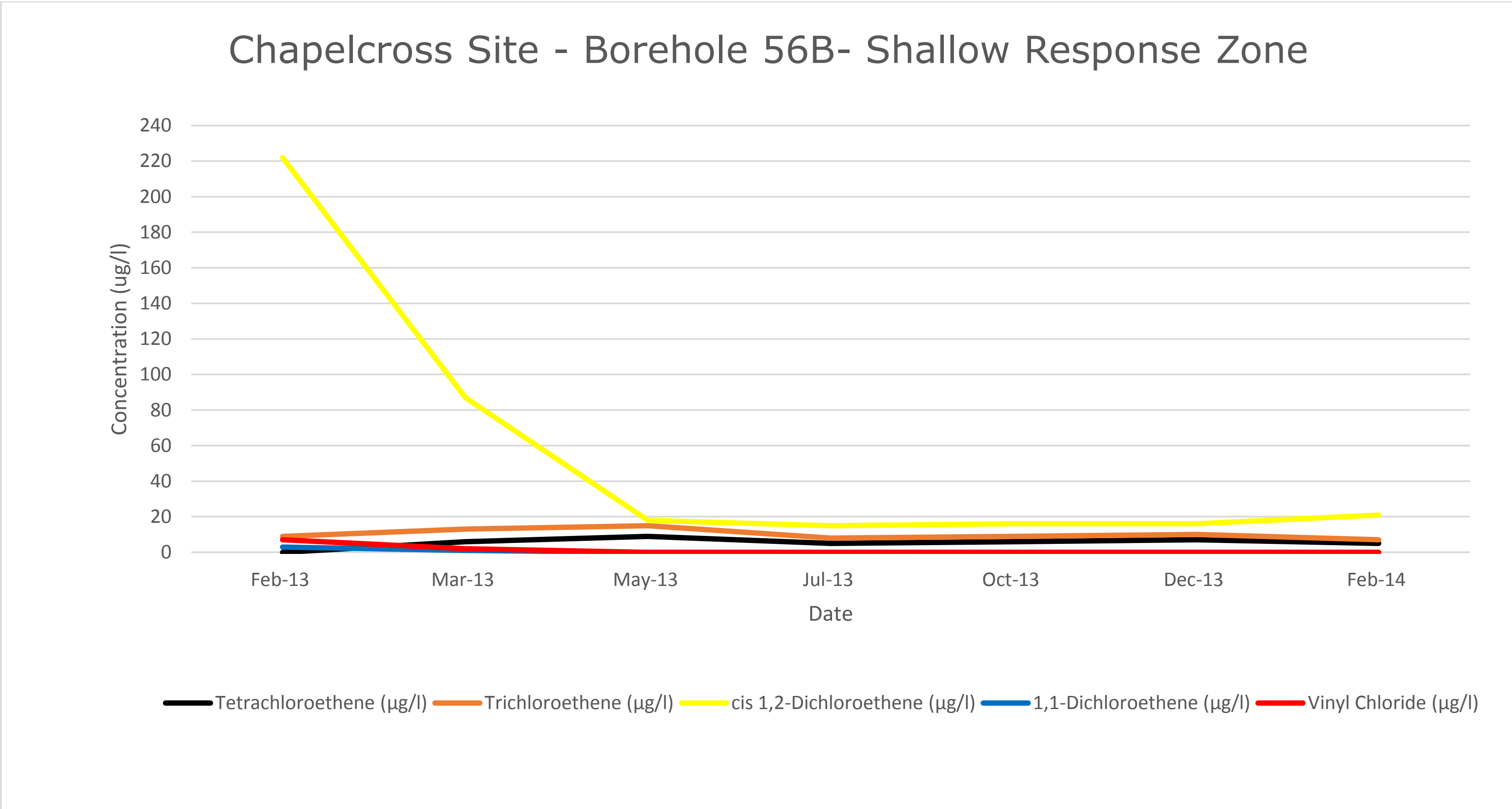


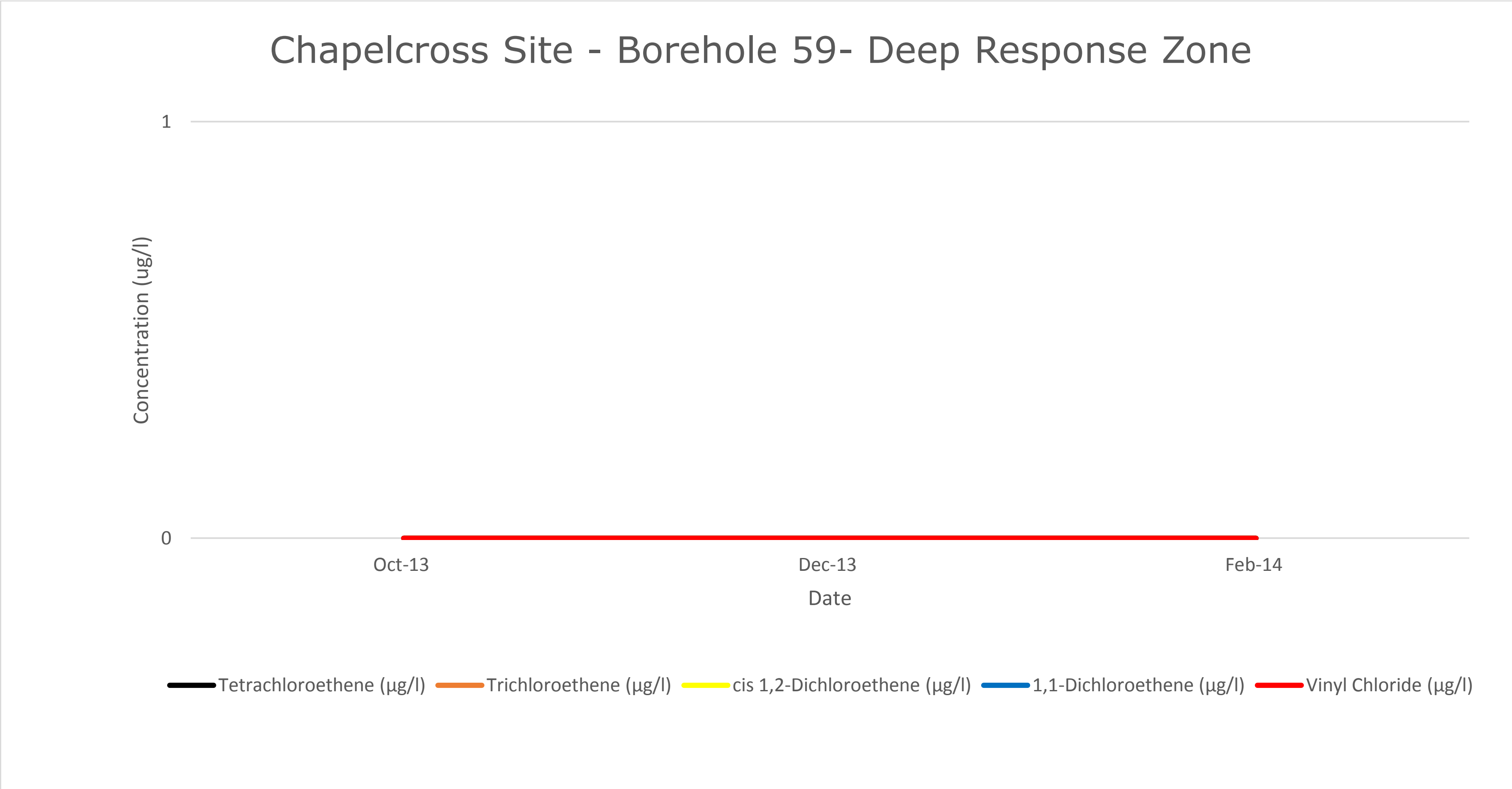
Chapelcross Site - Borehole 56A- Deep Response Zone
Concentration (ug/l)
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Feb-13
Mar-13
May-13
Jul-13
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)



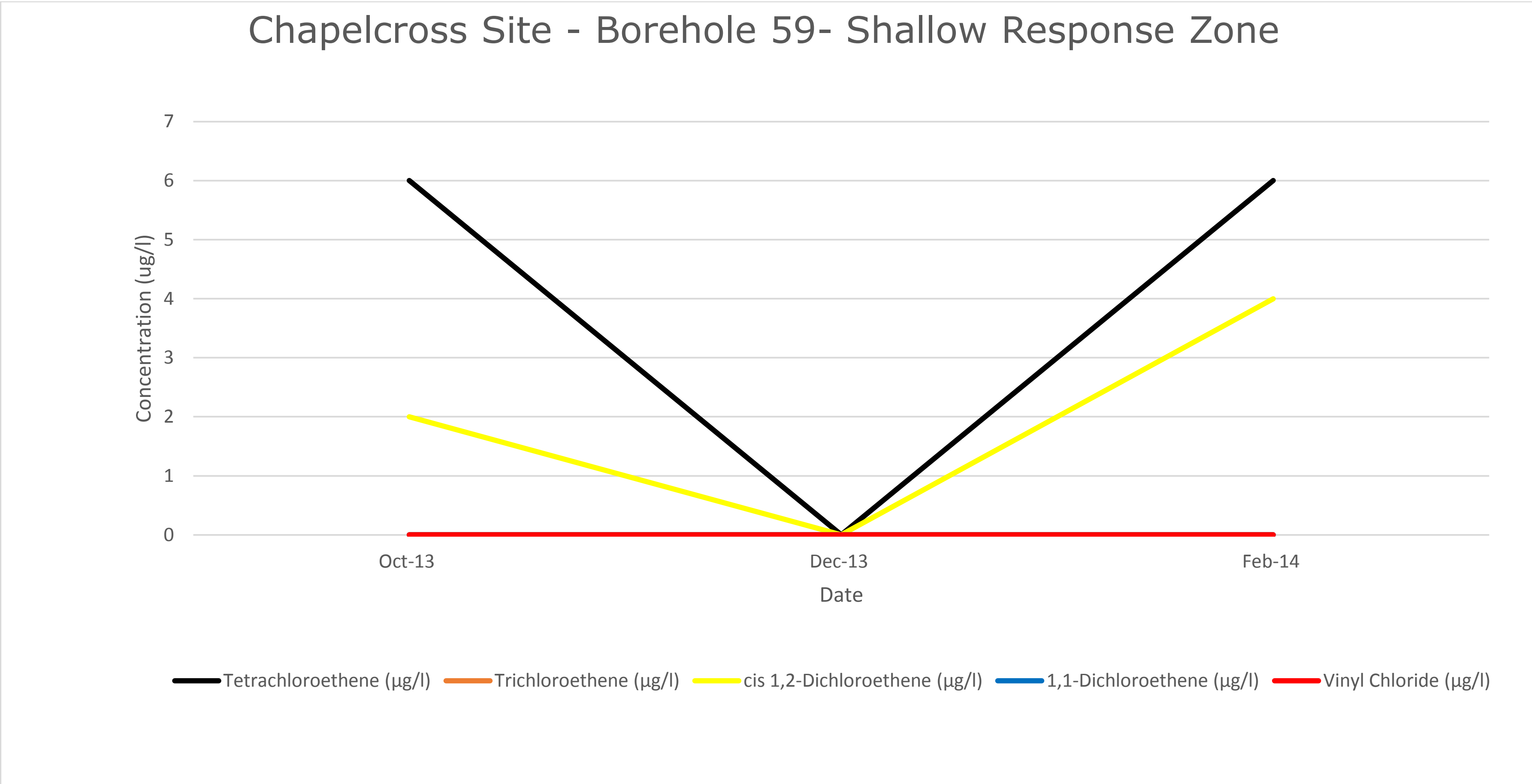
Chapelcross Site - Borehole 56A- Shallow Response Zone
Concentration (ug/l)
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
Feb-13
Mar-13
May-13
Jul-13
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)


Chapelcross Site - Borehole 56B- Deep Response Zone
Concentration (ug/l)
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Feb-13
Mar-13
May-13
Jul-13
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)

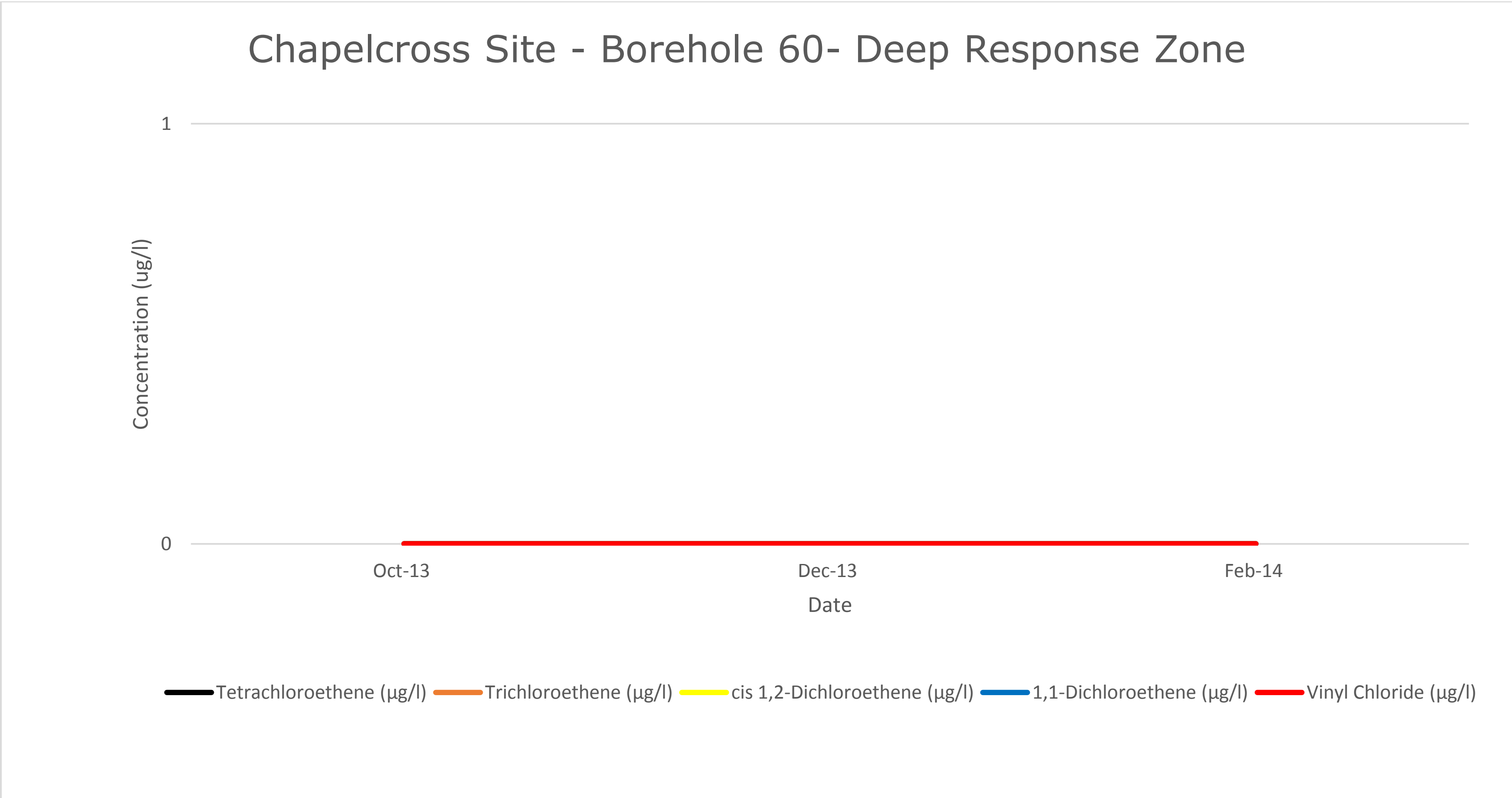

Chapelcross Site - Borehole 56B- Shallow Response Zone
Concentration (ug/l)
240
220
200
180
160
140
120
100
80
60
40
20
0
Feb-13
Mar-13
May-13
Jul-13
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)



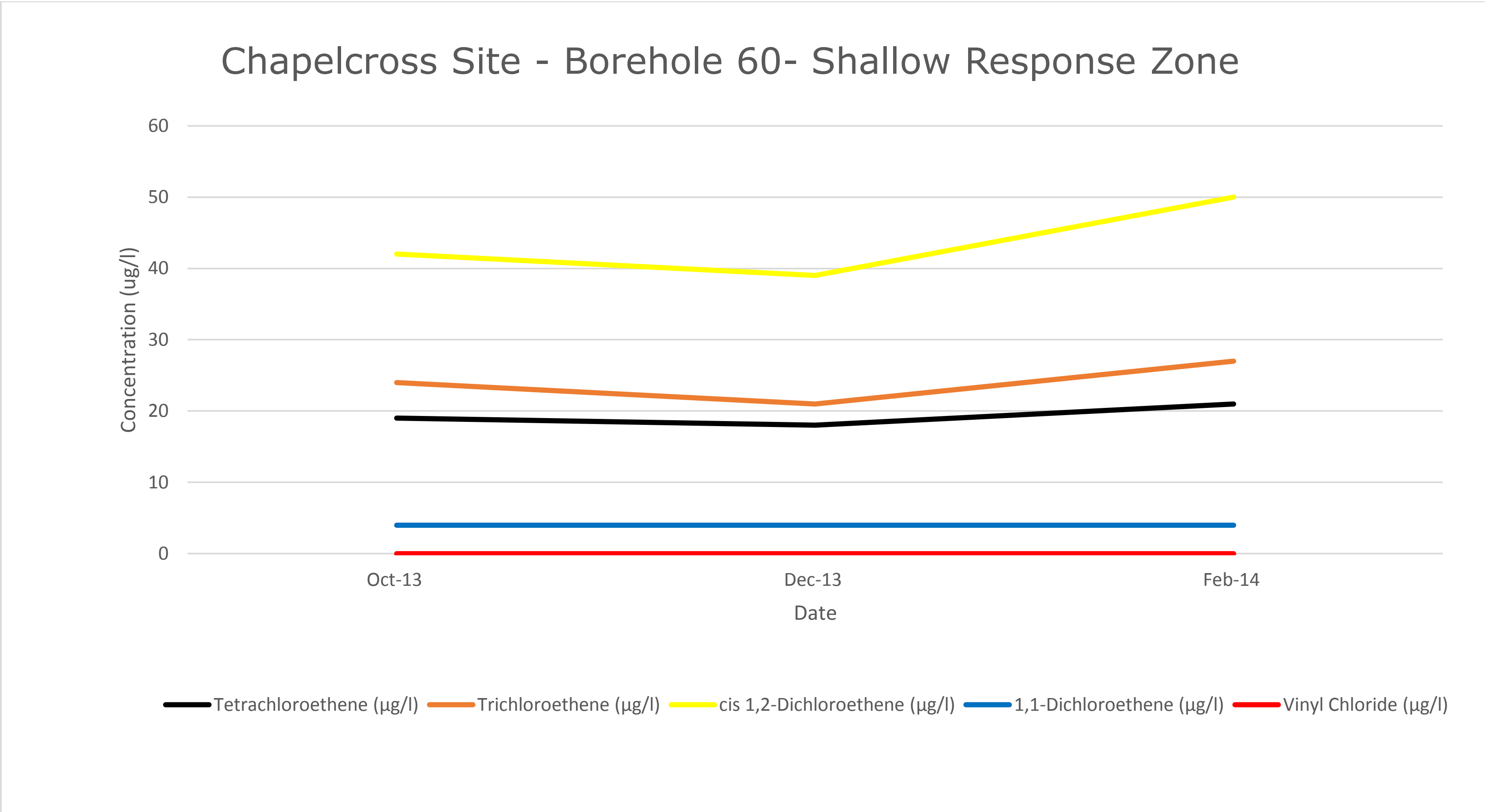
Chapelcross Site - Borehole 59- Deep Response Zone
1
0
Concentration (ug/l)
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)



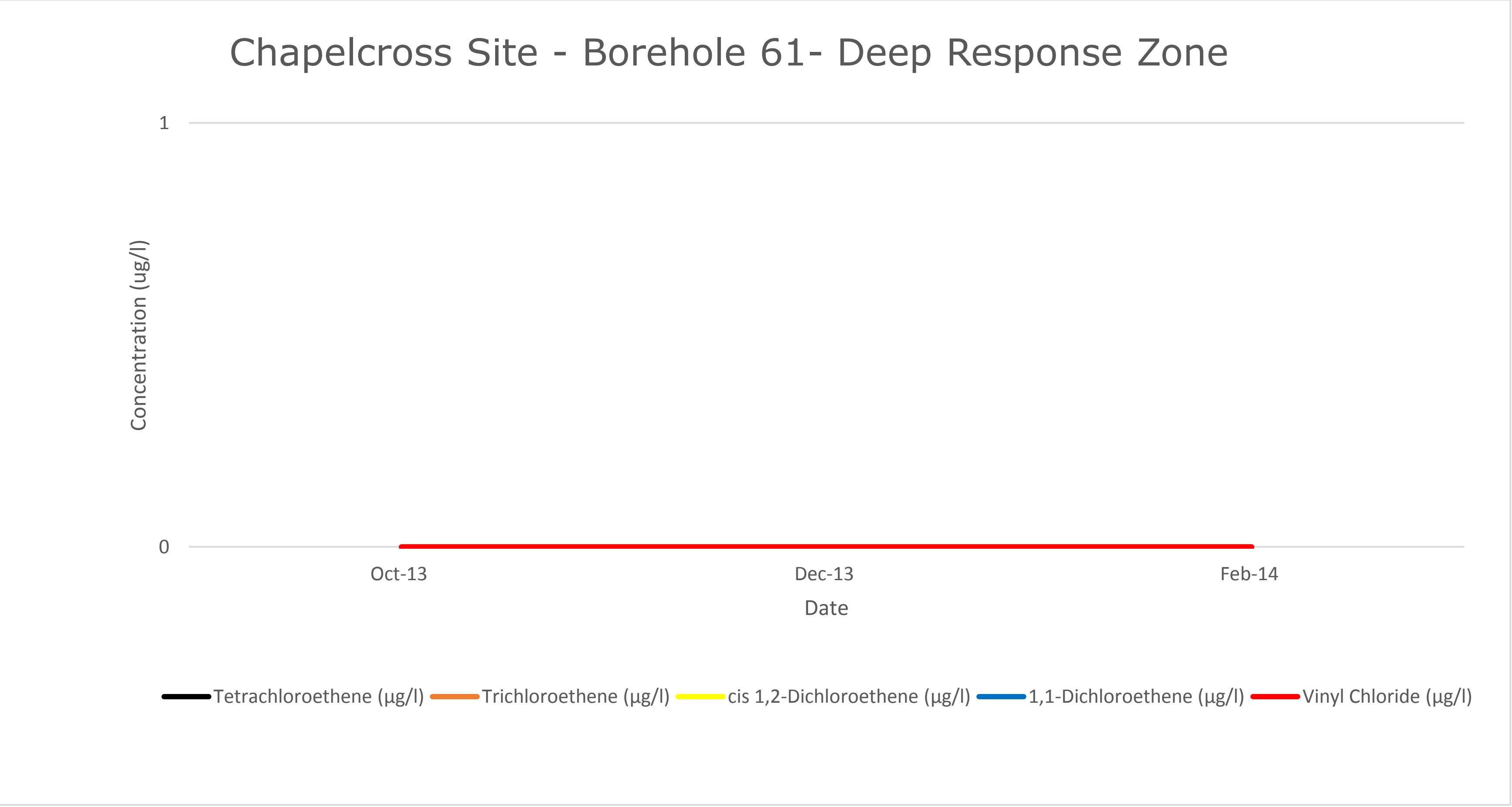
Chapelcross Site - Borehole 59- Shallow Response Zone
Concentration (ug/l)
0
1
2
3
4
5
6
7
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)

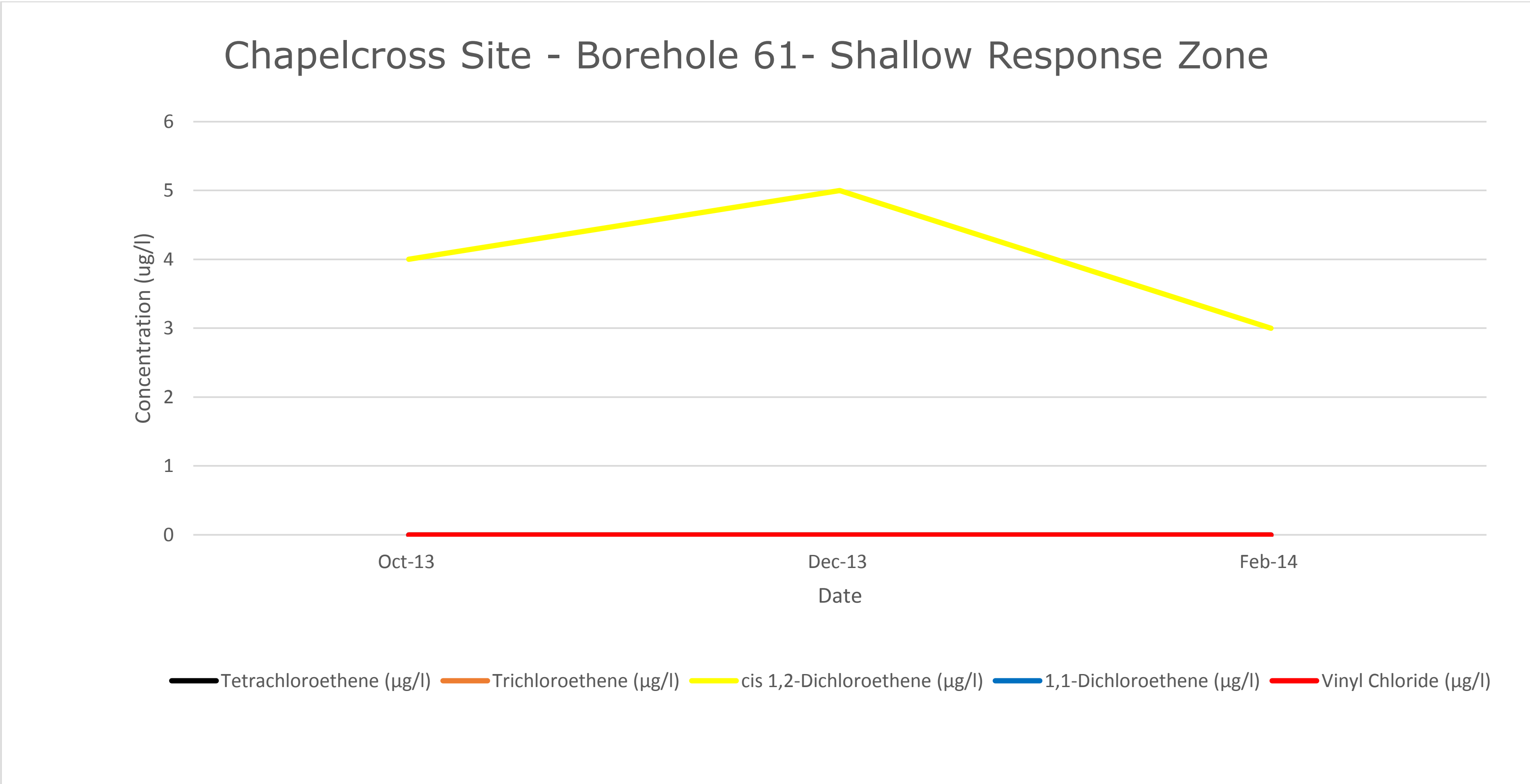


Chapelcross Site - Borehole 60- Deep Response Zone
1
0
Concentration (µg/l)
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)

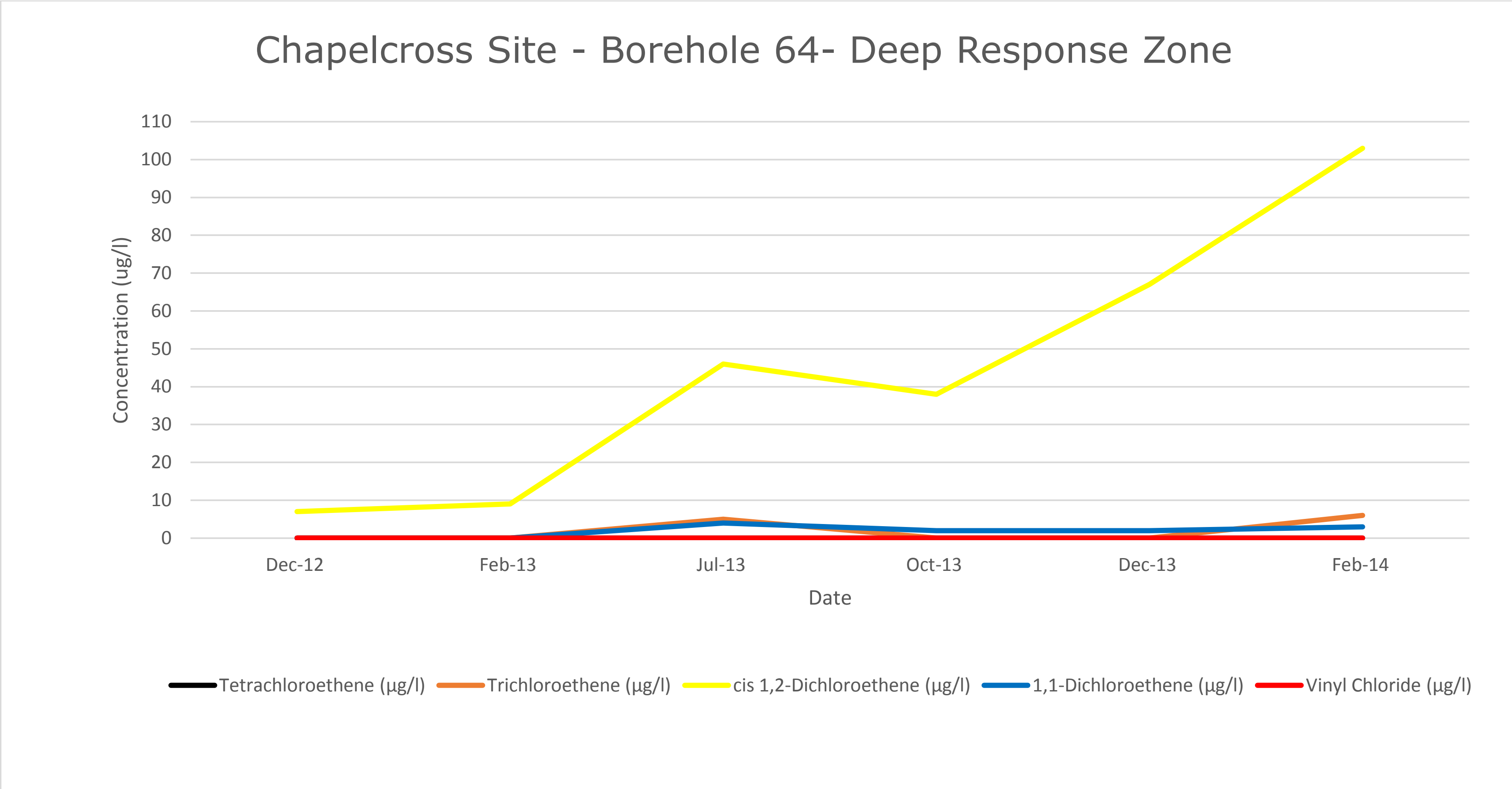


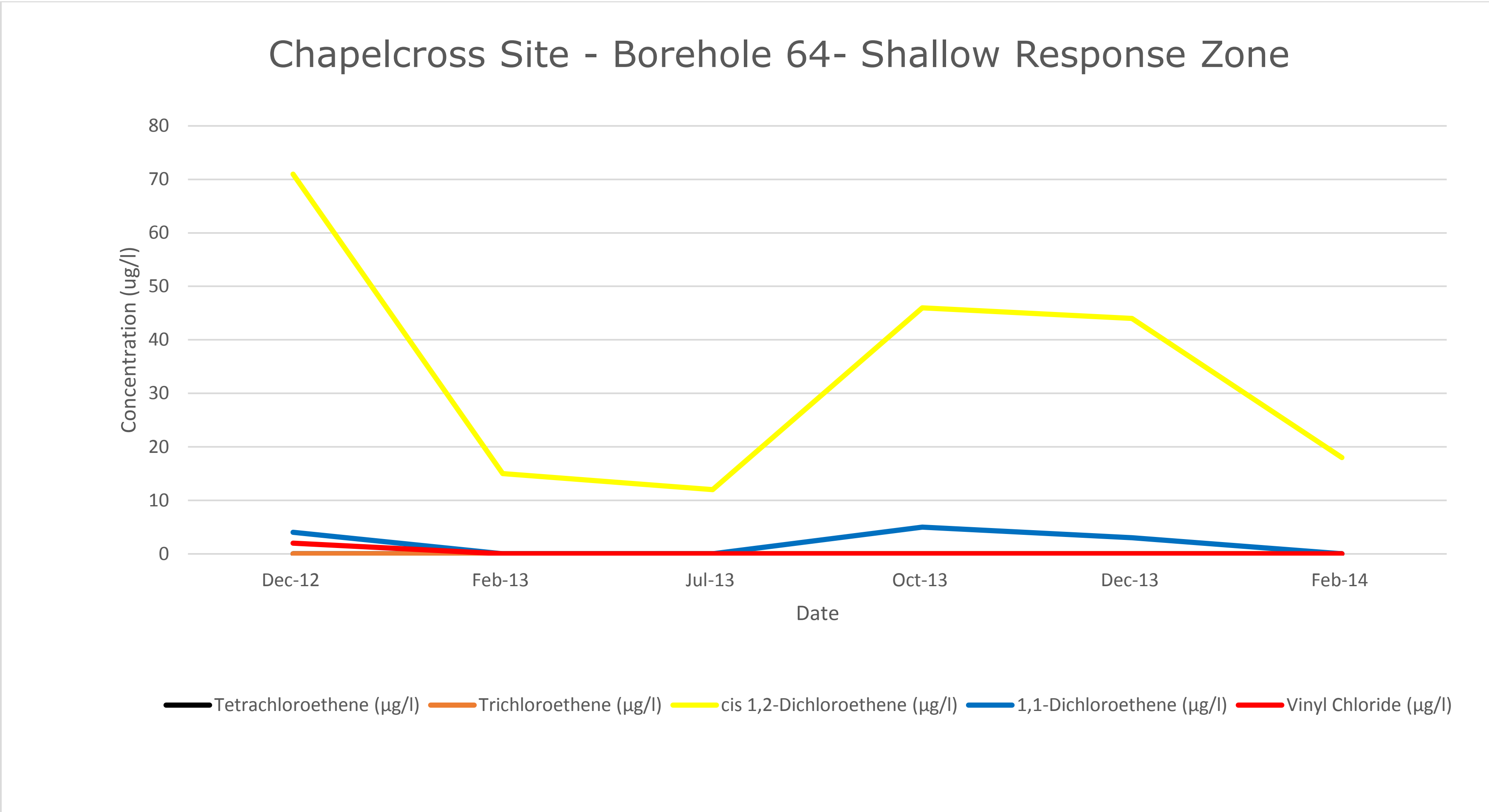
Chapelcross Site - Borehole 60- Shallow Response Zone
60
50
40
30
20
10
0
Concentration (ug/l)
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)


Chapelcross Site - Borehole 61- Deep Response Zone
1
0
Concentration (ug/l)
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)



Chapelcross Site - Borehole 61- Shallow Response Zone
6
5
4
3
2
1
0
Concentration (ug/l)
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)


Chapelcross Site - Borehole 64- Deep Response Zone
110
100
90
80
70
60
50
40
30
20
10
0
Concentration (ug/l)
Dec-12
Feb-13
Jul-13
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)



Chapelcross Site - Borehole 64- Shallow Response Zone
80
70
60
50
40
30
20
10
0
Concentration (ug/l)
Dec-12
Feb-13
Jul-13
Oct-13
Dec-13
Feb-14
Date
Tetrachloroethene (µg/l)
Trichloroethene (µg/l)
cis 1,2-Dichloroethene (µg/l)
1,1-Dichloroethene (µg/l)
Vinyl Chloride (µg/l)

Drilling Method Rotary Cored Equipment Knebel Drill Fluid Air/Mist Orientation (°) 90 Dates Drilled Start 23/11/2003 End 23/11/2003	Borehole Diameter 140mm to 9.20m Casing Diameter 200mm to 1.50m Logged by BC 02/12/2003 Compiled by rej 05/12/2003 Checked by BC 11/05/2004	BOREHOLE No. BH26 Coordinates (National Grid) 321674.47 E 569479.68 N Ground Level 72.31 m OD

Date & Time	Casing Depth (m)	Water Depth (m) (Flush Return) %	Sample/Core Recovery Depth (m) From To	Type / TCR %	No. / SCR %	RQD %	SPT Blows /N Core Size (mm)	Fracture Index	Description of Strata	Depth (Thickness) (m)	Level	Legend
23/11									MADE GROUND: Tarmacadam.	(0.20) 0.20	72.11	
		(0)	0.00-1.00						MADE GROUND: Grey gravel of crushed concrete and other aggregates.	(0.70)		
			0.60	PID				37ppb		0.90	71.41	
			1.00	PID				71ppb	Boulder CLAY.			
		(100)	1.00-2.50	30	30	NA						
			2.00	PID				43ppb				
			3.00	PID				28ppb		(3.60)		
		(100)	2.50-4.70	31	31	NA						
			4.00	PID				63ppb		4.50	67.81	
			5.00	PID				313ppb	Probably firm, becoming firm to stiff, red brown, sandy, gravelly CLAY. Gravel is subangular, fine to coarse limestone and sandstone. Sand is fine to coarse. Occasional cobbles.	(0.10) 4.60	67.71	
								26				
		(100)	4.70-6.20	83	80	21			Moderately weak, locally moderately strong, fractured locally thinly cross laminated, red brown fine to coarse grained SANDSTONE. Fractures closely locally very closely spaced, subhorizontal and occasional inclined 50 to 60 degrees. surfaces stained grey brown, penetrating <1mm.			
			6.00	PID				163ppb		(2.85)		
		(100)	6.20-7.20	100	94	42						
			7.00	PID				129ppb				
		(100)	7.20-7.70	100	93	64				7.45	64.86	
			8.00	PID				29ppb	Weak, thinly laminated, highly fractured red brown MUDSTONE. Fractures very closely spaced, randomly orientated and predominantly drilling induced. Surfaces locally stained grey. Between 7.70m and 8.20m: non intact (Drilling induced).	(1.55)		
		(100)	7.70-9.20	100	98	7						
23/11	1.50	DRY								9.00	63.31	
									Moderately strong, red brown, predominantly fine and medium grained SANDSTONE.	(0.20) 9.20	63.11	
									End of Borehole			

Remarks (See notes & keysheets)
1 Groundwater was not apparent during drilling.
2 Prior to boring a Cable Avoidance Tool (CAT) survey was carried out. An inspection pit was hand-dug to 1.00m depth and rescanned using the CAT to check for services. Services were not located.
3 Background PID monitoring 18 to 26ppb.

Scale 1:50

FUGRO

Project CHAPEL CROSS
SERCO ASSURANCE

Contract No. R39630

Figure No. BH26 (1 of 2)

304/03

Hyder Rotary Borehole Log — BH56b

Project	Project No.	Ground Level (m AOD)	Start Date	
Chapelcross Solvent Plume Investigation	UA004495	75.13	20-11-12	
Client	**Easting (OS)**	**Northing (OS)**	**Finish Date**	**Scale**
Magnox	321819.2	569488.1	29-11-12	1:50

Samples / Tests / Progress

Sample Type/No	Results	TCR% SCR% RQD%	IF (min ave max)	Date Time	Casing Water
				20/11/2012 15:30	Dry
				20/11/2012 17:00	Dry
				21/11/2012 08:00	
		95 70 45	NI 110 195		
PID1	0.000ppm				
PID2	0.100ppm	100 35 5			
PID3	0.000ppm				
		95 80 75			
PID4	0.000ppm		30 100 140		
			70 130 190		
PID5	0.100ppm	100 95 90			
PID6	0.000ppm				
		100 100 75	NI 110 175		
PID7	0.000ppm				

Strata

Description	Detail	Depth, Level (thickness)
MADE GROUND: Grass over dark brown very clayey fine and medium SAND with frequent roots and rootlets. [MADE GROUND]		(0.40) 0.40 74.73
MADE GROUND: Strong grey CONCRETE. [Concrete]		0.50 74.63
MADE GROUND: Dark grey angular fine and medium GRAVEL of igneous lithologies. [MADE GROUND]		0.75 74.38
Firm reddish brown sandy slightly gravelly CLAY. Gravel is subangular and subrounded fine and medium of igneous lithologies. [Glacial Till]		(0.45) 1.20 73.93
Rotary openhole drilling. Red brown slightly sandy CLAY. [Glacial Till]		(1.20) 2.40 72.73
Very weak locally weak reddish brown fine and medium SANDSTONE. Fractures are very closely and closely spaced subhorizontal and 45° undulating rough with clay infill. [ST BEES SANDSTONE]	2.80 - 3.00 Non-intact with black staining on fracture surfaces. 3.60 - 3.90 Weak with black staining. 3.95 - 4.40 Subvertical fracture with clay smear. 4.70 - 4.80 Non-intact. 4.90 - 4.95 Non-intact. 5.50 - 5.70 Subvertical fracture.	(3.45) 5.85 69.28
Very weak dark reddish brown MUDSTONE. Fractures are very closely and closely spaced subhorizontal stepped smooth with clay smear. [ST BEES SANDSTONE]		(0.70) 6.55 68.58
Weak dark reddish brown fine SANDSTONE. Fractures are closely spaced subhorizontal undulating rough with a clay smear. [ST BEES SANDSTONE]	6.45 - 6.55 Non-intact. 8.20 - 8.40 Fractures are very closely spaced.	(1.95) 8.50 66.63
Weak dark reddish brown fine SANDSTONE interbedded with very weak MUDSTONE. Fractures are very closely and closely spaced subhorizontal undulating and stepped with clay infill. Locally non-intact. [ST BEES SANDSTONE]	8.60 - 9.35 Mudstone. 9.50 - 9.60 Mudstone. 9.80 - 9.90 Mudstone.	

Drilling Technique

From	To	Technique
0.00	1.20	Inspection Pit
1.20	2.40	DC
2.40	54.40	Rotary Cored

Flush Details

From	To	Rtrn %	Flush Type
2.40	54.40	50	Water

Water Observations

Date/Time	Strike At	Rise To	Casing	Sealed

Hole/Casing Diameter

Hole Dia.	Depth	Casing Dia.	Depth
150	2.40	150	2.40
146	54.40		

Water Added

From	To	Volume

Remarks
Unable to determine waterstrikes as masked by the use of water flush.
Packer permeability tests undertaken 29.40 - 30.40m and 40.70 - 41.70m.
Borehole terminated on Engineer's instruction.

Termination Depth: 54.40m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used: Wheeled mounted Massenza MI6
Contractor: Hyder Consulting Ltd
Logged By: IP
Checked By: DH

Rotary Borehole Log

BH56b

Project	Project No.	Ground Level (m AOD)	Start Date	
Chapelcross Solvent Plume Investigation	UA004495	75.13	20-11-12	
Client	**Easting (OS)**	**Northing (OS)**	**Finish Date**	**Scale**
Magnox	321819.2	569488.1	29-11-12	1:50

SAMPLES Depth	Type	TESTS Type/No	Results	TCR% SCR% RQD%	IF (min ave max)	Water Strikes	PROGRESS Date Time	Casing Water	Description	STRATA Detail	Legend	Depth, Level (thickness)	Install/ Backfill
		PID8	0.000ppm	100 90 80					Weak dark reddish brown fine SANDSTONE interbedded with very weak MUDSTONE. Fractures are very closely and closely spaced subhorizontal undulating and stepped with clay infill. Locally non-intact. [ST BEES SANDSTONE] *(continued)*	10.10 - 10.15 Mudstone. 10.25 - 10.30 Mudstone. 10.60 - 10.70 45° fracture. 10.10 - 11.40 Strong sandstone. 10.80 - Open fracture infilled with clay. 11.20 - 11.40 Mudstone.		(3.05)	
		PID9	0.000ppm										
				100 90 75	NI 120 225							11.55 *63.58*	
		PID10	0.000ppm						Medium strong locally weak reddish brown fine SANDSTONE. Fractures are closely spaced locally medium spaced subhorizontal undulating rough locally with a clay infill. [ST BEES SANDSTONE]	11.90 - 12.00 Non-intact. 12.40 - 12.90 Fractures are very closely spaced. 13.50 - 13.52 15mm fracture infilled with clay. 14.00 - 1no. stepped fracture. 14.50 - 14.90 Subvertical fracture. 14.40 - 15.50 Fractures are very closely spaced. 15.30 - 15.35 Non-intact.		(3.85)	
		PID11	0.000ppm	100 100 95									
		PID12	0.000ppm				21/11/2012 18:00	2.40 *2.60*					
				100 65 65			22/11/2012 08:00	2.40 *3.30*					
		PID13	0.000ppm									15.40 *59.73*	
					35 120 250				Medium strong dark reddish brown fine SANDSTONE interbedded with very weak MUDSTONE. Fractures are closely spaced locally very closely and medium spaced subhorizontal undulating rough with a clay smear. Mudstone has black staining on fracture surfaces. [ST BEES SANDSTONE]	16.45 - 17.00 Mudstone. 17.50 - 17.70 Mudstone. 18.75 - 19.00 Mudstone.		(6.95)	
		PID14	0.100ppm	90 90 90									
		PID15	0.000ppm										
				100 95 90									
		PID16	0.000ppm										
		PID17	0.000ppm	90 85 75									

DRILLING TECHNIQUE From	To	Technique	FLUSH DETAILS From	To	Rtrn %	Flush Type	WATER OBSERVATIONS Date/Time	Strike At	Rise To	Casing	Sealed	HOLE/CASING DIAMETER Hole Dia.	Depth	Casing Dia.	Depth	WATER ADDED From	To	Volume

Remarks
Unable to determine waterstrikes as masked by the use of water flush.
Packer permeability tests undertaken 29.40 - 30.40m and 40.70 - 41.70m.
Borehole terminated on Engineer's instruction.

Termination Depth: 54.40m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used	Contractor	Logged By	Checked By
Wheeled mounted Massenza MI6	Hyder Consulting Ltd	IP	DH

Rotary Borehole Log

BH56b

Project	Project No.	Ground Level (m AOD)	Start Date	
Chapelcross Solvent Plume Investigation	UA004495	75.13	20-11-12	
Client	**Easting (OS)**	**Northing (OS)**	**Finish Date**	**Scale**
Magnox	321819.2	569488.1	29-11-12	1:50

Samples Depth	Samples Type	Tests Type/No	Tests Results	TCR% SCR% RQD%	IF (min ave max)	Water Strikes	Progress Date Time	Progress Casing Water	Strata Description	Strata Detail	Depth, Level (thickness)
		PID18	0.000ppm						Medium strong dark reddish brown fine SANDSTONE interbedded with very weak MUDSTONE. Fractures are closely spaced locally very closely and medium spaced subhorizontal undulating rough with a clay smear. Mudstone has black staining on fracture surfaces. [ST BEES SANDSTONE] *(continued)*	19.95 - 20.15 Mudstone. *(continued)*	
										20.15 - 20.40 Fractures are very closely spaced.	
				100 95 90							
										20.90 - 21.00 Mudstone.	
										21.20 - 21.35 Mudstone.	
										21.60 - 21.85 Mudstone.	
				100 95 95						22.10 - 22.20 Mudstone.	22.35 *52.78*
					340 600 1050				Very strong dark reddish brown fine SANDSTONE. Fractures are medium and widely spaced subhorizontal undulating rough with a slight clay infill (<1mm). [ST BEES SANDSTONE]		
							22/11/2012 18:00	2.40 *3.10*			
				100 100 100			23/11/2012 08:00	2.40 *3.30*		23.35 - 24.00 Mudstone.	
				100 95 90							
26.20-26.30	ES1	PID19	0.000ppm	100 100 100						26.10 - 26.35 Mudstone.	
										26.35 - 26.40 Fractures are closely spaced.	
										26.45 - 26.50 Mudstone.	
26.90-27.00	ES2	PID20	0.000ppm							26.80 - 27.00 Mudstone.	
											(9.65)
				100 100 100							
							23/11/2012 14:00	2.40 *3.30*		28.60 - 28.70 Mudstone.	
28.80-28.90	ES3	PID21	0.100ppm	100 90 85			26/11/2012 08:00	2.40 *4.60*			
										29.70 - 30.10 Mudstone.	

Drilling Technique From	To	Technique	Flush From	To	Rtrn %	Flush Type	Water Obs. Date/Time	Strike At	Rise To	Casing	Sealed	Hole Dia.	Depth	Casing Dia.	Depth	Water Added From	To	Volume

Remarks
Unable to determine waterstrikes as masked by the use of water flush.
Packer permeability tests undertaken 29.40 - 30.40m and 40.70 - 41.70m.
Borehole terminated on Engineer's instruction.

Termination Depth: 54.40m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used: Wheeled mounted Massenza MI6
Contractor: Hyder Consulting Ltd
Logged By: IP
Checked By: DH

Hyder Rotary Borehole Log

BH56b

Project	Project No.	Ground Level (m AOD)	Start Date	
Chapelcross Solvent Plume Investigation	UA004495	75.13	20-11-12	
Client	**Easting (OS)**	**Northing (OS)**	**Finish Date**	**Scale**
Magnox	321819.2	569488.1	29-11-12	1:50

Samples / Tests / Progress

Sample Depth	Type	Test Type/No	Results	TCR% SCR% RQD%	IF (min ave max)	Water Strikes	Progress Date/Time	Casing / Water
30.30-30.40	ES4	PID22	0.000ppm					
				100 100 95				
31.70-31.80	ES5	PID23	0.000ppm					
				100 75 55	30 110 165			
32.80-32.90	ES6	PID24	0.000ppm				26/11/2012 18:00	2.40 / 3.90
				100 100 100	110 340 660		27/11/2012 08:00	2.40 / 4.60
34.00-34.10	ES7	PID25	0.000ppm					
				100 95 90				
35.60-35.70	ES8	PID26	0.000ppm					
				100 100 100	40 110 180			
37.10-37.20	ES9	PID27	0.000ppm					
				100 85 75				
37.70-37.80	ES10	PID28	0.000ppm					
				100 100 95				
39.00-39.10	ES11	PID29	0.000ppm					
					210 800 2020			

Strata

Description	Detail	Depth, *Level* (thickness)
Very strong dark reddish brown fine SANDSTONE. Fractures are medium and widely spaced subhorizontal undulating rough with a slight clay infill (<1mm). [ST BEES SANDSTONE] *(continued)*	30.35 - 30.60 Mudstone. 31.75 - 31.90 Mudstone.	32.00 *43.13*
Strong dark reddish brown fine SANDSTONE interbedded with very weak MUDSTONE. Fractures are very closely and closely spaced subhorizontal undulating rough with clay smear. Locally non-intact; recovered as angular fine to coarse gravel. [ST BEES SANDSTONE]	32.45 - 32.60 Mudstone. 32.90 - 33.15 Mudstone.	(1.20) 33.20 *41.93*
Very strong dark reddish brown fine SANDSTONE. Fractures are medium and widely spaced subhorizontal undulating smooth. [ST BEES SANDSTONE]	33.20 - 33.40 Mudstone. 35.50 - 35.70 Weak mudstone.	(2.80) 36.00 *39.13*
Strong dark reddish brown fine and medium SANDSTONE interbedded with weak reddish brown MUDSTONE. Fractures are very closely and closely spaced subhorizontal undulating smooth locally with black staining. [ST BEES SANDSTONE]	36.20 - 36.40 Mudstone. 36.55 - 36.70 Mudstone. 37.10 - 37.25 Mudstone. 37.65 - 37.85 Non-intact mudstone. 37.95 - 37.97 Open fracture (22mm) with black staining and rounded surfaces. 38.60 - 38.70 Mudstone. 39.00 - 39.20 Mudstone with 45° fracture. 39.30 - 39.35 Mudstone.	(3.40) 39.40 *35.73*
Very strong dark reddish brown fine SANDSTONE. Fractures are widely spaced locally very widely subhorizontal undulating rough. [ST BEES SANDSTONE]		

DRILLING TECHNIQUE			FLUSH DETAILS				WATER OBSERVATIONS					HOLE/CASING DIAMETER				WATER ADDED		
From	To	Technique	From	To	Rtrn %	Flush Type	Date/Time	Strike At	Rise To	Casing	Sealed	Hole Dia.	Depth	Casing Dia.	Depth	From	To	Volume

Remarks
Unable to determine waterstrikes as masked by the use of water flush.
Packer permeability tests undertaken 29.40 - 30.40m and 40.70 - 41.70m.
Borehole terminated on Engineer's instruction.

Termination Depth: 54.40m

Rotary Borehole Log

BH56b

Project	Project No.	Ground Level (m AOD)	Start Date	
Chapelcross Solvent Plume Investigation	UA004495	75.13	20-11-12	
Client	**Easting (OS)**	**Northing (OS)**	**Finish Date**	**Scale**
Magnox	321819.2	569488.1	29-11-12	1:50

Samples Depth	Type	Tests Type/No	Results	TCR% SCR% RQD%	IF (min ave max)	Water Strikes	Progress Date Time	Casing Water	Description	Strata Detail	Depth, Level (thickness)
				100 100 100					Very strong dark reddish brown fine SANDSTONE. Fractures are widely spaced locally very widely subhorizontal undulating rough. [ST BEES SANDSTONE] *(continued)*		
							27/11/2012 18:00	2.40 *4.20*			
				100 90 90			28/11/2012 08:00	2.40 *4.60*		41.95 - Fracture with black staining.	
										42.45 - Fracture with black staining and clay smear.	
43.10-43.20	ES12	PID30	0.000ppm							43.05 - 43.15 Non-intact mudstone.	
				100 98 95							(8.30)
										43.30 - 44.45 Fractures are closely spaced.	
44.20-44.30	ES13	PID31	0.000ppm								
				100 95 90							
45.30-45.40	ES14	PID32	0.000ppm							45.30 - 45.55 Mudstone.	
										45.70 - 45.75 Non-intact.	
										46.10 - 45° fracture.	
				100 98 95							
47.50-47.60	ES15	PID33	0.000ppm							47.50 - 47.65 Non-intact sandstone with clay infill.	47.70 *27.43*
				100 80 70	35 100 145				Weak dark reddish brown MUDSTONE. Fractures are closely spaced locally very closely spaced subhorizontal stepped smooth clay infill and black staining on fracture surfaces. Locally weathered to clay. [ST BEES SANDSTONE]		
48.40-48.50	ES16	PID34	0.000ppm				28/11/2012 18:00	2.40 *4.20*			
				100 100 100			29/11/2012 08:00	2.40 *4.60*		48.55 - 48.90 Strong sandstone.	
49.50-49.60	ES17	PID35	0.000ppm	100 100 80							

Drilling Technique From	To	Technique	Flush Details From	To	Rtrn %	Flush Type	Water Observations Date/Time	Strike At	Rise To	Casing	Sealed	Hole/Casing Diameter Hole Dia.	Depth	Casing Dia.	Depth	Water Added From	To	Volume

Remarks
Unable to determine waterstrikes as masked by the use of water flush.
Packer permeability tests undertaken 29.40 - 30.40m and 40.70 - 41.70m.
Borehole terminated on Engineer's instruction.

Termination Depth: 54.40m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used: Wheeled mounted Massenza MI6
Contractor: Hyder Consulting Ltd
Logged By: IP
Checked By: DH

Hyder Rotary Borehole Log

BH56b

Project	Project No.	Ground Level (m AOD)	Start Date	
Chapelcross Solvent Plume Investigation	UA004495	75.13	20-11-12	
Client	**Easting (OS)**	**Northing (OS)**	**Finish Date**	**Scale**
Magnox	321819.2	569488.1	29-11-12	1:50

Samples Depth	Type	Tests Type/No	Results	TCR% SCR% RQD%	IF (min ave max)	Water Strikes	Progress Date Time	Casing Water	Description	Detail	Depth, Level (thickness)	Install/ Backfill
				100 90 85					Weak dark reddish brown MUDSTONE. Fractures are closely spaced locally very closely spaced subhorizontal stepped smooth clay infill and black staining on fracture surfaces. Locally weathered to clay. [ST BEES SANDSTONE] *(continued)*	50.60 - 45° fracture.	(4.90)	
51.50-51.60	ES18	PID36	0.000ppm	100 75 50						51.40 - 51.50 Strong sandstone. 51.75 - 51.85 Strong sandstone.		
					220 300 610						52.60 *22.53*	
									Strong dark reddish brown fine SANDSTONE. Fractures are medium spaced subhorizontal planar rough. [ST BEES SANDSTONE]	52.90 - 53.10 Subvertical fracture.	(0.60) 53.20 *21.93*	
				100 95 40	65 95 195				Weak dark reddish brown MUDSTONE. Fractures are closely spaced subhorizontal stepped and undulating smooth. [ST BEES SANDSTONE]	53.50 - 53.60 Strong sandstone.	(1.20)	
							29/11/2012 14:00	2.40 *4.60*	**End of Exploratory Hole**		54.40 *20.73*	

Drilling Technique From	To	Technique	Flush Details From	To	Rtrn %	Flush Type	Water Observations Date/Time	Strike At	Rise To	Casing	Sealed	Hole/Casing Diameter Hole Dia.	Depth	Casing Dia.	Depth	Water Added From	To	Volume

Remarks
Unable to determine waterstrikes as masked by the use of water flush.
Packer permeability tests undertaken 29.40 - 30.40m and 40.70 - 41.70m.
Borehole terminated on Engineer's instruction.

Termination Depth: 54.40m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used: Wheeled mounted Massenza MI6
Contractor: Hyder Consulting Ltd
Logged By: IP
Checked By: DH

Hyder Rotary Borehole Log — BH61

Project	Project No.	Ground Level (m AOD)	Start Date	
CHAPELCROSS SOLVENT PLUME PHASE 2	UA004495	60.61	23-09-13	
Client	**Easting (AOD)**	**Northing (AOD)**	**Finish Date**	**Scale**
MAGNOX	321251.0	569326.3	27-09-13	1:50

SAMPLES Depth	Type	TESTS Type/No	Results	TCR% SCR% RQD%	IF (min ave max)	Water Strikes	PROGRESS Date Time	Casing Water	STRATA Description	Detail	Depth, *Level* (thickness)
									Soft brown slightly sandy CLAY with frequent rootlets. [Topsoil]		0.20 *60.41*
									Firm reddish brown slightly sandy CLAY. [Glacial Deposits]		(1.00) 1.20 *59.41*
						▼			Rotary openhole drilling. Boulder clay (Driller's description). [Glacial Deposits]		(4.70) 5.90 *54.71*
6.20-7.30	C	PID1	0.00ppm	90 40 15	60 95 125				Rotary openhole drilling. Weathered brown sandstone (Driller's description). [ST BEES SANDSTONE]		6.20 *54.41*
6.90-7.00	ES								Medium strong dark reddish brown medium SANDSTONE. Fractures are closely spaced subhorizontal and 45° undulating rough with black staining. [ST BEES SANDSTONE]	6.80 - 7.30 Non intact with a clay infill.	(1.30)
7.30-8.50	C	PID2	0.00ppm	100 90 50	30 100 210						7.50 *53.11*
8.00-8.10	ES	PID3	0.00ppm						Medium strong light reddish brown fine SANDSTONE. Fractures are very closely to medium spaced subhorizontal and subvertical undulating rough with black staining. [ST BEES SANDSTONE]		(0.90) 8.40 *52.21*
8.50-10.00	C	PID4	0.00ppm	100 60 10	5 70 120				Weak dark reddish brown medium SANDSTONE interbedded with extremely weak dark reddish brown MUDSTONE. Fractures are extremely closely to closely spaced subhorizontal and subvertical undulating smooth with a clay infill. [ST BEES SANDSTONE]	8.70 - 8.85 Subvertical fracture. 9.10 - 9.15 Mudstone. 9.30 - 9.40 Mudstone. 9.70 - 9.80 Mudstone.	(1.70)
9.50-9.60	ES						24/09/2013 18:00	6.50 *3.20*			10.10

DRILLING TECHNIQUE

From	To	Technique
0.00	1.20	Inspection Pit
1.20	6.20	Rotary Open Holed
6.20	37.50	Rotary Cored

FLUSH DETAILS

From	To	Rtrn %	Flush Type
1.20	6.20	100	Air
6.20	37.50	0	Water

WATER OBSERVATIONS

Date/Time	Strike At	Rise To	Casing	Sealed
	3.20	3.20	2.70	

HOLE/CASING DIAMETER

Hole Dia.	Depth	Casing Dia.	Depth
150	6.50	150	6.50
146	37.50		

WATER ADDED

From	To	Volume

Remarks
Borehole terminated on Engineer's instruction.

Termination Depth: 37.50m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used: Track mounted Massenza MI4
Contractor: JB SITE INVESTIGATIONS
Logged By: IP
Checked By: CW

Rotary Borehole Log

BH61

Project	Project No.	Ground Level (m AOD)	Start Date	
CHAPELCROSS SOLVENT PLUME PHASE 2	UA004495	60.61	23-09-13	
Client	**Easting (AOD)**	**Northing (AOD)**	**Finish Date**	**Scale**
MAGNOX	321251.0	569326.3	27-09-13	1:50

Samples / Tests / Progress

Depth	Type	Type/No	Results	TCR% SCR% RQD%	IF (min ave max)	Water Strikes	Progress Date Time	Casing Water
10.00-11.00	C	PID5	0.00ppm	100 / 90 / 80	60 / 130 / 230		25/09/2013 08:00	
11.00-11.30	C							
11.00-11.10	ES	PID6	0.00ppm					
11.30-12.50	C			95 / 75 / 55				
		PID7	0.00ppm					
12.50-14.00	C			100 / 70 / 45	5 / 70 / 105			
12.80-12.90	ES							
		PID8	0.00ppm					
					80 / 130 / 250			
14.00-15.50	C	PID9	0.00ppm	100 / 95 / 80				
14.90-15.00	ES							
		PID10	0.00ppm					
15.50-16.90	C			95 / 50 / 30	10 / 60 / 90			
16.10-16.20	ES	PID11	0.00ppm					
					90 / 130 / 210			
16.90-17.30	C			100 / 100 / 80				
		PID12	0.00ppm					
17.30-18.80	C			80 / 75 / 60	10 / 90 / 140			
17.40-17.50	ES							
		PID13	0.00ppm					
18.80-20.30	C			100 / 95 / 85				
19.30-19.40	ES	PID14	0.00ppm					
					80			

Strata

Description	Detail	Depth, Level (thickness)
		50.51
Medium strong dark reddish brown medium SANDSTONE. Fractures are closely and medium spaced subhorizontal undulating rough. [ST BEES SANDSTONE]	10.90 - 11.10 Subvertical fracture. 11.50 - 11.70 45° fracture. 12.00 - 12.50 Fractures are extremely closely spaced.	(2.55) 12.65 47.96
Weak dark reddish brown MUDSTONE. Fractures are extremely closely to closely spaced subhorizontal and subvertical planar smooth with a clay smear. [ST BEES SANDSTONE]	12.90 - 13.05 Non intact. 13.20 - 13.25 Non intact.	(0.80) 13.45 47.16
Medium strong dark reddish brown fine SANDSTONE. Fractures are closely and medium spaced subhorizontal planar rough. [ST BEES SANDSTONE]	14.40 - 14.60 Fractures are very closely spaced.	(2.15) 15.60 45.01
Weak dark reddish brown MUDSTONE interbedded with medium strong fine SANDSTONE. Fractures are extremely and very closely spaced stepped smooth stained black. [ST BEES SANDSTONE]	15.95 - 16.10 Sandstone.	(0.95) 16.55 44.06
Medium strong dark reddish brown fine SANDSTONE. Fractures are closely and medium spaced subhorizontal planar rough. [ST BEES SANDSTONE]		(0.80) 17.35 43.26
Weak dark reddish brown MUDSTONE interbedded with medium strong fine SANDSTONE. Fractures are extremely and very closely spaced stepped smooth stained black. [ST BEES SANDSTONE]	18.90 - 19.10 Sandstone. 19.25 - 19.40 Sandstone.	(2.50) 19.85 40.76

DRILLING TECHNIQUE			FLUSH DETAILS				WATER OBSERVATIONS					HOLE/CASING DIAMETER				WATER ADDED		
From	To	Technique	From	To	Rtrn %	Flush Type	Date/Time	Strike At	Rise To	Casing	Sealed	Hole Dia.	Depth	Casing Dia.	Depth	From	To	Volume

Remarks
Borehole terminated on Engineer's instruction.

Termination Depth: 37.50m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used: Track mounted Massenza MI4

Contractor: JB SITE INVESTIGATIONS

Logged By: IP

Checked By: CW

Rotary Borehole Log

BH61

Hyder

Project	Project No.	Ground Level (m AOD)	Start Date	
CHAPELCROSS SOLVENT PLUME PHASE 2	UA004495	60.61	23-09-13	
Client	**Easting (AOD)**	**Northing (AOD)**	**Finish Date**	**Scale**
MAGNOX	321251.0	569326.3	27-09-13	1:50

Samples Depth	Type	Tests Type/No	Results	TCR% SCR% RQD%	IF (min ave max)	Water Strikes	Progress Date Time	Casing Water
20.00-20.10	ES				130 260		25/09/2013 18:00	6.50 3.20
20.30-21.60	C	PID15	0.00ppm	95 85 75			26/09/2013 08:00	
		PID16	0.00ppm					
21.60-22.90	C			90 85 70				
		PID17	0.00ppm					
22.70-22.80	ES							
22.90-24.40	C	PID18	0.00ppm	100 85 70				
23.40-23.50	ES							
		PID19	0.00ppm					
24.40-25.60	C			100 100 100				
		PID20	0.00ppm					
25.60-26.30	C			100 50 25	95 165 295			
		PID21	0.00ppm					
26.30-27.80	C			100 100 100				
		PID22	0.00ppm					
27.80-29.30	C			100 100 65				
28.40-28.50	ES	PID23	0.00ppm					
		PID24	0.00ppm				26/09/2013 18:00	6.50 3.20
29.30-30.80	C			100 50 0	95 200 350		27/09/2013 08:00	

Strata Description	Detail	Depth, Level (thickness)
Medium strong dark reddish brown medium SANDSTONE interbedded with very weak dark reddish brown MUDSTONE. Fractures are closely and medium spaced subhorizontal undulating rough with occasional black staining. [ST BEES SANDSTONE] *(continued)*	20.45 - 20.70 Mudstone. 20.95 - 21.20 Mudstone. 21.50 - 21.60 Mudstone. 21.75 - 21.85 Mudstone. 22.75 - 22.90 Mudstone. 23.20 - 23.40 Mudstone. 23.60 - 23.75 Mudstone. 24.15 - 24.40 Mudstone. 24.25 - 24.35 Non intact 24.95 - 25.10 Mudstone.	(5.90) 25.75 *34.86*
Medium strong dark reddish brown fine and medium SANDSTONE. Fractures are closely and medium spaced subhorizontal undulating rough. [ST BEES SANDSTONE]	26.65 - 26.90 Subvertical fracture. 27.20 - 27.60 Undulating stratification. 28.40 - 28.60 Fractures are very closely spaced.	(3.85) 29.60 *31.01*

Drilling Technique From	To	Technique	Flush Details From	To	Rtrn %	Flush Type	Water Observations Date/Time	Strike At	Rise To	Casing	Sealed	Hole Dia.	Depth	Casing Dia.	Depth	Water Added From	To	Volume

Remarks
Borehole terminated on Engineer's instruction.

Termination Depth: 37.50m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used: Track mounted Massenza MI4

Contractor: JB SITE INVESTIGATIONS

Logged By: IP

Checked By: CW

Rotary Borehole Log

BH61

Project	Project No.	Ground Level (m AOD)	Start Date	
CHAPELCROSS SOLVENT PLUME PHASE 2	UA004495	60.61	23-09-13	
Client	**Easting (AOD)**	**Northing (AOD)**	**Finish Date**	**Scale**
MAGNOX	321251.0	569326.3	27-09-13	1:50

SAMPLES Depth	Type	TESTS Type/No	Results	TCR% SCR% RQD%	IF (min ave max)	Water Strikes	PROGRESS Date Time	Casing *Water*	Description	STRATA Detail	Legend	Depth, *Level* (thickness)	Install/ Backfill
		PID25	0.00ppm						Medium strong dark reddish brown medium SANDSTONE interbedded with very weak MUDSTONE. Fractures are closely and medium spaced undulating rough with a clay infill. [ST BEES SANDSTONE] *(continued)*				
30.80-31.50	C			100 100 85									
		PID26	0.00ppm										
31.50-33.00	C			100 100 100									
		PID27	0.00ppm							31.30 - 32.90 Siltstone laminae.			
33.00-34.50	C			100 100 100									
		PID28	0.00ppm									(7.90)	
		PID29	0.00ppm							34.20 - 34.40 Mudstone.			
34.50-36.70	C			100 90 90									
							27/09/2013 18:00	6.50 *3.20*					
							30/09/2013 08:00						
		PID30	0.00ppm							34.90 - 35.20 Mudstone.			
										35.50 - 35.60 Mudstone.			
		PID31	0.00ppm							36.20 - 36.40 Non intact.			
										36.50 - 36.70 Mudstone.			
36.70-37.50	C			100 95 90									
		PID32	0.00ppm				30/09/2013 10:00	6.50 *3.20*	**End of Exploratory Hole**			37.50 *23.11*	

DRILLING TECHNIQUE From	To	Technique	FLUSH DETAILS From	To	Rtrn %	Flush Type	WATER OBSERVATIONS Date/Time	Strike At	Rise To	Casing	Sealed	HOLE/CASING DIAMETER Hole Dia.	Depth	Casing Dia.	Depth	WATER ADDED From	To	Volume

Remarks
Borehole terminated on Engineer's instruction.

Termination Depth: 37.50m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used: Track mounted Massenza MI4

Contractor: JB SITE INVESTIGATIONS

Logged By: IP

Checked By: CW

Rotary Borehole Log

BH64

Project	Project No.	Ground Level (m AOD)	Start Date	
Chapelcross Solvent Plume Investigation	UA004495	72.04	06-12-12	
Client	**Easting (OS)**	**Northing (OS)**	**Finish Date**	**Scale**
Magnox	321628.1	569514.6	10-12-12	1:50

Samples / Tests

Depth	Type	Type/No	Results
11.90-12.00	ES1		
12.90-13.00	ES2	PID1	0.035ppm
14.55-14.60	ES3	PID2	0.182ppm
16.85-16.90	ES4	PID3	0.045ppm
18.00-18.05	ES5	PID4	0.005ppm
19.80-19.90	ES6	PID5	0.023ppm

TCR% SCR% RQD%
100 / 45 / 40
60 / 25 / 0
100 / 90 / 40
100 / 95 / 70
100 / 100 / 50
100 / 95 / 85
100 / 95 / 90

IF (min ave max)
NA / NA / NA
NI / 25 / 70
5 / 60 / 150
NI / 15 / 140
10 / 80 / 180
80 / 190 / 340
30 / 110 / 180

Progress

Water Strikes	Date	Time	Casing	Water
1	06/12/2012	18:00	10.50	0.20
	07/12/2012	08:00	10.50	1.60
	07/12/2012	18:00	12.00	1.00
	10/12/2012	08:00	12.00	2.60
	10/12/2012	18:00	13.00	2.40

Strata

Description	Detail	Depth	Level	(thickness)
		10.50	61.54	
Dark reddish brown sandy CLAY with medium cobbles and boulders content. Cobbles and boulders are of sandstone. [Glacial Till]	10.90 - 11.60 Boulder of sandstone.	11.60	60.44	(1.10)
Reddish brown silty slightly gravelly fine and medium SAND. Gravel is angular fine and medium of sandstone. [ST BEES SANDSTONE]		12.70	59.34	(1.10)
Very weak dark reddish brown MUDSTONE interbedded with weak SANDSTONE. Fractures are extremely closely to closely spaced randomly orientated stepped smooth with black staining. [ST BEES SANDSTONE]	12.80 - 12.90 Sandstone.	13.10	58.94	(0.40)
Medium strong dark reddish brown fine SANDSTONE interbedded with extremely weak and very weak MUDSTONE. Fractures are very closely and closely spaced subhorizontal undulating rough with clay infill and black staining. [ST BEES SANDSTONE]	13.35 - 13.40 Mudstone. 13.85 - 13.90 Mudstone. 14.15 - 14.20 Mudstone. 14.55 - 14.60 Mudstone. 14.90 - 15.00 Subvertical fracture. 15.15 - 15.20 Mudstone. 15.25 - 15.30 Mudstone. 15.40 - 15.45 Mudstone.	15.70	56.34	(2.60)
Very weak dark reddish brown MUDSTONE interbedded with weak SANDSTONE. Fractures are extremely closely to closely spaced subhorizontal undulating smooth with black staining. [ST BEES SANDSTONE]	15.80 - 15.90 Non-intact sandstone. 16.20 - 16.35 Sandstone. 16.50 - 16.55 Sandstone.	16.60	55.44	(0.90)
Medium strong dark reddish brown fine SANDSTONE interbedded with extremely weak and very weak MUDSTONE. Fractures are very closely and closely spaced subhorizontal undulating rough locally with clay infill and black staining. [ST BEES SANDSTONE]		17.45	54.59	(0.85)
Strong dark reddish brown fine and medium SANDSTONE. Fractures are closely and medium spaced subhorizontal undulating rough. [ST BEES SANDSTONE]	18.00 - 18.05 Very weak mudstone. 18.35 - 30° fracture	19.10	52.94	(1.65)
Weak dark reddish brown MUDSTONE interbedded with very weak MUDSTONE. Fractures are very closely and closely spaced subhorizontal undulating smooth with a clay infill. [ST BEES SANDSTONE]	19.20 - 19.25 Non-intact. 19.40 - 19.50 Mudstone. 19.70 - 19.75 Mudstone.	20.00	52.04	(0.90)

DRILLING TECHNIQUE			FLUSH DETAILS				WATER OBSERVATIONS					HOLE/CASING DIAMETER				WATER ADDED		
From	To	Technique	From	To	Rtrn %	Flush Type	Date/Time	Strike At	Rise To	Casing	Sealed	Hole Dia.	Depth	Casing Dia.	Depth	From	To	Volume

Remarks
Borehole terminated on Engineer's instruction.

Termination Depth: 4.40m

All depths in meters (unless otherwise stated)
All diameters in mm (unless otherwise stated)
Time is expressed hhmm (unless otherwise stated)

Equipment Used	Contractor	Logged By	Checked By
Wheeled mounted Massenza MI6	Hyder Consulting Ltd	IP	DH

HYDER SITE INVESTIGATION SERVICES GINT LIBRARY VER 2.3A (ISSUE2).GLB Log SIS ROTARY BOREHOLE LOG \\HC-UKR-CA-FS-01\CA_TECHNICAL\GEOTECHNICS\GINT\GINT PROJECT FILES\UA004495 CHAPELCROSS SOLVENT PLUME.GPJ AGS 3_1.GDT <<DrawingFileSpec>> 30/01/2013 15:28:50

Appendix 2- PRB screening criteria sheet for Bradwell Site

Bradwell Site "North End"

Table 2.2 Summary of Screening Criteria to Assess the Feasibility of PRB (Section 2.3)

Screening criteria	Feasibility: High	Feasibility: Intermediate	Feasibility: Low
A. Technical screening factors (section 2.3)			
Site characterisation and plume definition (heterogeneity)	Well defined	-	Poorly defined
Contaminant amenability to treatment	Track record of use of PRB technology to treat contaminant	Contaminant properties suggest that treatment can be achieved.	Significant doubt or lack of evidence that contaminant is traceable
Pollution potential of daughter products	Less polluting than parent	Equally polluting	More polluting than parent (reclassify as high if design can also treat daughter products)
Source of groundwater contamination	Eliminated or being removed	Controlled and timescale for removal is short to medium term	Continuing release such that timescale to achieve remedial objectives is unacceptable to stakeholders
Combined effects of multiple contaminants	All contaminants of concern amenable to treatment	Some contaminants will require additional treatment	Contaminants can impair effectiveness of PRB
Remobilisation of contaminants	Process destructive or rate of desorption/re-mobilisation represents no risk to receptors	-	Risk of desorption or remobilisation of contaminants (reclassify as high if design allows replacement of reactive material)
Aquifer heterogeneity (complexity) and isotropy	Relatively homogeneous aquifer (e.g. Sand & Gravel)	Moderately heterogeneous aquifer (e.g. indurated sandstones)	Highly heterogeneous and anisotropic (e.g. karstic limestone) such that uncertainty that PRB can deal with contaminant flux
Long-term performance of PRB	Design will incorporate measures to rehabilitate or replace PRB. Track record of performance of proposed PRB Technology	- Zeolites used for Sr-90 elsewhere.	Risk of clogging or loss in reactivity of reactive material (reclassify as high if design allows replacement of reactive material)
Flow direction	Consistent flow rate, direction and level	-	Uncertainty associated with whether PRB can accommodate variations in water level or flow direction with time.
Depth of aquifer	Shallow aquifer (less than 20 m)	Aquifer between 20 and 50 m deep.	Deep aquifer (greater than 50 m). Reclassify to "intermediate' if plume is well-defined and less than 10 m thick.

Table 2.2 (continued) Summary of Screening Criteria to Assess the Feasibility of PRB (Section 2.3)

Screening criteria	Feasibility: High	Intermediate	Low
B. Regulatory screening factors			
Receptor	No receptors identified / at risk. PRB design will protect identified receptors.	Receptors present (low risk)	**PRB will not protect receptors, or will have an adverse effect on a European site.** Insufficient time for design and construction of PRB before unacceptable impact at receptor, i.e. PRB unacceptable as sole remedial solution.
Maintenance	The long-term operation of the PRB can be guaranteed		Design does not allow for rehabilitation or decommissioning of PRB
Time frame	Remedial objectives can be achieved in an acceptable time frame to stakeholders		Uncertainty over time period for remedial objectives to be achieved
Can be monitored	Monitoring can be implemented to verify treatment process	-	**Monitoring cannot be implemented to verify treatment process**
Acceptability to regulator	Relevant authorisations obtained. No policy objection. Technical support provided.	No policy objection. Technical concerns.	**Relevant permits refused.** Policy objections in principle. Major technical concerns.
C. Practical and financial constraints			
Cost benefit	Favourable in relation to other remedial options	-	Other remedial options provide more favourable cost benefit
Financial provisions	Long-term, legally-binding budget provisions secured	Long-term, non-legally binding budget provision secured	No long-term budget provisions
Access	Access available	Access possible	**Buildings/services prevent access for construction, rehabilitation and/or decommissioning of PRB**
Monitoring locations (including off-site if required by nature of site)	Access available	Access possible	Limited /no access
OVERALL	All high/ intermediates No lows or design can be modified	High, medium and lows, but no "show-stoppers"	One or more show-stopping criteria present, *or* No factors of high feasibility rating

N.B. Criteria shown in **bold** will normally preclude the use of a PRB as the sole remedial option i.e. are "show stoppers". It indicates the need to use a different remedial technology in isolation, or in combination with a PRB.

Appendix 3- PRB screening criteria sheet for Chapelcross Site

- Chapelcross - "solvent plume"

Table 2.2 Summary of Screening Criteria to Assess the Feasibility of PRB (Section 2.3)

Screening criteria	Feasibility: High	Feasibility: Intermediate	Feasibility: Low
A. Technical screening factors (section 2.3)			
Site characterisation and plume definition (heterogeneity)	Well defined	-	Poorly defined
Contaminant amenability to treatment	Track record of use of PRB technology to treat contaminant	Contaminant properties suggest that treatment can be achieved.	Significant doubt or lack of evidence that contaminant is traceable
Pollution potential of daughter products	Less polluting than parent	Equally polluting If VC gets through	More polluting than parent (reclassify as high if design can also treat daughter products)
Source of groundwater contamination	Eliminated or being removed	Controlled and timescale for removal is short to medium term	Continuing release such that timescale to achieve remedial objectives is unacceptable to stakeholders
Combined effects of multiple contaminants	All contaminants of concern amenable to treatment	Some contaminants will require additional treatment	Contaminants can impair effectiveness of PRB
Remobilisation of contaminants	Process destructive or rate of desorption/re-mobilisation represents no risk to receptors	- DNAPL at depth - diffusion →	Risk of desorption or remobilisation of contaminants (reclassify as high if design allows replacement of reactive material)
Aquifer heterogeneity (complexity) and isotropy	Relatively homogeneous aquifer (e.g. Sand & Gravel)	Moderately heterogeneous aquifer (e.g. indurated sandstones)	Highly heterogeneous and anisotropic (e.g. karstic limestone) such that uncertainty that PRB can deal with contaminant flux
Long-term performance of PRB	Design will incorporate measures to rehabilitate or replace PRB. Track record of performance of proposed PRB Technology	- LTP costs will need to include long term replacement of media.	Risk of clogging or loss in reactivity of reactive material (reclassify as high if design allows replacement of reactive material)
Flow direction	Consistent flow rate, direction and level	-	Uncertainty associated with whether PRB can accommodate variations in water level or flow direction with time.
Depth of aquifer	Shallow aquifer (less than 20 m)	Aquifer between 20 and 50 m deep.	Deep aquifer (greater than 50 m). Reclassify to "intermediate' if plume is well-defined and less than 10 m thick.

Table 2.2 (continued) Summary of Screening Criteria to Assess the Feasibility of PRB (Section 2.3)

Screening criteria	Feasibility: High	Feasibility: Intermediate	Feasibility: Low
B. Regulatory screening factors			
Receptor	No receptors identified / at risk. PRB design will protect identified receptors.	Receptors present (low risk)	**PRB will not protect receptors, or will have an adverse effect on a European site.** Insufficient time for design and construction of PRB before unacceptable impact at receptor, i.e. PRB unacceptable as sole remedial solution.
Maintenance	The long-term operation of the PRB can be guaranteed	Between high + intermediate. Agreement on LTP costs for replacing media	Design does not allow for rehabilitation or decommissioning of PRB
Time frame	Remedial objectives can be achieved in an acceptable time frame to stakeholders		Uncertainty over time period for remedial objectives to be achieved
Can be monitored	Monitoring can be implemented to verify treatment process	-	**Monitoring cannot be implemented to verify treatment process**
Acceptability to regulator	Relevant authorisations obtained. No policy objection. Technical support provided.	No policy objection. Technical concerns. Agreement would be needed with SEPA/Local Authority + Magnox.	**Relevant permits refused.** Policy objections in principle. Major technical concerns.
C. Practical and financial constraints			
Cost benefit	Favourable in relation to other remedial options	- Probably similar cost to other options - TBD in NPV calculations	Other remedial options provide more favourable cost benefit
Financial provisions	Long-term, legally-binding budget provisions secured	Long-term, non-legally binding budget provision secured LTP dependent	No long-term budget provisions - long term funding secured - new Govt?
Access	Access available	Access possible	**Buildings/services prevent access for construction, rehabilitation and/or decommissioning of PRB**
Monitoring locations (including off-site if required by nature of site)	Access available	Access possible. prior agreement to access fields will be required but has been given previously for characterisation works.	Limited /no access
OVERALL	All high/ intermediates No lows or design can be modified	High, medium and lows, but no "show-stoppers" Mainly High's + Intermediate's	One or more show-stopping criteria present, or No factors of high feasibility rating

N.B. Criteria shown in **bold** will normally preclude the use of a PRB as the sole remedial option i.e. are "show stoppers". It indicates the need to use a different remedial technology in isolation, or in combination with a PRB.

Appendix 4 – Detailed cost breakdown for Chapelcross Site

Option 1 - ISTT/SVE & Enhanced Bioremediation & MNA

Costings have been taken from Kueper et al, 2014 where example remedial case studies have been costed for DNAPL contamination in a low permeability source area. Costings have also been taken from a remediation undertaken by Provectus Group, 2009 at RSRSL Harwell site where chlorinated solvent contamination was remediated with thermal conductive heating (TCH).

Notes:

- Exchange rate of £1= $1.5368 (as at 30/04/2015- will be used for all future estimates where $ estimates are used) http://www.bankofengland.co.uk/boeapps/iadb/Rates.asp?into=)
- Where costings are older than 2014 dates a consumer price index (CPI) will be applied to index prices to current day value (http://www.whatsthecost.com/cpi.aspx)

Capital Costs	Cost (£)	Comments	References
Design & Procurement	165,929	Design and procurement costs for TCH = $255,000/ 1.5368 exchange rate = £165,929. Note 2014 costs. No CPI applied as recent data.	Kueper et al, 2014
Mobilisation and Demobilisation	137,298	Case study for remedial costing of DNAPL in low permeability source area mobilisation/demobilisation costs for TCH = $211,000/ 1.5368 = £137,298. Note 2014 costs. No CPI applied as recent data.	

Drilling & Installation of heater borings to install heating element and SVE wells	161,894	Case study based on a 1500m^2 source area. Area originally excavated at CHX is 20 x 30m = 600m^2, the area to be thermally treated is slightly larger than the initial excavation to ensure that the edges of the initial excavation (source 1) are treated so would be 30 x 40m = 1,200m^2. The costings have therefore taken into account the area size as CHX would require less heater borings and SVE wells due to the area being less than the case study. Cost $311,000/ 1500m^2 = $207.33 per/m^2 $207.33 x 1200m^2 = $248,800. $248,800/ 1.5368 exchange rate = £161,894. Note 2014 costs. No CPI applied as recent data	
Thermal and SVE Equipment Installation	51,954	£45,000. CPI applied to 2009 costs to bring to 2015 costs = £51,954.	Provectus Group, 2009.
Operation and Maintenance	34,636	General start up costs, commissioning, monitoring = £30,000 in Provectus case study in 2009. CPI applied to 2009 costs to bring to 2015 costs = £34,636.	Provectus Group, 2009.

Variable Costs	**Cost (£)**	**Comments**	**References**
Waste GAC- off gas treatment	35,625	Provectus case study ~3500m^3 treated area cost ~£3,000. Therefore £3,000/ 3500m^3 = £0.85714 per/m^3 CHX area to be treated is 36,000m^3 (based on 30m x 40m x 30m depth of DNAPL). Therefore 36,000m^3 x £0.85714 = £30,857. CPI applied to 2009 costs to bring to 2015 costs = £35,625	Provectus Group, 2009.
Waste GAC condensate treatment	17,812	Provectus case study based on ~3500m3 treated for ~ £1,500. Therefore £1,500/ 3500m^3 = £0.42857. CHX area to be treated is 36,000m3 (based on 30m x 40m x 30m depth of DNAPL). Therefore 36,000m^3 x £0.42857 = £15,428. CPI applied to 2009 costs to bring to 2015 costs = £17,812	
Energy Consumption	1,033,302	TCH can use up to 120-300kWh per yd^3 30 x 40m and depth of 30m required treatment area = 36,000m^3 equates to 47,086 yd^3. TCH energy demand of 120-300kWh per yd^3, have chosen a mid point of 210 kWh per yd^3 required. 47,086 yd^3 x 210kWh = 9,888,060 kWh x 0.1045 = £1,033,302 (10.45p/ kWh, Department of energy and Climate Change, 2015).	Kueper et al, 2014. Department of energy and Climate Change, 2015.
TOTAL COST (£)	1,638,450		

O&M Costs (£)	Cost (£)	Comments	References
Soil Sampling (1st Year)	7,808	Soil sampling (first year only) to assess concentrations in soil from initial thermal treatment then enhanced bioremediation monitoring to follow soil sampling= $12,000= £7,808/ 1.5368 exchange rate = £7,808.	Kueper et al, 2014.
Validation/ Enhanced Bioremediation Monitoring Costs Year 1	14,431	Groundwater monitoring wells in the source area and mid plume will be used to monitor for indicators of bioremediation such as pH, temperature, alkalinity and BioTraps will be installed to measure for presence of Dhc. Monitoring will be undertaken quarterly for 2 years after the initial remediation. Quarterly Monitoring for 2 years, estimate taken from Provectus case study at £25,000 based on 8 visits a year (including BioTrap sampling) £25,000/8 = £3,125 x 4 visits required for CHX Site = £12,500. As 2009 costs, CPI applied to get current cost of £14,431 for one year of sampling.	Kueper et al, 2014. Provectus Group, 2009.
Year 2	14,431		
Yearly monitoring (for 5 years)	18,035	If after 2 years parameters for enhanced bioremediation continue to be favourable for dehalogenating bacteria, continued reductions in concentrations of chlorinated solvents and no rebound is detected then yearly monitoring for 5 years can occur with a review after this period. These costs will be included within the NPV calculation within the out years. Yearly monitoring after first two years if parameters favourable = £14,431/4 = £3,607 a year for next five years.	Kueper et al, 2014. Provectus Group, 2009.
TOTAL O&M COSTS (£)	54,705		

NOTES/ ASSUMPTIONS	Based on 2 year operation, comprising 4 months mobilisation, setup, drilling of heater borings and system installation. Active treatment time of 3 months and 1 month demobilisation, 6 month cooling period so as then enhanced bioremediation indicators can then be monitored (Provectus, 2009).

Option 2 - ISCR, Enhanced Bioremediation & MNA
Costings have been taken from Kueper et al, 2014 where example remedial case studies have been costed for DNAPL contamination in a low permeability source area. For injection of Regenesis 3DMe a case study from 2010 of a large scale application to a chlorinated solvent plume cost data has been used from an example site. Notes: - Exchange rate of £1= $1.5368 (as at 30/04/2015- will be used for all future estimates where $ estimates are used) http://www.bankofengland.co.uk/boeapps/iadb/Rates.asp?into=) - Where costings are older than 2014 dates a consumer price index (CPI) will be applied to index prices to current day value (http://www.whatsthecost.com/cpi.aspx)

Capital Costs	Cost (£)	Comments	References
Injection of 3DMe at 10m intervals (Based on 3DMe trial)	260,410	As in situ ZVI/clay soil mixing will be applied at the source zone, 3DMe injections will be applied to the plume area and DNAPL at depth beneath the ATB area. Therefore in advance of the in situ soil mixing 3DMe injections will be injected to the DNAPL at depths of ~25m below the ATB. Some existing boreholes will be able to be used for this, to ensure that the edges (source 1) are treated the area 30 x 40m = 1,200m^2 would need to be treated. (Based on going slightly larger than previous excavation of ATB in 2008. Therefore a 10m x 10m radius of influence would mean that 12 injection points would be required in the source area but due to existing boreholes in the area, an estimate of 9 injection points has been estimated. 3DMe injection costs taken from Regenesis case study showed injection costs at £95,000 were given for 126 injection points, £95,000/ 126 = £753.96 per injection x 9 injection points = £6,785, as 2010 costs CPI applied to get 2015 costs = £7,584 for source area. To deal with the rest of the plume a total area of roughly 500m in length and 60m wide would need to be targeted. This equates to 30,000m^2. Therefore 300 injection points would be required at varying depths over this area, 300 x £753.96 per injection = £226,188 as 2010 costs CPI applied to get 2015 costs = £252,826 £252,826+ £7,584 = £260,410	Regenesis, 2010 Serco, 2008
Design & Procurement in situ ZVI mixing	72,228	Case study design and procurement costs for ISCR ZVI/clay mixing at source area= $111,000/ 1.5368 exchange rate = £72,228	Kueper et al, 2014.

Mobilisation and Demobilisation in situ ZVI mixing	97,605	Case study for ISCR mobilisation/demobilisation costs of crane mounted auger for ZVI/clay mixing equipment to site = \$150,000/ 1.5368 = £97,605	Kueper et al, 2014.
Removal of top 1m of soil, mixed with iron and bentonite clay for re-use	22,384	Case study, removal of soil is required to create space for the expansion of soil from in situ mixing. CHX site will require 1200m^2 to be removed which will be mixed with iron and betonite and stockpiled on site so as once in situ mixing is completed the soil can be re-used on top of the source area to accelerate drain-age and compress underlying soils. The case study area is 1500m^2 and excavation, mixing and re-use cost \$43,000. Therefore \$43,000/ 1500m^2 = \$28.66 per m^2. \$28.66 x 1200 m^2 = \$34,400/ 1.5368 = £22,384	Kueper et al, 2014.
Soil Mixing	249,868	ISCR soil mixing based on 1500m^2 area at 3m depth mixing cost \$240,000. A deeper depth would be required for CHX site to around 6m to ensure that the chlorinated solvents are dealt with at these depths identified in the boreholes in this area. Therefore \$240,000/ 1500m^2 = \$160 a m^2 \$160 X 1200 m^2 = \$192,000/ 1.5368 = £124,934, taking into account double the depth required the cost has been doubled = £249,868	Kueper et al, 2014.

Materials (ZVI/ bentonite clay)	193,258	Case study applied 50D micro scale iron and unmodified sodium bentonite clay at 2% by weight of DNAPL loading. The case study had a residual TCE DNAPL loading of 15,000 kg and TCE present in groundwater at 500mg/l and cis-1,2-di-chloroethene present at 20mg/l. The cost of materials $297,000. Compared to CHX Site TCE present around 1.29 mg/l and cis-1,2-dichloroethene at 1.55mg/l (Appendix 1- BH1). WS9 borehole data showed PCE present at 20.3 mg/kg. As the CHX data can not be compared exactly to the quantities within the case study case and the exact quantities of materials required for CHX is not known unless further detailed quotations from specialist contractor. For CHX site in order to cost the materials the direct costings from the case study have been assumed but in reality would be different once calculated properly. $297,000/ 1.5368 = £193,258	Kueper et al, 2014.
Air Monitoring during excavation and mixing of soil ex situ	6,507	ISCR air monitoring costs = $10,000/ 1.5368 =£6,507	Kueper et al, 2014.
TOTAL COST (£)	902,260		

O&M Costs	Cost (£)	Comments	References
Soil Sampling (1st Year)	7,808	Soil sampling (first year only) to assess concentrations in soil. Soil sampling= \$12,000= £7,808/ 1.5368 exchange rate = £7,808.	Kueper et al, 2014.
Validation/ Enhanced Bioremediation Monitoring Costs Year 1	29,802	Existing wells in source area will be used to monitor groundwater in source area after treatment to monitor concentrations. Quarterly monitoring for first three years. ISCR quarterly monitoring costs = \$3,000 for analytical + \$7,200 labour + \$1,250 reports = \$11,450 / 1.5368 (Exchange rate) =£7,450 per quarter x 4 = £29,802.	Kueper et al, 2014.
Year 2	29,802		
Year 3	29,802		
Year 4	7,450	Yearly monitoring after first three years once conditions established.	
Year 5 - Maintenance Activity- Addition of 3DMe	260,410	3DMe has shown to be effective for periods of 3-4 years therefore consideration needs to be given that future injection may be required if remedial concentrations have not been met. In order to meet 4 years optimal conditions is required such as low permeability and low consumption environments. An assumption has been made that CHX will require one further future round of 3DMe injections in 4 years time based on the area being of low permeability and the 3DMe trial showing positive results from borehole monitoring. If the first 3-4 years monitoring shows concentrations meeting remedial targets then this cost may then become a saving.	Regenesis, 2015
Yearly Monitoring for 4 years after re-addition of 3DMe	29,800	Will go to yearly monitoring after further application of 3DMe.	

TOTAL O&M COSTS (£)	394,874		
NOTES/ ASSUMPTIONS	Injection of 3DMe duration based on 12 days to inject 126 points from the example case study would be 12/126 = 0.0952 x 309 injection points = 29-30 days. Due to some of these injection points being in neighbouring fields timing with permissioning and access over the area could extend this period slightly. ZVI/clay soil mixing duration based on 2 weeks to mobilise and set up mixing equipment, 30 days to perform the in situ mixing (Kueper et al, 2014).		

Option 3 - PRB

Costings taken from Naval Facilities Engineering Command PRB cost and performance report, case study of Hunters Point Naval Yard, San Francisco, California, USA, where pneumatic fracturing/ injection was used to inject ZVI as a PRB in 2008.

Notes:
- Exchange rate of £1= $1.5368 (as at 30/04/2015- will be used for all future estimates where $ estimates are used) http://www.bankofengland.co.uk/boeapps/iadb/Rates.asp?into=)
- Where costings are older than 2014 dates a consumer price index (CPI) will be applied to index prices to current day value (http://www.whatsthecost.com/cpi.aspx)

Capital Costs	Cost (£)	Comments	References
Design & Procurement	232,413	Hunters Point case study costs from 2008 = $303,000/ 1.5368 = £197,162. CPI applied to 2008 costs to bring to 2015 costs = £232, 413.	NAVFAC, 2012.
Mobilisation and Demobilisation	18,408	Case study costs from 2008 = $24,000 for mobilising mixing plant for ZVI to site and injection equipment $24,000/ 1.5368 = £15,616 CPI applied to 2008 costs to bring to 2015 costs = £18,408	

Drilling & application of ZVI into boreholes to create PRB	224,313	ITRC, PRB Technology Update recommends for vertical hydrofracturing that drilling of 6 inch boreholes every 15 ft and installation of split winged casing to control the direction and pathway of the PRB wall. Hunters point used pneumatic fracturing/injection to apply ZVI as biodegradable pumped slurry into the formation. ZVI was mixed aboveground in a mobile mixing/injection plant to form a slurry and injection involved bulk nitrogen gas as a carrier for the ZVI slurry. CHX Site has a 60m wide plume, therefore boreholes every 15ft (4.5m) would require 13 boreholes to cover the 60m plume. To ensure coverage of the full extent of the plume an assumption that 20 boreholes would be required. Slurry would be pumped through the split winged casing making the soil separate creating an iron treatment zone. Costs from Hunters point = $14,622 per injection point x 20 points at CHX site = $292,440 / 1.5368 = £190,291 CPI applied to 2008 costs to bring to 2015 costs = £224,313	ITRC, 2011. NAVFAC, 2012.
Installation of monitoring boreholes	30,365	In line with Hunters point case study and ITRC PRB Technology update, monitoring wells will be installed at each end of the PRB to monitor for hydraulic changes to ensure that the plume is not migrating around the injected PRB. 4 Monitoring wells will be installed within 5m in front of the PRB and 5m post the PRB (~ every 20m), totalling 8 wells to monitor the geochemical parameters of dissolved oxygen, pH & oxidation reduction potential and also concentrations of chlorinated solvents within the water. Cost to install a total of 10 monitoring boreholes taken from Contractor quotes at CHX.	ITRC, 2011. NAVFAC, 2012. Appendix 9

Verification Monitoring	7,032	Assuming in line with Hunters point case study verification monitoring cost \$917 per monitoring point, after the initial ZVI injection the groundwater and soil vapour concentrations were monitored to verify that reductions in concentrations were occurring. \$917 X 10 monitoring boreholes = \$9,170/ 1.5368 = £5,966 CPI applied to 2008 costs to bring to 2015 costs = £7,032	NAVFAC, 2012.
TOTAL COST (£)	512,531		
O&M Costs			
Monitoring Costs Year 1 (Quarterly)	28,128	As recommended within ITRC PRB Technology update typically most PRB's are monitored on a quarterly basis in the first year. Assumption has been taken to use the verification costs for the first year of monitoring, therefore £7,032 x 4 = £28,128	ITRC, 2011. NAVFAC, 2012.
Monitoring costs year 2-4 (6 monthly)	42,192	Monitoring will move to 6 monthly over the next 2-4 years based on some field sites showing ZVI PRB performance can be relatively fast with some declining within 1–5 years, especially where finer grained nanoscale ZVI has been injected due to shorter longevity than coarser ZVI. In order to partially overcome this, CHX site would be injected with a combination of fine and coarse ZVI, in order to still allow the phenumatic injection to occur. The 6 monthly monitoring would need to include hydraulic testing of the injected zone to see if biofouling was occurring and if permeability of the aquifer was still ok. £7,032 x 2 = £14,064 x 3 years = £42,192	ITRC, 2011. NAVFAC, 2012.

Maintenance Activities - Addition of new media (year 5)	242,721	Assumption has been made that reactive media will have to be re-injected every 5 years if the remedial concentrations in samples have not been met, this is likely with the highest concentrations being identified in the source zone which will still be adding to the plume. The mobilisation, drilling and application of ZVI costs previously used above have been applied. Mobilisation costs of £18,408 and application of ZVI into boreholes at a cost of £224,313 = £242,721	NAVFAC, 2012.
Monitoring costs year 6-10 (6 monthly)	70,320	6 monthly monitoring would continue after addition of new media if required up until year 10 at which point if the PRB is still required an assessment of future viability will need to be made. £14,064 x 5 = £70,320	ITRC, 2011. NAVFAC, 2012.
TOTAL O&M COSTS (£)	383,361		

Option 4 – "Status Quo"	**Cost (£)**	**Comments**	**References**
O&M Costs	"Status Quo" approach is based on yearly monitoring just continuing.		
Yearly Monitoring Costs (£)	486,064	Is based on estimated monitoring costs for just solvent plume area at the site from contractors bill of quantities for one monitoring event per year. Does not take into account if further intervention/ remedial action is required within this period of monitoring. Yearly monitoring will be assumed to cover a period of 68 years throughout C&M to FSC. £7,148 x 68 yrs	Magnox, 2015 Appendix 8
Total costs for throughout C&M (£)	486,064		

Appendix 5 – Detailed cost breakdown for Bradwell Site

Option 1 - Selective Excavation, removal of OAEDL and a Cover/Capping system

Actual costs were taken from the contractors cost estimate who undertook the selective excavation and capping of the "North End" based on a 28 week programme. Items of equipment which would have had close contact with the soil were purchased outright due to the likelihood of them becoming contaminated, so as to avoid hire charges and then a purchase price as well.

Where comment is given to a "platform for excavating" having to be created this was required due to surface contamination in the area needing to be covered in advance of any movement over it. This was required so as personnel and equipment were protected from contamination and to reduce the further spread within the area and mobilisation of it outside the area through machinery, people and weather.

Capital Costs	Cost (£)	Comments	References
Design & Procurement	200,000	Contractors Design and Procurement Costs.	Magnox, 2013
Mobilisation and Demobilisation	224,718	Includes site induction - £14,795.12, contractual meetings - £8,836.07, preparation of risk assessments/ method statements/ pre works information - £18,385.11, contractor weekly costs/ equipment - £93,337.00, items purchased such as monitoring equipment, heras fencing, silt buster, tanks - £38,726.00, compounds and site establishment - £4,547.50, Machinery- £14,120.40. Includes also Nuvia mobilisation/ demobilisation costs - £31,970.57	Magnox, 2013

Management Costs	305,444	Includes contractors costs for site manager, project manager, contracts manager, site scientist, administrator, H&S Advisor, Technical and contract support, ecology supervision, engineering management.	Magnox, 2013
Preparation of Area/ Set up for selective excavation	89,029	Included: vegetation removal - £11,632.00, cable tray removal - £8,337.59, Borehole decommissioning - £8,750.00, Reprofiling of the slope and surrounding area - £6,685.56, laydown/platform for excavating/ haul roads - £22,800.12, extension to security fence at bottom of slope - £16,662.00. Set up of equipment/ "C2" change area dressing/un dressing, protective measures which need to be worn such as coveralls, hats, gloves and overshoes- £14,161.56 (C standing for potential of workers to be exposed to radiological contamination such as dust or contamination which could gather on clothing or exposed skin. The number 1 to 4 indicating the degree where 1 low, 4 high)	Magnox, 2013
Earthworks- Selective excavation	52,788	Includes excavating soil into 1 tonne bags, sentencing over the Nuvia Hi ram and temporary storage within the area.	Magnox, 2013
OAEDL- Preparation works	42,736	This preparation works was required to fill in the open trench (figure 8- "Trench Area") in order to create a working platform for excavating so as to gain access to the OAEDL. A temporary storage area also had to be created for the 1 tonne bags going over the Nuvia Hi ram.	Magnox, 2013
Earthworks-Removal of OAEDL/ EDL	101,319	Includes grouting of the OAEDL firstly, breaking it out, excavating the soil and concrete from the OAEDL into 1 tonne bags, sentencing over the Nuvia Hi ram and temporary storage within the area.	Magnox, 2013

Capping- Excavation of anchor trenches	52,322	Excavation of soil into 1 tonne bags where anchor trenches are required for the capping system. Sentencing of soils from anchor trenches over Nuvia Hi ram.	Magnox, 2013
Capping system- Liner	103,511	Installation of liner by sub contractor with contractor support	Magnox, 2013
Capping system - Soil	73,950	Installation of regulatory fill and landscaping material. Management of import, movement, grading and testing.	Magnox, 2013
Capping system -Gravel	125,345	Installation of geocell and gravel within this on slope. Management of import, movement, grading and testing.	Magnox, 2013
Reinstating reptile fencing	6,834		Magnox, 2013
Reporting phase	9,952	Collation of Health and Safety File Information,Materials Management Records, Quality Control Information on the installation of the Cap.	Magnox, 2013
Waste Disposal- LLW	115,140	Total of 34 bags (22.08 tonnes) went as LLW 2 HHISO's were filled with the 34 bags. £3,038 a m^3 (bags took around 15 m^3 in a HHISO). Transport £2,000 per HHISO and initial cost for a HHISO is £10,000. £3,038 x 15 m^3 = £45,570 + £2,000 Transport + £10,000 HHISO cost = £57,570 per HHISO £57,570 X 2 HHISO = £115,140	LLW Repository Ltd, 2015 Appendix 11 (Magnox, 2013).

Waste Disposal- VLLW	248,478	Total geotechnically unsuitable VLLW produced that had to go for disposal was 476 bags (332.56 tonnes) £1,000 Transport, £595 per tonne & £80.00 per tonne Landfill Tax. 332.56 tonnes x £595 per tonne & £80.00 per tonne Landfill Tax = £224,478 Total cost to dispose of bags. A total of 24 VLLW shipments were made (Total of 476 bags, 20 bags a shipment), therefore £1,000 x 24 = £24,000. £224,478 + £24,000 = £248,478.	Appendix 10 (Magnox, 2013). LLW Repository Ltd, 2014 & 2012
Waste Disposal-Conventional	24,547	Total of 144 bags (94.88 tonnes) went as conventional waste. There was also other conventional waste from the area from legacy waste, off cuts of materials used so a total of 34 skips (16 cubic yard) of conventional waste were removed from the site. Skip company removing the soil and conventional waste charged £325.00 per skip for the first 1 tonne. Additional cost of £119.00 a tonne thereafter. This came to a cost of 34 skips = £ 325 x 34 (for first 34 tonne) = £11,050. Total tonnes of conventional waste removed from the site soil bags + other waste = 147.426 tonnes - 34 tonnes = 113.426 tonnes x £119.00 = £13,497. Total skips costs = £13,497 + £11,050 = £24,547	Appendix 12 (Magnox, 2013) Green Recycling, 2015
TOTAL COST (£)	1,776,113		

O&M Costs	**Cost (£)**	**Comments**	**References**
Yearly Monitoring/ Inspection Costs for 10 years	175,000	Yearly borehole monitoring will cost £15,000 and will be required for the first 10 years which after this time period a review will be required to see if monitoring can be reduced. Inspection of the "North End" cap will be required annually to ensure that the soil and gravel are still in place and protecting the liner and after any weather events which could lead to movement of material above the liner. This will be undertaken at an estimated cost of £1,500 a year by a Magnox Engineer based at a central Hub site who will visit to inspect the cap. An assumption has been made that £10,000 will have to be spent very 10 years on general maintenance of the cap, like replacement of top soils from erosion especially on the slope at the "North End".	Magnox, 2013 Golder, 2015
Yearly Inspection costs of cap up until FSC	137,000	(58 years) including maintenance on cap. (Assumed every 10 years)	Magnox, 2013 Golder, 2015
TOTAL O&M COSTS (£)	312,000		

Option 2 - Capping/ Cover System, with grouting of remaining OAEDL, draw pits

Actual costs were taken from the contractors cost estimate for selective excavation and then capping. Therefore it has been assumed for just a capping strategy that the time frame would be reduced from the original estimate of a 28 week duration to a 10 week duration (4 weeks for preparation of anchor trenches/ removal of legacy waste, 4 weeks to install the cap and 2 weeks spare if required).

Capital Costs	Cost (£)	Comments	References
Design & Procurement	200,000	Contractors Design and Procurement Costs.	Magnox, 2013
Mobilisation and Demobilisation	105,247	Includes site induction - £14,795.12, contractual meetings - £8,836.07, preparation of risk assessments/ method statements/ pre works information - £18,385.11. Weekly costs/ equipment - £93,337.00/28 weeks= £3,333 x 10 = £33,330. Items purchased such as monitoring equipment, heras fencing - £15,354, compounds and site establishment - £4,547.50, Machinery- £10,000	Magnox, 2013
Management Costs	97,286	Original quote was based on a 28 week programme for selective excavation. For just installing a cap an estimate of 10 weeks has been assumed. 4 weeks for preparation of anchor trenches/ removal of legacy waste, 4 weeks to install the cap and 2 weeks spare if required. Project Manager - £19,405, Site Manager- £19,405, Contracts Manager - £20,690, Site Scientist - £17,270, Admin - £9,550. H&S Advisor - £633.40, Ecology Supervision- £5,342. Engineering - £4,991.	Magnox, 2013

Preparation of Area	52,066	Included: vegetation removal - £11,632.00, cable tray removal - £8,337.59, Borehole decommissioning - £8,750.00, Reprofiling of the slope and surrounding area - £6,685.56, extension to security fence at bottom of slope - £16,662.00. Set up of equipment/ "C2" change area dressing/un dressing, protective measures which need to be worn such as coveralls, hats, gloves and overshoes- £14,161.56 (C standing for potential of workers to be exposed to radiological contamination such as dust or contamination which could gather on clothing or exposed skin. The number 1 to 4 indicating the degree where 1 low, 4 high)	Magnox, 2013
Preparation works	42,736	This preparation works was required to fill in the open trench (shown in figure 8) so as a smooth surface can be achieved for installing the cap.	Magnox, 2013
Grouting of OAEDL/ EDL	25,990	Includes grouting of the OAEDL at a cost of £10,000 and two operatives at a cost of £7,995.00 each	Magnox, 2013
Capping- Excavation of anchor trenches	29,868	As only 35 bags of soil were created from the anchor trenches it would not be economically viable to hire the Nuvia Hi-ram in for this amount of bags, samples would be taken from varying depths of the soil in the bag as being loaded as these would be run through the on site gamma spectrometry analysis for sentencing of the soil bags.	Magnox, 2013
Capping system- Liner	103,511	Installation of liner by sub contractor with contractor support	Magnox, 2013
Capping system - Soil	73,950	Installation of regulatory fill and landscaping material. Management of import, movement, grading and testing.	Magnox, 2013

Capping system - Gravel	125,345	Installation of geocell and gravel within this on slope. Management of import, movement, grading and testing.	Magnox, 2013
Reinstating reptile fencing	6,834		Magnox, 2013
Reporting phase	5,000	Collation of Health and Safety File Information, Quality Control Information on the installation of the Cap. As the quantity of information to put into the reporting phase would be reduced as no Materials Management records would be required the cost estimate for this has been reduced to an estimate of £5,000	Magnox, 2013
Waste Disposal Conventional	4,308	Total of 24 bags (14.09 tonnes) from the anchor trenches went as conventional waste. Going on the basis of 5 bags in each skip and other conventional waste from the area from legacy waste, off cuts of materials used, estimate that total of 7 skips (16 cubic yard) of conventional waste would have to be removed from site. Skip company removing the soil and conventional waste charged £325.00 per skip for the first 1 tonne. Additional cost of £119.00 a tonne thereafter. 7 skips = £ 325 x 7 (for first 7 tonne) = £2,275 Total tonnes of conventional waste removed from the site soil bags + other waste estimate = 7.09 tonnes from bags + 10 tonnes legacy waste/ general waste = 17.09 tonnes x £119.00 = £2,033. Total skips costs = £2,275 + £2,033 = £4,308	Appendix 12 (Magnox, 2013) Green Recycling, 2015

Waste Disposal-Anchor Trenches - VLLW	6,550	Total geotechnically unsuitable VLLW produced from anchor trenches was 11 bags (8.89 tonne) £595 per tonne & £80.00 per tonne Landfill Tax. 8.89 tonnes x £595 per tonne & £80.00 per tonne Landfill Tax = £6,000 Total cost to dispose of bags. These bags would form part of VLLW consignment with other VLLW waste on site therefore transport cost of £1,000 for 20 bags can be divided. £1,000/ 20 bags = £50 per bag x 11 = £550 for Transport. £550 transport + £6,000 to dispose of VLLW bags = £6,550.	Appendix 10 (Magnox, 2013). LLW Repository Ltd, 2014 & 2012.
TOTAL COST (£)	878,691		
O&M Costs			
Yearly Monitoring/ Inspection Costs for 10 years	175,000	Yearly borehole monitoring will cost £15,000 and will be required for the first 10 years which after this time period a review will be required to see if monitoring can be reduced. Inspection of the "North End" cap will be required annually to ensure that the soil and gravel are still in place and protecting the liner and after any weather events which could lead to movement of material above the liner. This will be undertaken at an estimated cost of £1,500 a year by a Magnox Engineer based at a central Hub site who will visit to inspect the cap. An assumption has been made that £10,000 will have to be spent very 10 years on general maintenance of the cap, like replacement of top soils from erosion especially on the slope at the "North End".	Magnox, 2013 Golder, 2015
Yearly Inspection (until FSC)	137,000	(58 years) including maintenance on cap. (Assumed every 10 years)	Magnox, 2013 Golder, 2015
TOTAL O&M COSTS (£)	312,000		

Option 3 - "Status Quo"	Cost (£)	Comments	References
O&M Costs	"Status Quo" approach is based on yearly monitoring continuing throughout		
68 years of annual monitoring	450,000	Is based on estimated monitoring costs for "North End" for one monitoring event per year. Does not take into account if further intervention/ remedial action is required within this period of monitoring. Yearly monitoring will be assumed to cover a period of 68 years throughout C&M to FSC. £15,000 a year.	Magnox, 2013 Golder, 2015
TOTAL O&M COSTS (£)	450,000		

Appendix 6 – Chapelcross Site NPV calculations

NPV Calculation - Option 1- ISTT/SVE & Enhanced Bioremediation & MNA				
HM Treasury Nuclear Provision Discount Rates			Sensitivity Applied	
Discount Rate yrs 0-5 =	-1.9%		Discount Rate yrs 0-5 =	-0.9%
NPV (£)	(1,695,086)		**NPV (£)**	1,582,843
Initial Investment	-1638450		Initial Investment	1638450
Year 1	-22239		Year 1	-22239
Year 2	-14431		Year 2	-14431
Year 3	-3607		Year 3	-3607
Year 4	-3607		Year 4	-3607
Year 5	-3607		Year 5	-3607
Discount Rate yrs 5-10=	-0.65%		Discount Rate yrs 5-10=	-0.35%
Year 6	-3607		Year 6	-3607
Year 7	-3607		Year 7	-3607

NPV Calculation - Option 2 - ISCR, Enhanced Bioremediation& MNA				
HM Treasury Nuclear Provision Discount Rates			Sensitivity Applied	
Discount Rate yrs 0-5 =	-1.9%		Discount Rate	-0.9%
NPV (£)	(1,328,092)		**NPV (£)**	(1,311,417)
Initial Investment	-902260		Initial Investment	-902260
Year 1	-37610		Year 1	-37610
Year 2	-29802		Year 2	-29802
Year 3	-29802		Year 3	-29802
Year 4	-7450		Year 4	-7450
Year 5	-260410		Year 5	-260410
Discount Rate yrs 5-10=	-0.65%		Discount Rate yrs 5-10=	-0.35%
Year 6	-7450		Year 6	-7450
Year 7	-7450		Year 7	-7450
Year 8	-7450		Year 8	-7450
Year 9	-7450		Year 9	-7450

NPV Calculation - Option 3 - PRB				
HM Treasury Nuclear Provision Discount Rates			Sensitivity Applied	
Discount Rate yrs 0-5 =	-1.9%		Discount Rate	-0.9%
NPV (£)	(924,767)		**NPV (£)**	(909,277)
Initial Investment	-512531		Initial Investment	-512531
Year 1	-28128		Year 1	-28128
Year 2	-14064		Year 2	-14064
Year 3	-14064		Year 3	-14064
Year 4	-14064		Year 4	-14064
Year 5	-242721		Year 5	-242721
Discount Rate yrs 5-10=	-0.65%		Discount Rate yrs 5-10=	-0.35%
Year 6	-14064		Year 6	-14064
Year 7	-14064		Year 7	-14064
Year 8	-14064		Year 8	-14064
Year 9	-14064		Year 9	-14064
Year 10	-14064		Year 10	-14064

NPV Calculation - Option 4 - "Status Quo"				
HM Treasury Nuclear Provision Discount Rates			Sensitivity Applied	
Discount Rate yrs 0-5 =	-1.9%		Discount Rate	-0.9%
NPV (£)	(312,390)		**NPV (£)**	(266,274)
Initial Investment	-7148		Initial Investment	-7148
Year 1	-7148		Year 1	-7148
Year 2	-7148		Year 2	-7148
Year 3	-7148		Year 3	-7148
Year 4	-7148		Year 4	-7148
Year 5	-7148		Year 5	-7148
Discount Rate yrs 5-10=	-0.65%		Discount Rate yrs 5-10=	-0.35%
Year 6	-7148		Year 6	-7148
Year 7	-7148		Year 7	-7148
Year 8	-7148		Year 8	-7148
Year 9	-7148		Year 9	-7148
Year 10	-7148		Year 10	-7148
Discount Rate yrs 10 yrs +	2.20%		Discount Rate yrs 10 yrs +	3.20%
Year 11	-7148		Year 13	-7148
Year 12	-7148		Year 14	-7148
Year 13	-7148		Year 15	-7148
Year 14	-7148		Year 16	-7148
Year 15	-7148		Year 17	-7148
Year 16	-7148		Year 18	-7148
Year 17	-7148		Year 19	-7148
Year 18	-7148		Year 20	-7148
Year 19	-7148		Year 21	-7148
Year 20	-7148		Year 22	-7148
Year 21	-7148		Year 23	-7148
Year 22	-7148		Year 24	-7148
Year 23	-7148		Year 25	-7148
Year 24	-7148		Year 26	-7148

Year 25	-7148	Year 27	-7148
Year 26	-7148	Year 28	-7148
Year 27	-7148	Year 29	-7148
Year 28	-7148	Year 30	-7148
Year 29	-7148	Year 29	-7148
Year 30	-7148	Year 30	-7148
Year 31	-7148	Year 31	-7148
Year 32	-7148	Year 32	-7148
Year 33	-7148	Year 33	-7148
Year 34	-7148	Year 34	-7148
Year 35	-7148	Year 35	-7148
Year 36	-7148	Year 36	-7148
Year 37	-7148	Year 37	-7148
Year 38	-7148	Year 38	-7148
Year 39	-7148	Year 39	-7148
Year 40	-7148	Year 40	-7148
Year 41	-7148	Year 41	-7148
Year 42	-7148	Year 42	-7148
Year 43	-7148	Year 43	-7148
Year 44	-7148	Year 44	-7148
Year 45	-7148	Year 45	-7148
Year 46	-7148	Year 46	-7148
Year 47	-7148	Year 47	-7148
Year 48	-7148	Year 48	-7148
Year 49	-7148	Year 49	-7148
Year 50	-7148	Year 50	-7148
Year 51	-7148	Year 51	-7148
Year 52	-7148	Year 52	-7148
Year 53	-7148	Year 53	-7148
Year 54	-7148	Year 54	-7148
Year 55	-7148	Year 55	-7148
Year 56	-7148	Year 56	-7148
Year 57	-7148	Year 57	-7148
Year 58	-7148	Year 58	-7148
Year 59	-7148	Year 59	-7148
Year 60	-7148	Year 60	-7148
Year 61	-7148	Year 61	-7148

Year 62	-7148		Year 62	-7148
Year 63	-7148		Year 63	-7148
Year 64	-7148		Year 64	-7148
Year 65	-7148		Year 65	-7148
Year 66	-7148		Year 66	-7148
Year 67	-7148		Year 67	-7148

Appendix 7 – Bradwell Site NPV calculations

NPV Calculation -Option 1 - Selective Excavation, removal of OAEDL and a Cover/Capping system			
HM Treasury Nuclear Provision Discount Rates		Sensitivity Analysis	
Discount Rate yrs 0-5 =	-1.9%	Discount Rate	-0.9%
NPV (£)	(2,034,156)	**NPV (£)**	(2,015,187)
Initial Investment	-1776111	Initial Investment	-1776111
Year 1	-16500	Year 1	-16500
Year 2	-16500	Year 2	-16500
Year 3	-16500	Year 3	-16500
Year 4	-16500	Year 4	-16500
Year 5	-16500	Year 5	-16500
Discount Rate yrs 5-10=	-0.65%	Discount Rate yrs 5-10=	-0.35%
Year 6	-16500	Year 6	-16500
Year 7	-16500	Year 7	-16500
Year 8	-16500	Year 8	-16500
Year 9	-16500	Year 9	-16500
Year 10	-26500	Year 10	-26500
Discount Rate yrs 10 yrs +	2.20%	Discount Rate yrs 10 yrs +	3.20%
Year 11	-1500	Year 11	-1500
Year 12	-1500	Year 12	-1500
Year 13	-1500	Year 13	-1500
Year 14	-1500	Year 14	-1500
Year 15	-1500	Year 15	-1500
Year 16	-1500	Year 16	-1500
Year 17	-1500	Year 17	-1500
Year 18	-1500	Year 18	-1500
Year 19	-1500	Year 19	-1500
Year 20	-11500	Year 20	-11500
Year 21	-1500	Year 21	-1500
Year 22	-1500	Year 22	-1500

Year 23	-1500
Year 24	-1500
Year 25	-1500
Year 26	-1500
Year 27	-1500
Year 28	-1500
Year 29	-1500
Year 30	-11500
Year 31	-1500
Year 32	-1500
Year 33	-1500
Year 34	-1500
Year 35	-1500
Year 36	-1500
Year 37	-1500
Year 38	-1500
Year 39	-1500
Year 40	-11500
Year 41	-1500
Year 42	-1500
Year 43	-1500
Year 44	-1500
Year 45	-1500
Year 46	-1500
Year 47	-1500
Year 48	-1500
Year 49	-1500
Year 50	-11500
Year 51	-1500
Year 52	-1500
Year 53	-1500
Year 54	-1500
Year 55	-1500
Year 56	-1500
Year 57	-1500
Year 58	-1500
Year 59	-1500

Year 23	-1500
Year 24	-1500
Year 25	-1500
Year 26	-1500
Year 27	-1500
Year 28	-1500
Year 29	-1500
Year 30	-11500
Year 31	-1500
Year 32	-1500
Year 33	-1500
Year 34	-1500
Year 35	-1500
Year 36	-1500
Year 37	-1500
Year 38	-1500
Year 39	-1500
Year 40	-11500
Year 41	-1500
Year 42	-1500
Year 43	-1500
Year 44	-1500
Year 45	-1500
Year 46	-1500
Year 47	-1500
Year 48	-1500
Year 49	-1500
Year 50	-11500
Year 51	-1500
Year 52	-1500
Year 53	-1500
Year 54	-1500
Year 55	-1500
Year 56	-1500
Year 57	-1500
Year 58	-1500
Year 59	-1500

Year 60	-11500
Year 61	-1500
Year 62	-1500
Year 63	-1500
Year 64	-1500
Year 65	-1500
Year 66	-1500
Year 67	-1500
Year 68	-1500

Year 60	-11500
Year 61	-1500
Year 62	-1500
Year 63	-1500
Year 64	-1500
Year 65	-1500
Year 66	-1500
Year 67	-1500
Year 68	-1500

NPV Calculation -Option 2-Capping/ Cover System, with grouting of remaining OAEDL, draw pits			
HM Treasury Nuclear Provision Discount Rates		Sensitivity Analysis	
Discount Rate yrs 0-5 =	-1.9%	Discount Rate	-0.9%
NPV (£)	(1,136,736)	**NPV (£)**	(1,117,767)
Initial Investment	-878691	Initial Investment	-878691
Year 1	-16500	Year 1	-16500
Year 2	-16500	Year 2	-16500
Year 3	-16500	Year 3	-16500
Year 4	-16500	Year 4	-16500
Year 5	-16500	Year 5	-16500
Discount Rate yrs 5-10=	-0.65%	Discount Rate yrs 5-10=	-0.35%
Year 6	-16500	Year 6	-16500
Year 7	-16500	Year 7	-16500
Year 8	-16500	Year 8	-16500
Year 9	-16500	Year 9	-16500
Year 10	-26500	Year 10	-26500
Discount Rate yrs 10 yrs +	2.20%	Discount Rate yrs 10 yrs +	3.20%
Year 11	-1500	Year 11	-1500
Year 12	-1500	Year 12	-1500
Year 13	-1500	Year 13	-1500
Year 14	-1500	Year 14	-1500
Year 15	-1500	Year 15	-1500
Year 16	-1500	Year 16	-1500
Year 17	-1500	Year 17	-1500
Year 18	-1500	Year 18	-1500
Year 19	-1500	Year 19	-1500
Year 20	-11500	Year 20	-11500
Year 21	-1500	Year 21	-1500
Year 22	-1500	Year 22	-1500
Year 23	-1500	Year 23	-1500
Year 24	-1500	Year 24	-1500
Year 25	-1500	Year 25	-1500

Year 26	-1500
Year 27	-1500
Year 28	-1500
Year 29	-1500
Year 30	-11500
Year 31	-1500
Year 32	-1500
Year 33	-1500
Year 34	-1500
Year 35	-1500
Year 36	-1500
Year 37	-1500
Year 38	-1500
Year 39	-1500
Year 40	-11500
Year 41	-1500
Year 42	-1500
Year 43	-1500
Year 44	-1500
Year 45	-1500
Year 46	-1500
Year 47	-1500
Year 48	-1500
Year 49	-1500
Year 50	-11500
Year 51	-1500
Year 52	-1500
Year 53	-1500
Year 54	-1500
Year 55	-1500
Year 56	-1500
Year 57	-1500
Year 58	-1500
Year 59	-1500
Year 60	-11500
Year 61	-1500
Year 62	-1500

Year 26	-1500
Year 27	-1500
Year 28	-1500
Year 29	-1500
Year 30	-11500
Year 31	-1500
Year 32	-1500
Year 33	-1500
Year 34	-1500
Year 35	-1500
Year 36	-1500
Year 37	-1500
Year 38	-1500
Year 39	-1500
Year 40	-11500
Year 41	-1500
Year 42	-1500
Year 43	-1500
Year 44	-1500
Year 45	-1500
Year 46	-1500
Year 47	-1500
Year 48	-1500
Year 49	-1500
Year 50	-11500
Year 51	-1500
Year 52	-1500
Year 53	-1500
Year 54	-1500
Year 55	-1500
Year 56	-1500
Year 57	-1500
Year 58	-1500
Year 59	-1500
Year 60	-11500
Year 61	-1500
Year 62	-1500

Year 63	-1500	Year 63	-1500
Year 64	-1500	Year 64	-1500
Year 65	-1500	Year 65	-1500
Year 66	-1500	Year 66	-1500
Year 67	-1500	Year 67	-1500
Year 68	-1500	Year 68	-1500

NPV Calculation - Option 3 -"Status Quo"			
HM Treasury Nuclear Provision Discount Rates		Sensitivity Analysis	
Discount Rate yrs 0-5 =	-1.9%	Discount Rate	-0.9%
NPV (£)	(659,793)	**NPV (£)**	(561,187)
Initial Investment	-15000	Initial Investment	-15000
Year 1	-15000	Year 1	-15000
Year 2	-15000	Year 2	-15000
Year 3	-15000	Year 3	-15000
Year 4	-15000	Year 4	-15000
Year 5	-15000	Year 5	-15000
Discount Rate yrs 5-10=	-0.65%	Discount Rate yrs 5-10=	-0.35%
Year 6	-15000	Year 6	-15000
Year 7	-15000	Year 7	-15000
Year 8	-15000	Year 8	-15000
Year 9	-15000	Year 9	-15000
Year 10	-15000	Year 10	-15000
Discount Rate yrs 10 yrs +	2.20%	Discount Rate yrs 10 yrs +	3.20%
Year 11	-15000	Year 11	-15000
Year 12	-15000	Year 12	-15000
Year 13	-15000	Year 13	-15000
Year 14	-15000	Year 14	-15000
Year 15	-15000	Year 15	-15000
Year 16	-15000	Year 16	-15000
Year 17	-15000	Year 17	-15000
Year 18	-15000	Year 18	-15000
Year 19	-15000	Year 19	-15000
Year 20	-15000	Year 20	-15000
Year 21	-15000	Year 21	-15000
Year 22	-15000	Year 22	-15000
Year 23	-15000	Year 23	-15000
Year 24	-15000	Year 24	-15000
Year 25	-15000	Year 25	-15000
Year 26	-15000	Year 26	-15000

Year 27	-15000
Year 28	-15000
Year 29	-15000
Year 30	-15000
Year 31	-15000
Year 32	-15000
Year 33	-15000
Year 34	-15000
Year 35	-15000
Year 36	-15000
Year 37	-15000
Year 38	-15000
Year 39	-15000
Year 40	-15000
Year 41	-15000
Year 42	-15000
Year 43	-15000
Year 44	-15000
Year 45	-15000
Year 46	-15000
Year 47	-15000
Year 48	-15000
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Year 51	-15000
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Year 53	-15000
Year 54	-15000
Year 55	-15000
Year 56	-15000
Year 57	-15000
Year 58	-15000
Year 59	-15000
Year 60	-15000
Year 61	-15000
Year 62	-15000
Year 63	-15000

Year 27	-15000
Year 28	-15000
Year 29	-15000
Year 30	-15000
Year 31	-15000
Year 32	-15000
Year 33	-15000
Year 34	-15000
Year 35	-15000
Year 36	-15000
Year 37	-15000
Year 38	-15000
Year 39	-15000
Year 40	-15000
Year 41	-15000
Year 42	-15000
Year 43	-15000
Year 44	-15000
Year 45	-15000
Year 46	-15000
Year 47	-15000
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Year 55	-15000
Year 56	-15000
Year 57	-15000
Year 58	-15000
Year 59	-15000
Year 60	-15000
Year 61	-15000
Year 62	-15000
Year 63	-15000

Year 64	-15000	Year 64	-15000
Year 65	-15000	Year 65	-15000
Year 66	-15000	Year 66	-15000
Year 67	-15000	Year 67	-15000
Year 68	-15000	Year 68	-15000

Appendix 8 – Contractor cost data for borehole monitoring (Magnox, 2015).

Contractor Cost Data			
CHX Site Contractor Borehole Monitoring Costs			
Item	**Quantity**	**Rate**	**Amount (£)**
Monitoring Technician	5	£187.00 p.day	935
Experienced Ground Engineer	5	£327.25 p.day	1636.25
Geoenvironmental laboratory testing	-	-	1750.11
Preparation of Health and Safety documentation and Safety Risk Assessment	-	-	792.63
One master copy of the Monitoring Report	-	-	1200
Digital data in AGS transfer format	-	-	119
All other expenses incurred where an over night stay is required.	5	£71.50 a night for 2 people	715
		Total (£)	**7147.99**

Appendix 9 – Contractor costs for installing boreholes (Magnox, 2015).

CHX Site Contractor Borehole Drilling Costs (for PRB)			
Item	**Quantity**	**Rate**	**Amount (£)**
Experienced Ground Engineer	10	£238.00 p.day	2380
Ground Engineer Specialist	10	£326.40 p.day	3264
All other expenses incurred where an over night stay is required.	10	£71.50 a night for 2 people	1430
Rotary Drilling	-	-	22499.25
Preparation of Health and Safety documentation and Safety Risk Assessment	-	-	792.63
		Total (£)	**30365.88**

Appendix 10 – VLLW Waste created from "North End" selective excavation

VLLW (Geotechnically unsuitable)			
Area	**Number of Bags (1 tonne)**	**tonnes**	**References**
Selective Excavations	57	33.15	Magnox, 2013
OAEDL/EDL	327	231.45	
Anchor trenches/ drilling cores	11	8.89	
Legacy soil/ concrete	12	5.67	
North End concrete (primarily OAEDL and other excavated pockets of made ground)	69	53.4	
Total Bags	476	332.56	
@ 20 bags per vehicle	24 Loads		
Total vehicular moves to and from site	48 vehicular moves		

Appendix 11 – LLW Waste created from "North End" selective excavation

LLW			
Area	**Number of Bags (1 tonne)**	**tonnes**	**References**
Selective Excavations	32	21.13	Magnox, 2013
OAEDL/EDL	2	0.95	
Totals	34	22.08	
Bags were split between 2 HHISO's	2 loads		
Total vehicular moves to and from site	4 vehicular moves		

Appendix 12 – Conventional Waste created from "North End" selective excavation

Conventional Waste			
Area	**Number of Bags (1 tonne)**	**tonnes**	**References**
Selective Excavations	16	9.5	Magnox, 2013
OAEDL/EDL	95	66.26	
Anchor trenches/ drilling cores	24	14.09	
Legacy soil/ concrete	9	5.03	
North End concrete (primarily OAEDL and other excavated pockets of made ground)	0	0	
Totals	144	94.88	
Total no. of waste skips	34		Inclusive of other conventional waste arisings from the area.
Total vehicular moves to and from site	68 vehicular moves		

Appendix 13 – Bradwell Site "North End" Co2e emissions to air

Emissions to air (co2e)					
Waste Type	**Total vehicular moves to and from site**	**Location of disposal site**	**km from Bradwell (CM0 7HP) to disposal site**	**Total km (vehicular moves x km)**	**References**
VLLW	48	Augean, Kingscliffe, North-amptonshirePE8 6XX	194.2	9321.6	Magnox, 2013
			CO2e Emissions for VLLW (kg) *0.99463 (Defra, 2014)	9271.54 co2e (kg)	Defra, 2014 (Based on HGV (diesel) Articulated >33t)

Waste Type	Total vehicular moves to and from site	Location of disposal site	km from Bradwell (CM0 7HP) to disposal site	Total km (vehicular moves x km)	References
LLW	4	LLWR, Cumbria, CA19 1XH	579	2316	
			CO2e Emissions for LLW (kg) * 0.90657 (DEFRA)	2099.62 co2e (kg)	Defra, 2014. (Based on All HGV)
Conventional Waste	68	Green Recycling, Maldon, Essex, CM9 5FA	34.3	2332.4	Green Recycling, 2015
			CO2e Emissions for conventional waste (kg) *0.72677 (DEFRA)	1695.12 co2e (kg)	(Based on Rigid (>7.5 tonnes-17 tonnes))

			Total CO2e Emissions (kg) for all waste removed from Site	13066.28 co2e (kg)	
			Tonnes of CO2e	**13.07**	
Capping	**Total vehicular moves to and from site**	**Location of site**	**km from importing site to Bradwell (CM0 7HP)**	**Total km (vehicular moves x km)**	**References**
Importing of gravel/ soil and regulatory fill	366	Dewicks, Southminster, Essex, CM0 7HL	4.8	1756.8	Defra, 2014
			CO2e Emissions (kg) *0.99463 (DEFRA)	1747.37 co2e (kg)	**(Based on HGV (diesel) Articulated >33t)**
			Tonnes of CO2e	**1.75**	

Option 1- co2e total = 13.07 (waste disposal) + 1.75 (capping) tonnes = 14.82 tonnes.

Option 2 - co2e total = 1.75 (capping) tonnes.

Appendix 14– Bradwell Site "North End" aggregate required for Capping

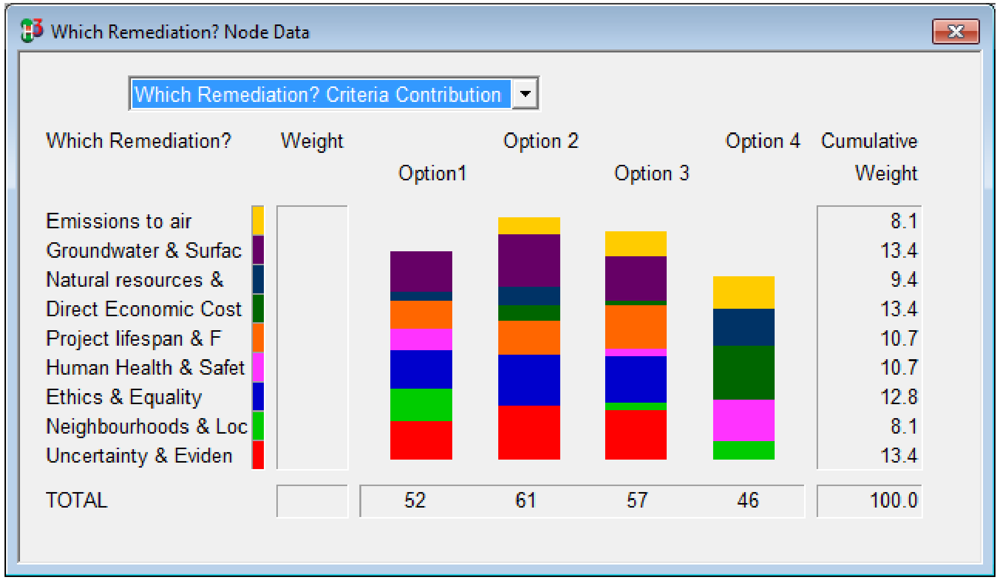
Aggregate to site for Capping System	m^3 required	References
GRAVEL	665	Magnox, 2013
SOIL	1800	
REGULATORY FILL	100	
TOTAL m^3	2565	
Total number of vehicular moves to the site with capping aggregate	183	Atlas Bulk Carriers, 2015. Based on an 8 wheel tipper being able to carry $14m^{3}$.
Total vehicular moves to and from site	366	

Appendix 15 - Chapelcross Site Hiview Calculations

SuRF UK Cateory	Weight	Total of Indicator Weights	Cumulative weight	Option	Preference Score	Weighted Score
Emissions to Air	60		60 /745 = 0.0805	1	0	0.0805 x 0 = 0
				2	55.56	0.0805 x 55.56 = 4.47
				3	77.78	0.0805 x 77.78 = 6.26
				4	100	0.0805 x 100 = 8.05
Groundwater & Surface Water	100		100/745 = 0.134	1	76.92	0.134 x 76.92 = 10.33
				2	100	0.134 x 100 = 13.42
				3	84.62	0.134 x 84.62 = 11.36
				4	0	0.134 x 0 = 0
Natural Resources and Waste	70		70/745 = 0.0939	1	0	0.0939 x 0 = 0
				2	33.33	0.0939 x 33.33 = 3.13
				3	66.67	0.0939 x 66.67 = 6.26
				4	100	0.0939 x 100 = 9.4
Direct Economic Cost	100		100/745 = 0.134	1	0	0.134 x 0 = 0
				2	24.48	0.134 x 24.48 = 3.29
				3	51.39	0.134 x 51.39 = 6.9
				4	100	0.134 x 100 = 13.42
Project Lifespan and Flexibility	80	745	80/745 = 0.1073	1	80	0.1073 x 80 = 8.59
				2	100	0.1073 x 100 = 10.74
				3	0	0.1073 x 0 = 0
				4	10	0.1073 x 10 = 1.07

Human Health & Safety	80	80/745 = 0.1073	1	50	0.1073 x 50 = 5.37
			2	0	0.1073 x 0 = 0
			3	16.67	0.1073 x 16.67 = 1.79
			4	100	0.1073 x 100 = 10.74
Ethics & Equality	95	95/745 = 0.1275	1	76.92	0.1275 x 76.92 = 9.81
			2	100	0.1275 x 100 = 12.75
			3	61.54	0.1275 x 61.54 = 7.85
			4	0	0.1275 x 0 = 0
Neighbourhoods & Locality	60	60/745 = 0.0805	1	100	0.0805 x 100 = 8.05
			2	0	0.0805 x 0 = 0
			3	22.22	0.0805 x 22.22 = 1.79
			4	55.56	0.0805 x 55.56 = 4.47
Uncertainty & Evidence	100	100/745 = 0.134	1	71.43	0.134 x 71.43 = 9.59
			2	100	0.134 x 100 = 13.42
			3	78.57	0.134 x 78.57 = 10.55
			4	0	0.134 x 0 = 0

Appendix 16 - Hiview Reassessment of Option 3 Incorporating Source Zone Treatment



The Hiview remediation criteria contribution table shows what effect adding 'In Situ ZVI' source zone mixing has on the score of option 3.

SuRF UK Category	Weight	Option	Input Score	Preference Score	Weighted Score
ENV 5 - Natural resources & Waste- Energy use during remediation. Material resources used remediation. Waste Generation.	70	Option1	40.0	25.00	2.35
		Option 2	50.0	50.00	4.70
		Option 3	**30.0**	**0.00**	**0.00**
		Option 4	70.0	100.00	9.40
ECON 1 - Direct Economic Cost- NPV	100	Option1	£1,695,085.5	0.00	0.00
		Option 2	£1,328,092.2	26.54	3.56
		Option 3	**£1,566,617.0**	**9.29**	**1.25**
		Option 4	£312,390.0	100.00	13.42
ECON 5 - Project Lifespan & Flexibility Flexibility to cope with changing circumstances	80	Option1	50.0	63.64	6.83
		Option 2	60.0	81.82	8.79
		Option 3	**70.0**	**100.00**	**10.74**

		Option 4	15.0	0.00	0.00
SOC 2 - Ethics & Equality Avoid transfer of issues to future generations	95	Option1	50	76.92	9.81
		Option 2	65	100.00	12.75
		Option 3	**60**	**92.31**	**11.77**
		Option 4	0	0.00	0.00
SOC 5 Uncertainty & Evidence Compliance with remedial criteria (TBD) Long term robustness/ validation of remediation	100	Option1	50	71.43	9.59
		Option 2	70	100.00	13.42
		Option 3	**65**	**92.86**	**12.46**
		Option 4	0	0.00	0.00

The above table shows only the indicators where the input scores were changed under option 3 in line with adding 'In Situ ZVI' source zone treatment along with a PRB.