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Remedial Targets Methodology

Hydrogeological Risk Assessment for Land Contamination

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Remedial Targets Methodology

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Statement of use:
This report describes the Environment Agency's recommended approach to assessing the risks associated with soil and groundwater contamination, and for deriving site-specific remedial objectives that are protective of the water environment.

Assessors should assess risks to the water environment alongside risks to other receptors including human health, property and ecosystems. Guidance on assessing risks to non-water receptors is provided elsewhere.

Environment Agency Project Managers:

Kirsten Johnstone, Neil Wootton

Environment Agency, Geoscience Process

Preface

This report has been produced by the Environment Agency with the support of the Scottish Environment Protection Agency (SEPA) and the Northern Ireland Heritage and Environment Service.

This report supersedes *Methodology for the Derivation of Remedial Targets for Soil and Groundwater to Protect Water Resources* (R&D Publication 20) published by the Environment Agency in 1999.

Remedial Targets Worksheet

This report is accompanied by a Microsoft® Excel worksheet and a User Manual. Both are available free of charge from the Environment Agency's website (www.environment-agency.gov.uk/publications).

The Environment Agency has also developed a probabilistic modelling package, ConSim, which can be used within the framework described in this report. A free demonstration of the latest version, ConSim release 2, can be downloaded from www.consim.co.uk

FOREWORD

This Remedial Targets Methodology : Hydrogeological Risk Assessment for Land Contamination replaces the Methodology for the Derivation of Remedial Targets for Soil and Groundwater to Protect Water Resources.

Since it was published in 1999, the original Methodology has provided a consistent framework for controlled waters risk assessment. It is used to identify unacceptable risks of pollution of controlled waters and as the basis for facilitating discussion and establishing remedial targets for contaminated soil and groundwater. In the same way, acceptable risks are identified and so unnecessary remediation is avoided.

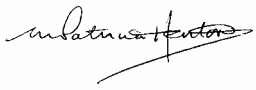
The requirement for the detailed assessment of land contamination has increased dramatically in recent years and it is important that the tools to assist in that process are available and up to date.

The Model Procedures for the Management of Land Contamination (contaminated land report 11 or CLR 11), set out a national framework for risk assessment and remediation of land affected by contamination. The *Remedial Targets Methodology* is one of the tools that supports CLR 11.

The European Union Water Framework Directive and Groundwater Daughter Directive will require some changes to the way that we assess and protect our valuable water resources in the UK, building on many of the procedures we already have in place.

The methodology has now been reviewed and updated to reflect these important new pieces of legislation and guidance.

In partnership with our colleagues in Scotland and Northern Ireland, we hope that this updated document will continue to facilitate discussion and robust assessment of the risks posed to the water environment by land contamination, and so continue to improve decision making on the need for, and standard of, remediation.



Tricia Henton

Director of Environment Protection

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Executive Summary

This report presents a recommended methodology for deriving site-specific remedial objectives for contaminated soils and/or groundwater to protect the aquatic environment. The methodology is based on a phased approach to risk assessment and management as set out in government guidance. The approach is underpinned by progressive data collection and analysis, structured decision-making and cost-benefit assessment.

The methodology applies to soils and groundwater that are already contaminated, where the original surface source of the contamination has ceased. The principles may be of wider application but where, for example, there are on-going surface sources of pollution, the "prevent or limit" requirements of the Groundwater Directive and other relevant pollution control legislation may override the more flexible approaches to the assessment of remedial targets noted in this document.

The methodology consists of up to four assessment levels which progressively follow the pathway from the contaminant source through to the receptor. A remedial target is derived at each level, but this is likely to be less stringent at the next level as additional processes such as dilution and attenuation, which may affect contaminants along the pathway from the source to the receptor, are taken into account.

This approach enables attention to be focused on those sites where the risks are greatest. With successive levels, the data requirements and the sophistication of the analysis increase and should be supported by a better conceptual understanding of pollutant linkages.

Procedure for developing site-specific remedial targets

The procedure for determining site-specific remedial targets is summarised below:

1) Develop an initial site conceptual model, including identification of all **pollutant** linkages around the site. Refine the conceptual model through site characterisation.

2) Identify appropriate locations at which compliance with an agreed threshold must be met in order to protect the receptors. A **compliance point** may be at the receptor itself or at some point nearer to the source.

3) Determine a **target concentration** at the compliance point that takes account of baseline environmental conditions, the current and potential use of the water resource(s), and relevant environmental standards. A **remedial target** is derived at each level.

4) Undertake an assessment to determine whether the contaminant source would result in the target concentration being exceeded at the receptor or compliance point.

5) If the measured contaminant concentration on-site exceeds the calculated remedial target, decide whether it is appropriate to progress to more detailed risk assessment or whether to undertake remediation to achieve the remedial target. The decision should be based on:

   - the timescale – only choose to proceed to a more detailed risk assessment if the risk (ongoing or additional) involved in delaying the decision to implement remedial action is acceptable;
   - what additional information is required and can be obtained to refine the conceptual model and thus reduce uncertainty in the assessment and its conclusions;
   - an assessment of the likely costs and benefits associated with remediation, i.e. the cost of further site characterisation and detailed risk evaluation compared with the potential reduction in the cost of the remedial solution.

Assessment levels for contaminated soil

The four levels of assessment for contaminated soil are outlined below.

At **Level 1**, the assessor considers the initial conceptual model and evidence of pollutant linkages. The assessor then evaluates whether contaminant concentrations in 'pore water' in contaminated soil are sufficient to impact on the receptor but ignoring dilution, dispersion and attenuation along the pathway. The 'pore water' concentration is determined from:

- measured pore water concentrations or perched water quality;
- soil leaching tests;
- theoretical calculations based on soil/water partitioning equations.

At **Level 2**, the assessor considers the possible effects of attenuation processes in the soil and unsaturated zone, and predicts the effects of dilution by groundwater flow below the site.

At **Level 3**, the assessor considers the effects of attenuation between the site and a downgradient receptor or compliance point. The assessment can include processes such as:

- dilution
- dispersion
- retardation
- degradation by biotic or abiotic processes
- other attenuation processes.

At **Level 4**, the assessor can consider whether it is appropriate to take account of dilution in a receiving watercourse or abstraction. This represents a special case and the assessment will need to demonstrate that:

- any impact on groundwater does not jeopardise future use of the resource;
- the cost of remediation is disproportionate in relation to the improvement of groundwater or surface water quality.

The remedial target is calculated by multiplying the target concentration by a dilution factor (DF) and an attenuation factor (AF). At each level, the measured soil or pore water concentration in the contaminated soil is compared with the remedial target to determine the need for remedial action.

The sophistication of the analysis also varies. The initial assessment may be carried out using simple analytical models. However, more sophisticated numerical models may be used at a later stage if:

- this is necessary to represent dilution and attenuation processes;
- a high level of confidence is required for the assessment.

In all cases, it is essential to justify the applicability of the model and the parameter values used.

Assessment framework for contaminated groundwater

A similar assessment framework is presented for contaminated groundwater. There is no Level 1. At **Level 2** ***groundwater quality data*** are compared directly with the target concentration. At **Level 3**, the assessor considers the effects of attenuation between the site

and a downgradient receptor or compliance point. Finally, at **Level 4**, the assessor considers whether it is appropriate to take account of dilution in a receiving watercourse or a pumping abstraction borehole.

Other important issues

- It is recommended that sensitivity/uncertainty analysis is incorporated into each stage of the assessment.
- The report describes procedures for setting compliance points and siting monitoring boreholes.
- Before remedial action is implemented, the assessment should be subject to a final review to check that the objectives and practicalities of the remedial action have been considered fully.
- The assessment of risks to groundwater and surface water forms part of the overall process to evaluate the health and environmental risk posed by contaminated soil and groundwater. Guidance on assessing risks to other receptors is provided elsewhere, including:
  - human health (Defra and Environment Agency 2002a);
  - ecosystems (Environment Agency 2003a);
  - property (Environment Agency 2001a);
  - archaeological resources (Environment Agency and English Heritage 2005).

Key to Parameters and Units

A	=	area of contaminant source (m^2)
AF	=	attenuation factor (dimensionless)
a_x,a_y,a_z	=	dispersivity in three dimensions (m)
C	=	concentration of contaminant at point x (mg/l)
C_S	=	concentration of contaminant in soil (mg/kg)
C_C	=	concentration of contaminant in contaminated water (mg/l)
C_{ED}	=	simulated compliance point concentration (mg/l)
C_0	=	initial concentration of contaminant (mg/l)
C_T	=	target concentration for contaminant in water (mg/l)
C_U	=	background concentration of contaminant (mg/l)
d_a	=	aquifer thickness (m)
DF	=	dilution factor (dimensionless)
f_{OC}	=	fraction of organic carbon (fraction)
i	=	hydraulic gradient
Inf	=	infiltration (m/d)
K	=	hydraulic conductivity (m/d)
K_d	=	soil water partition coefficient (l/kg)
K_{OC}	=	organic carbon partition coefficient (l/kg)
$K_{OC,n}$	=	sorption coefficient for related species (l/kg)
$K_{OC,i}$	=	sorption coefficient for ionised species (l/kg)
L	=	length of site in direction of groundwater flow (m)
M_z	=	mixing zone thickness (m)
n	=	effective porosity (as a fraction)
pH	=	pH value
pKa	=	acid dissociation constant
Q_A	=	abstraction rate (m^3/d)
Q_U	=	surface water flow upstream of groundwater discharge point (m^3/d)
Q_C	=	flow of contaminated groundwater into receptor (m^3/d)
R_f	=	retardation factor
RT_l	=	pore water remedial target concentration for in-situ soils (mg/l)
RTs	=	soil remedial target concentration for in-situ soils (mg/kg)
S_z, S_y	=	width and thickness of contaminant plume at source (m)
t	=	time (days)
$t_{0.5}$	=	half-life (days) for a first-order (degradation) reaction
u	=	contaminant velocity (m/d)
v	=	groundwater velocity (m/d)
w	=	width of site (metres)
θ_a	=	air filled soil porosity (fraction)
θ_w	=	water filled soil porosity (fraction)
ρ	=	dry bulk density (g/cm^3)
λ	=	decay constant (day-1) ($\lambda = \ln 2 / t_{0.5}$ for a first-order reaction)

1. Introduction

1.1 General

The Environment Agency has a duty under the Water Resources Act 1991 and the Environment Act 1995 to monitor, protect and enhance the environment including water resources. The Scottish Environment Protection Agency (SEPA) has a similar duty under the Water Environment (Controlled Activities) (Scotland) Regulations 2005 and the Environment and Heritage Service (EHS) under the Water (Northern Ireland) Order 1999.

These agencies identified the need to develop a standardised, practical and reasonable approach to soil and groundwater remediation for the protection of water resources that:

- can be applied on a site-by-site basis;
- is consistent with current legislation and guidance.

With this in mind and to help derive remedial targets, the Environment Agency published a report, *Methodology for the derivation of remedial targets for soil and groundwater to protect water resources* (R&D Publication 20) (Environment Agency 1999a).

The framework outlined in the present report updates R&D Publication 20 in the light of:

- legislative changes, e.g. the Water Framework Directive and Contaminated Land Regulations made under Part IIA of the Environmental Protection Act 1990 (DETR 2000);
- government guidance on environmental risk assessment and management (DETR *et al*. 2000);
- the Model Procedures for the Management of Contaminated Land (CLR 11) (Defra and the Environment Agency 2004). These provide guidance on the principles and processes that may be adopted for the assessment and management of risks associated with land contamination. They should be read before undertaking any detailed risk assessment on a potentially contaminated site.

The level of remediation required to protect other receptors may differ from those derived for the protection of water resources. Human health is generally perceived as the most important, but the persistence of some substances in groundwater and low concentrations of many environmental standards mean that this latter receptor is often (but not invariably) the most sensitive.

The methodology applies to soils and groundwater that are already contaminated, where the original surface source of the contamination has ceased. The principles may be of wider application but where, for example, there are on-going surface sources of pollution, the "prevent or limit" requirements of the Groundwater Directive and other relevant pollution control legislation may override the more flexible approaches to the assessment of remedial targets noted in this document.

The main objectives of this methodology are to determine which of the following are required:

- No remedial action, i.e. the level of contamination does not, or is not likely to, cause pollution of surface water or groundwater, or their dependent ecosystems;
- Remedial action to protect an identified groundwater or surface water receptor;
- Further data collection and analysis to better evaluate the degree of risk to the receptor.

The methodology is based on a staged approach (referred to as Levels) to determine risk-based remedial targets for soil and groundwater. A remedial target is derived at each Level, but this target is likely to be less stringent at the next Level as additional processes (e.g. dilution and attenuation), which affect contaminant concentrations along the pathway from the source to the receptor, are taken into account.

With successive Levels, the data requirements and the sophistication of the analysis increase, but the confidence in the predicted impact also increases. This could allow a relaxation of the remediation requirements if the risk assessment is acceptable.

This approach enables:

- low risk sites to be rapidly screened out;
- attention to be focused on those sites where the risks and information needs are greatest.

This methodology is one of the working tools that can be used in the overall process of evaluating the health and environmental risk posed by contaminated soil and groundwater. A separate methodology, the Contaminated Land Exposure Assessment (CLEA) Model (Defra and Environment Agency 2002a, 2002b), has been developed to derive human health based Soil Guideline Values. Other guidance is available on assessing risks to:

- ecosystems (Environment Agency 2003a);
- property (Environment Agency 2001a);
- archaeological resources (Environment Agency and English Heritage 2005).

To support the framework presented in this report and to assist the assessment of risks to controlled waters from land contamination (see Section 2.5), the Environment Agency has developed two software packages:

- ConSim (Environment Agency 2003b);
- Remedial Targets Worksheet (Environment Agency 2006a).

1.2 Legislative context

This section outlines the legislation in England & Wales relevant to:

- control or removal of residual contamination resulting from activities or releases that have ceased (historical contamination);
- control of the activity that caused the pollution of controlled waters.

Note: the legislative requirements in Scotland and Northern Ireland are similar in effect but in some cases are different in terms of the legislative instruments in force.

Control of residual contamination

Where soil or groundwater contamination is a result of historical contamination and this poses a risk to controlled waters, then the regulatory authority can require remediation to be implemented under either Section 161A of the Water Resources Act 1991 or Part IIA of the Environmental Protection Act 1990 (EPA 1990).

Part IIA of the EPA 1990 introduced a new regime for the identification and remediation of contaminated land. Part IIA and the enabling Contaminated Land Regulations for England, Wales and Scotland require local authorities to identify land within their boundaries that meets the statutory definition of contaminated land. It gives them powers to serve Remediation Notices on ‘appropriate persons’ (i.e. those who caused or permitted the pollution, the owner/occupier or those who have acquired liability of the site identified as

contaminated land). In all cases, a pollutant linkage must exist between the source of the contamination in the land and a relevant receptor.

Land may be classed as contaminated land by virtue of actual or likely pollution of controlled waters caused by substances in, on or under the land. Where pollution of controlled waters is an issue, then the Environment Agency must be consulted and its views taken into account.

In other situations where there is no existing pollutant linkage (e.g. because there has been human intervention to remove the source or to cut the pathway), Section 161 of the Water Resources Act 1991 and the Anti-pollution Works Regulations 1999 can be used. These allow Works Notices to be served on the person or persons who caused or knowingly permitted the pollution to arise in order that it can be remedied or forestalled.

Rather than undertake the work itself and face the difficulties of reclaiming the costs, the Environment Agency is therefore able to require those responsible for the pollution to undertake the requisite work. If such a person cannot be found or identified and if remediation is required, the Environment Agency may decide to undertake the work itself.

In some cases, the site owner may implement remediation voluntarily. In this case, the Environment Agency may invoke powers via the Waste Management Licensing Regulations to control the remediation. If the activity is subject to planning permission, planning controls such as a Town and Country Planning Act Section 106 Agreement could be used to provide institutional controls to the remediation process.

Some of the remediation activities that follow on from the assessment procedures described in this report may themselves constitute activities that could pose a risk to groundwater. These must therefore meet the requirements of the Groundwater Regulations 1998. The appropriate means of control is normally through the waste management licensing regime (e.g. mobile treatment licenses) (Environment Agency 2005c) or Water Resources Act 1991.

Control of contamination of groundwater from existing activities

Under the EC Groundwater Directive 80/68/EEC, Member States are obliged to take the necessary steps to prevent List I substances from entering groundwater and to restrict the entry of List II substances so as to prevent pollution. The main focus of the Groundwater Directive and how it is implemented in the UK is to ensure adequate controls on discharges, disposals or other (current) activities that could release listed substances to groundwater.

In England & Wales the Groundwater Directive is implemented via the Groundwater Regulations, 1998.

The control of deliberate discharges or disposals involving the release of listed substances into groundwater is via either:

- authorisations under the Groundwater Regulations 1998;

or one of the following permitting regimes, which must also be compliant with the these Regulations:

- discharge consents under the Water Resources Act 1991;
- Pollution Prevention and Control (PPC) authorisations;
- waste management licences granted under Part II of the EPA 1990.

Where other activities have caused pollution or where it is necessary to prevent future pollution, then the Environment Agency has powers to prohibit or condition the activity or require mitigating works. Examples of the legislation that can be used to enforce such work include:

- Section 19 Groundwater Regulations Notices;
- Section 86 Water Resources Act Prohibition Notices;

- Section 59 Environmental Protection Act 1990 (removal of unlawfully deposited waste);
- Section 161A Water Resources Act Works Notices.

Application of remedial targets methodology

This report is primarily concerned with the derivation of remedial targets applicable to residual (usually historic) contamination. Its main use will be in relation to:

- the application of Part IIA of EPA 1990 and Works Notices (see above);
- the redevelopment of contaminated sites through the planning process;
- When the site owner implements remediation voluntarily.

If justifiable, the underlying principles and calculations could be adapted for use in other circumstances such as the assessment of new discharges.

Water Framework Directive

The Water Framework Directive (WaterFD) 2000/60/EC came into force on 22 December 2000 and its transposition into UK legislation began in 2003. The WaterFD aims to reduce pollution, prevent deterioration and improve the health of aquatic ecosystems (and wetlands that depend on groundwater). This includes the aim of achieving good status for all water bodies.

For groundwater bodies to achieve good status, both their quantitative and chemical status need to be good. Good chemical status is defined such that the concentration of pollutants (Annex V 2.3.2 of the WaterFD):

- do not exceed the quality standards applicable under relevant European Community legislation (refer to Article 17 of the WaterFD);
- would not result in failure of associated surface water bodies to achieve environmental objectives (refer to Article 4 of the WaterFD);
- would not result in a significant diminution of the ecological or chemical quality of associated surface water bodies;
- would not result in any significant damage to groundwater dependent terrestrial ecosystems;
- do not exhibit the effects of saline or other intrusions.

In addition, the WaterFD sets further objectives. The most relevant for groundwater are that:

- measures are implemented to prevent or limit inputs of pollutants into groundwater;
- measures are implemented to reverse any significant and sustained upward trends;
- groundwater bodies should be protected such that their quality does not deteriorate to the point where additional treatment is required for drinking water supplies.

The objectives and criteria outlined above will be clarified and elaborated in the proposed Groundwater Daughter Directive or, in the absence of an agreed Directive, by UK-specific proposals. Please refer to the Environment Agency's website (www.environment-agency.gov.uk/wfd) for updated information.

The WaterFD requires a Programme of Measures (PoM) to be implemented in each River Basin District in order to meet its objectives. These PoMs will be set out in River Basin Management Plans, which will be published in December 2008 for public consultation and in their final form in December 2009.

In deriving remedial targets and deciding whether there is a need to undertake remediation at a particular site, the Environment Agency should be consulted to ensure that the overall remedial objectives for the site are:

- consistent with the requirements of the River Basin Management Plan for the area;
- meet WaterFD objectives (see Section 4.4).

1.3 Regulatory consultation, liaison and communication

This report focuses on the technical basis for deriving remedial targets to protect water resources. Throughout this process, appropriate liaison with regulatory bodies is essential; such bodies will respond in accordance with their duties and policies.

Before remedial measures are implemented, regulators should be given the opportunity to comment on the setting of:

- compliance points
- target concentrations
- remedial targets.

In many cases, statutory consents will be required from the Environment Agency or the planning authority and a formal liaison process will take place.

1.4 How to use this report

Chapter 2 sets out the assessment framework and the basic approach for determining remedial targets for contaminated soil or groundwater. Details of each stage of the assessment are described as shown in Table 1.1.

Table 1.1 Report structure

Assessment stage	**Source**
Initial assessment of pollutant linkages	Chapter 3
Derivation of target concentration to protect receptor	Chapter 4
Identification and selection of compliance point	Chapter 4
Determination of remedial target concentration for: • contaminated soil • contaminated groundwater • contaminated soil and groundwater • free product	 Chapter 5 Chapter 6 Chapter 7 Section 6.3
Use of fate and transport models, selection of parameter values and uncertainty	Chapter 8
Cost-benefit assessment, monitoring and final review	Chapter 9

A glossary of terms used in this report is provided in Chapter 11.

Due to the variability of soil and groundwater systems, this report is not intended to provide a prescriptive approach, but to identify the important decision factors in determining remedial targets. This decision process will generally require:

- a high level of technical expertise (particularly for the application of the higher levels of assessment);

- a detailed appreciation of hydrogeological and geochemical processes;
- expertise in the application of contaminant fate and transport models.

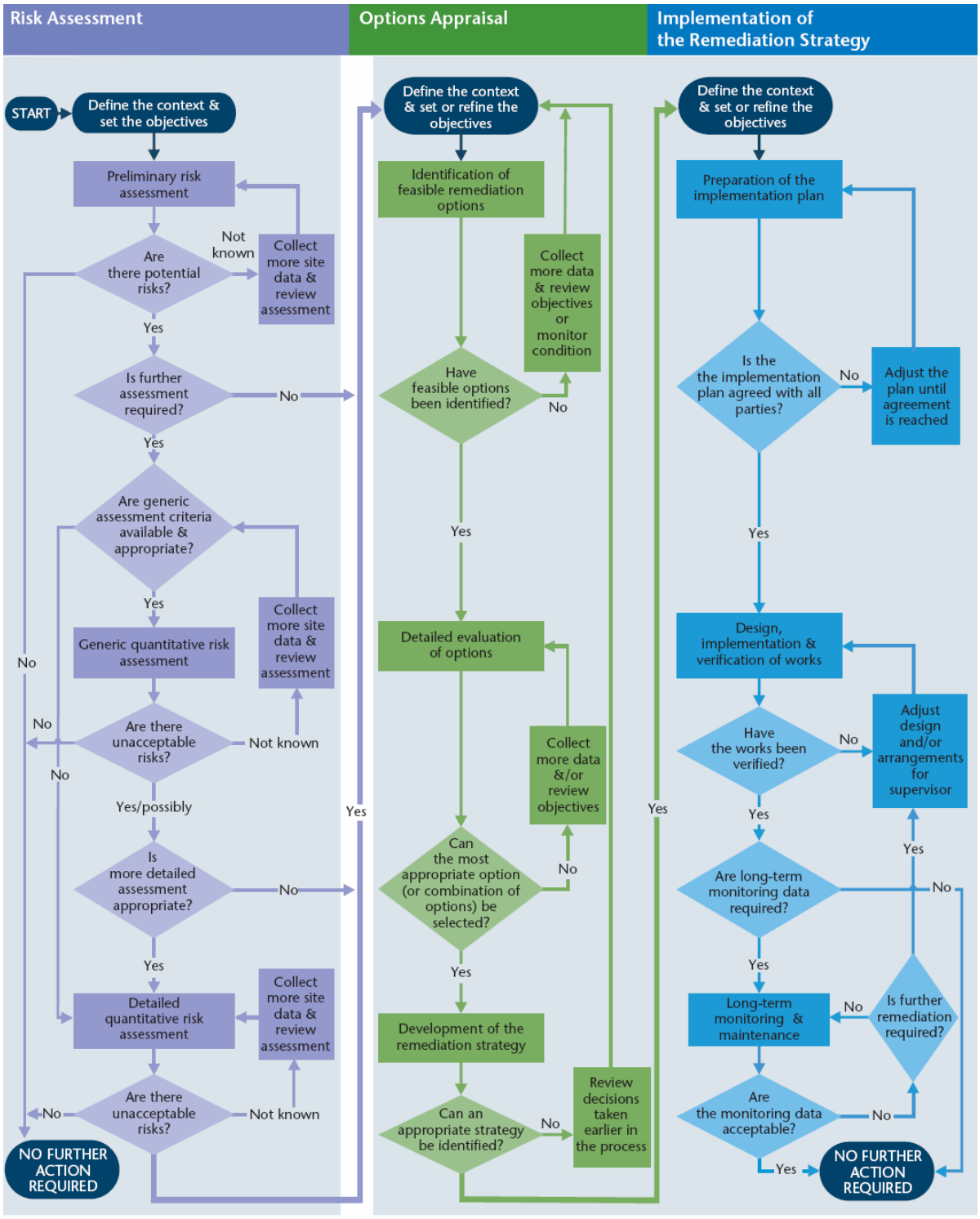
2. Framework

2.1 Overarching framework

The methodology described in this report assumes that the overall risk assessment will be undertaken as described in *Model procedures for the management of contaminated land* (Defra and Environment Agency 2004). Figure 2.1, reproduced from the Model Procedures, summarises the overall process for managing land contamination.

The hydrogeological risk assessment described in this report forms a subset of the overall risk assessment and sets out the methodology to derive site-specific remedial targets for soil and groundwater to protect groundwater and surface receptors. This report does not present generic values.

Figure 2.1 The process of managing land contamination



Note: The process may apply to one or more pollutant linkages each of which may follow a different route. For some linkages, it may be possible to stop at an early stage – others will progress all the way through the process. The level of complexity of each stage may also vary and in some cases may be very simple.

2.2 Basic steps

The basic steps in determining remedial targets and the need for remedial action to protect surface water or groundwater receptors are summarised in Table 2.1.

Table 2.1 Basic steps in determining remedial steps and the need for remedial action

Preliminary risk assessment (characterisation)
1) Identification and characterisation of the source including preliminary assessment of the contaminant spatial distributions and concentrations, together with their physical and chemical properties.
2) Identification and characterisation of the potential environmental (water-based) receptor(s).
3) Identification of the potential contaminant pathways to the identified receptors and identification of the potential consequences if the receptor(s) is polluted.
This will largely be a desk-based exercise but it may be supplemented by the results of an initial site investigation. If no pollutant linkage is identified, then no further action is required.
Risk assessment (determination of remedial targets)
4) Preliminary assessment including evaluation of the timescale for undertaking a more detailed risk assessment and the need for urgent or emergency remediation where the source has already affected water quality or where the source is in close proximity (a short travel time) to the receptor (see Section 2.4).
5) Determination of site-specific remedial targets for soil and groundwater to protect the identified receptor(s) based on a phased risk assessment approach (see Section 2.3).
6) Comparison of soil or groundwater contaminant concentrations with the remedial targets to determine which of the following actions are appropriate: • no action is required as the observed concentrations do not represent a risk to water quality at the receptor; • undertake more detailed risk assessment (i.e. move to a higher Level) including further data collection and analysis; • undertake remedial action to protect the receptor, taking account of environmental benefit and cost (refer to Chapter 9).

Options appraisal and implementation of remediation strategy

The Model Procedures (Defra and Environment Agency 2004) provide further guidance on the steps to be undertaken if remedial targets are exceeded (see Figure 2.1). In summary, these are likely to include:

- identification and evaluation of remediation options;
- development of the remediation strategy and preparation of an implementation plan;
- design and implementation of the remedial scheme (the design should also take account of environmental benefits and costs);
- environmental monitoring to verify the effectiveness of remediation;
- decommissioning of the scheme(s) once remediation is effectively completed (i.e. it is agreed that remedial objectives have been achieved).

The **remedial actions** that may be implemented to protect groundwater or surface receptors are:

- prevent further contamination, including removal or treatment of the source;

- control or intercept the movement of contaminants away from the source (i.e. break the pathway);
- implement treatment at the receptor.

Decisions on the need and scope of remedial actions should also take account of the results of risk assessments for other receptors such as human health.

2.3 Remedial target analysis

The procedure for deriving **remedial targets** involves up to four Levels (as summarised in Table 2.3, and Figures 2.2 and 2.3). The assessment considers whether the observed soil and/or groundwater contamination hazards pose a risk to the identified groundwater or surface water receptor(s).

Each Level focuses on a different component of the pathway from the contaminant source through to the receptor. The remedial target is likely to increase with each assessment Level. The data requirements and the sophistication of the analysis used to derive the remedial target are also likely to increase.

The procedure is described in detail in Chapters 3–7 and summarised below:

1) Identify receptor(s).

2) Identify contaminants that pose a potential risk to the identified receptor(s). The assessment will also need to consider the significance of any breakdown products from the degradation and whether these need to be included in the assessment.

3) Define one or more **compliance points** where the presence of identified contaminants at levels exceeding **target concentration** values would represent an unacceptable risk of harm to the receptor (e.g. pollution). A compliance point may be at the receptor itself or at some point nearer to the source (see Section 4.3).

4) Determine the **target concentration** to be applied at each compliance point. This will normally be derived from relevant environmental standards or based on consideration of the background water quality (see Section 4.2).

5) Determine whether the contaminant source would result in the target concentration being exceeded at the **compliance point(s)**. Assessment starts at Level 1 (for soil contamination) and Level 2 (for groundwater contamination).

   At each Level, a **remedial target** is determined taking account of processes such as dilution and attenuation that may affect contaminant concentrations. The remedial target is likely to increase with each Level.

   The assessment will also involve selection of an appropriate method for calculating a remedial target (see Section 8.1).

6) If the observed soil or groundwater contamination exceeds the remedial target, then a decision will need to be made on whether to undertake remediation or to upgrade the level of assessment. This decision will be based on:

   - cost-benefit evaluation (see Section 9.2), e.g. the cost of further site characterisation and detailed risk evaluation is warranted in relation to the potential decrease in the cost of the remedial solution;
   - what additional information is required and can be obtained;
   - the timescale – the decision to proceed to a more detailed risk assessment should only be made if any ongoing or additional risk involved in delaying the decision to implement the remedial action is acceptable.

Table 2.2 provides definitions of the key terms used above and in Table 2.3.

A slightly different procedure is used depending on whether the source of contamination is soil or groundwater.

- For soils, the procedure assumes that there is the potential for pollution of surface water or groundwater. A conservative (preventative) approach should be adopted to ensure protection of these receptors.
- For groundwater, contamination will already have occurred. In this case, the methodology recognises that complete remediation of groundwater (to pristine quality) is not always achievable or cost-beneficial, but seeks to prevent new pollution or to undertake best endeavours to do so.

The precise methodology may vary from site to site, and may also include a phased approach to modelling, starting with a relatively simple one-dimensional numerical transport model and ending with a three-dimensional transport model (if the problem merits this). This is particularly the case at Level 3 and 4 when downgradient receptors are considered. The decision to use a more sophisticated method of analysis will have time and cost implications.

The data requirements for each Level of the assessment are described in Chapters 3–7 and summarised in Appendix A. This information will be determined in increasing detail with each successive Level of assessment. The preferred strategy is to collect, where possible, site-specific data for parameters and particularly those that are critical to the assessment and which exhibit the greatest levels of uncertainty (see Chapter 8).

At most sites a number of contaminants will be present. These will need to be assessed individually, along each feasible pollutant linkage, in order to determine which is the most critical in relation to remediation. The assessment should aim to screen out those contaminants that do not pose a risk.

The **remedial targets** derived from this analysis and used to support decisions regarding the need to remediate should:

- be relevant to the site;
- relate to the actual, intended (planned) or plausible use of the most sensitive environmental receptor such as future land or groundwater use (environmental objectives for the receptor, e.g. under the WaterFD, should be considered where appropriate);
- be achievable within a reasonable (agreed) timescale;
- take account of the uncertainties in the assessment in terms of providing protection to the identified receptor(s);
- take account of the feasibility of achieving the targets and the associated costs;
- take account of background water quality.

Any remedial measure that is finally agreed will need to take into account these factors and possibly other policy considerations. Thus, the final remedial target applied at a site may not be the same as the output from the individual assessment tools described in this report.

It is important to document information from the assessment as it may be used as supporting evidence in plans for site or catchment-scale remedial measures.

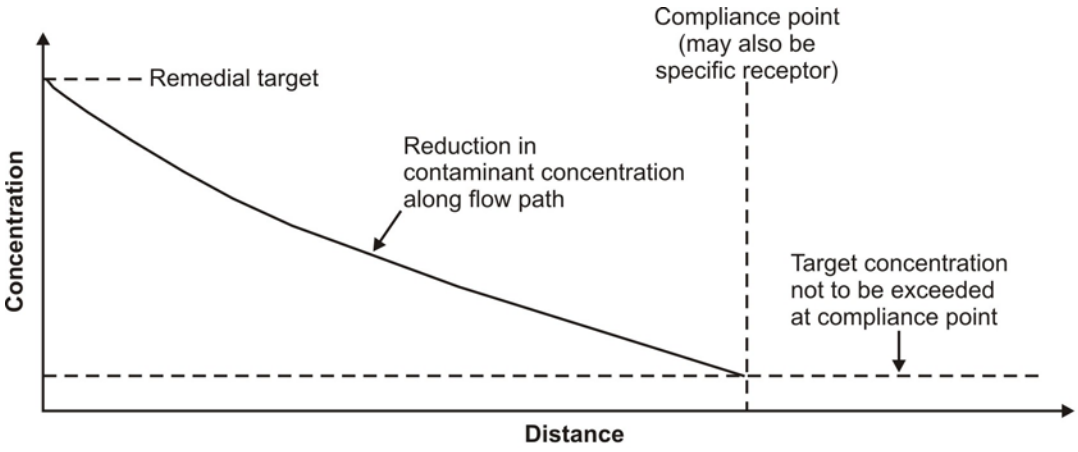
Table 2.2 Key definitions

Target concentration is the concentration at the compliance point that should not be exceeded. This will normally be based on a relevant environmental standard or background water quality. The target concentration remains constant during the assessment process.

Remedial target (or remedial target concentration) is the derived soil or groundwater concentration from the analysis, above which remediation is required. This may be set as equivalent to the target concentration or to the target concentration multiplied by a dilution and/or attenuation factor (depending on the Level of assessment). The remedial target concentration is site-specific and will change with each Level of assessment.

Compliance point is the point along the contaminant pathway where the target concentration should not be exceeded as this would represent an unacceptable risk of harm to the receptor. The compliance point may be the receptor (e.g. an abstraction), a specified point within the aquifer nearer to the contamination source, or even 'pore water' in the soil zone. Its location will depend on the Level of assessment.

Pore water. The term 'pore water' is used in this report to describe any free water (i.e. not adsorbed within the matrix of a soil or rock and incapable of participating in contaminant movement) contained within the primary Compliance Point thin fissures either in the unsaturated or the saturated zone.



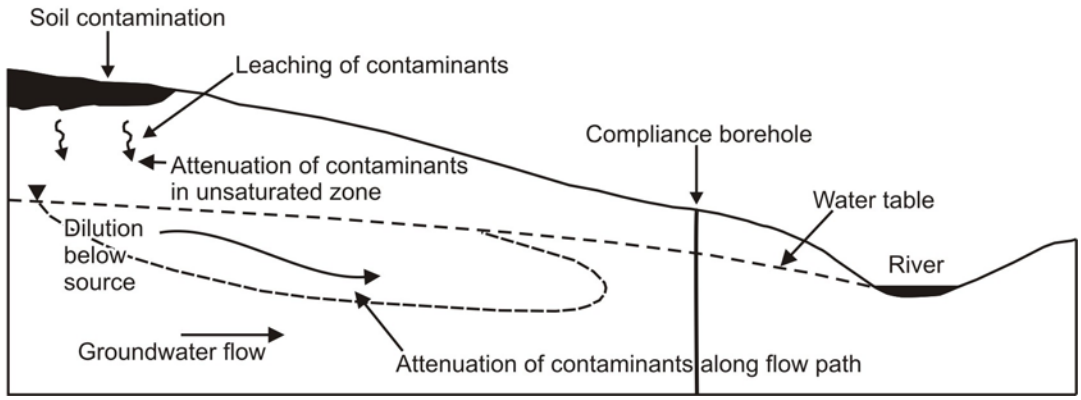


Table 2.3 Summary of assessment levels

Soil (Figure 2.2)

Level 1 (soil zone) develops an initial conceptual site model and then considers whether the concentrations in pore water in contaminated soil are sufficient to impact on the receptor when dilution, dispersion and attenuation along the pathway are ignored. The pore water concentration may be determined, in order of preference, by:

i) measured pore water concentrations or perched water quality;

ii) soil leaching tests;

iii) theoretical calculations based on soil/water partitioning equations.

In the absence of direct data, leaching tests are preferred for determining potential pore water concentrations. The pore water concentration is compared with the receptor target concentration to determine the need for remedial action. **The compliance point is the soil zone.**

Level 2 (unsaturated zone and dilution at the water table) considers whether attenuation of pollutants within the unsaturated zone and by dilution by groundwater flow are sufficient to reduce contaminant concentrations to acceptable levels. The remedial target is defined as the target concentration multiplied by a dilution factor (DF) and unsaturated attenuation factor (AF_u). The dilution factor is the ratio between groundwater flow below the site (the source area) and infiltration through the contaminated soil. The attenuation factor is the ratio between the contaminant concentration at the source and the concentration at the base of the unsaturated zone. Excluding attenuation from the assessment produces a more a conservative result. **The compliance point is groundwater beneath the source area.**

Level 3 (attenuation in the aquifer) considers whether attenuation in the saturated zone downgradient of the site is sufficient to reduce contaminant concentrations to acceptable levels. The remedial target is defined as the Level 2 remedial target multiplied by a saturated zone attenuation factor (AF_s). The attenuation factor is the ratio of the contaminant concentration in groundwater below the source to the calculated concentration at the compliance point. **The compliance point is a point down hydraulic gradient of the site.** This may be a specific receptor (e.g. an abstraction or groundwater-dependent surface water) or an agreed compliance point between the source and the receptor.

Level 4 (dilution in the receptor) considers dilution in the receptor. This is a special case and the assessment must demonstrate that any impact on groundwater does not jeopardise future use of the resource or that the cost of remediation is disproportionate in relation to the improvement of groundwater or surface water quality.

For each assessment, the pore water concentration determined for the soil zone is compared with the remedial target to determine the need for remedial action.

Groundwater (Figure 2.3)

A similar assessment framework is presented for contaminated groundwater. As the contaminants have already moved through the soil zone, the assessment for contaminated groundwater commences at Level 2. The only processes of significance are degradation, retardation, dispersion and dilution as the contaminant moves through the saturated zone to the receptor. For each level, the observed contaminant concentration in groundwater is compared with the remedial target to determine the need for remedial action.

At **Level 2 (groundwater below source)**, a site conceptual model is developed and receptors identified, i.e. groundwater abstractions, dependent surface water bodies and ecosystems, etc. Where a receptor is identified, measured groundwater quality data are compared directly with the target concentration. **The compliance point is groundwater below the site.**

At **Level 3 (attenuation in the aquifer)**, the observed groundwater contamination below the site is compared directly with the target concentration multiplied by an attenuation factor (AF). **The compliance point is a point down hydraulic gradient of the site.** This may be a specific receptor or an agreed compliance point between the source and the receptor.

Level 4 (dilution in the receptor) considers dilution in the receptor. In moving from Level 1 to Level 4, the data and resources required increase, but the degree of conservatism decreases and the cost-effectiveness of the remedial solution is likely to improve.

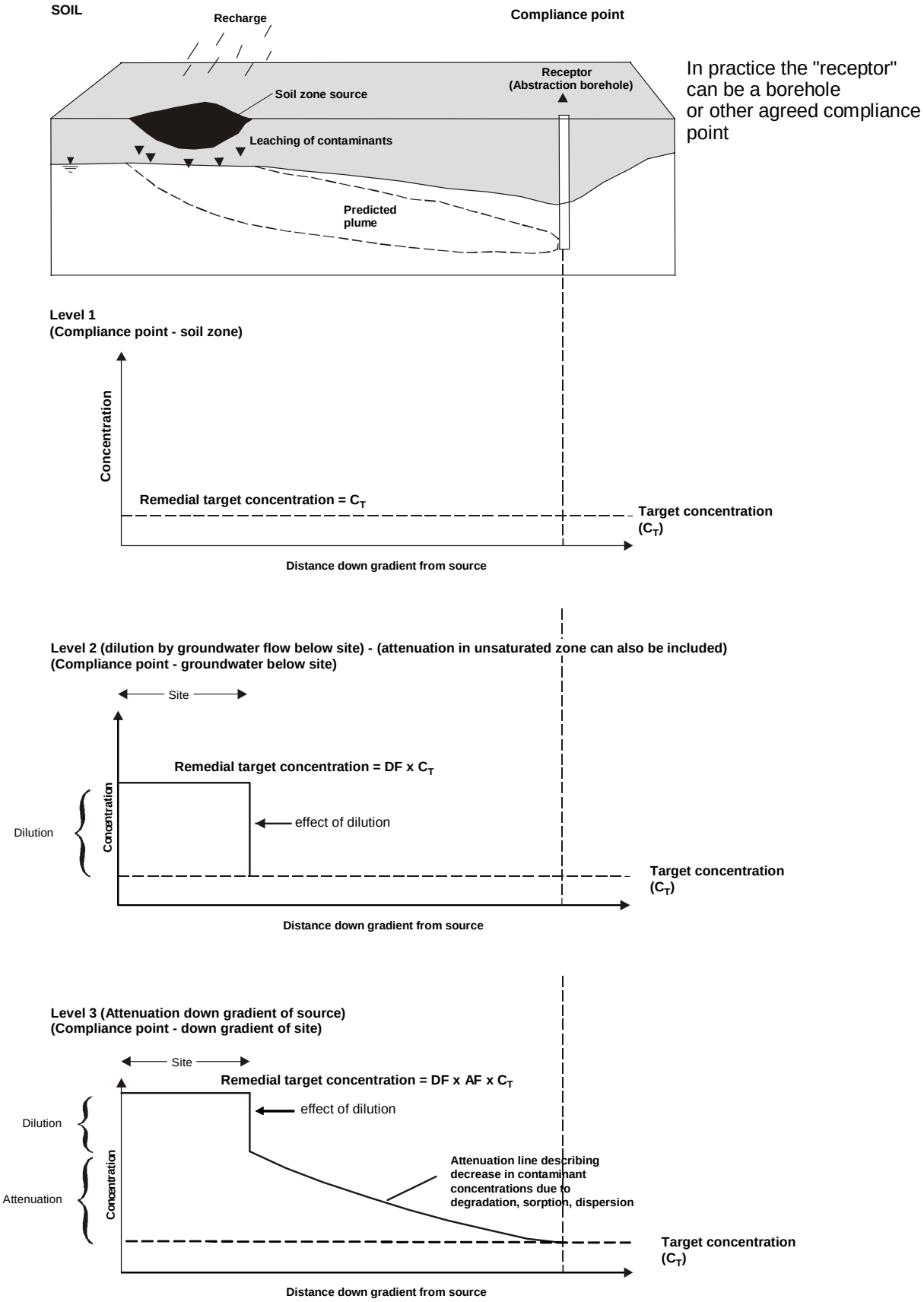


Figure 2.2 Summary of remedial target assessment for soils (Levels 1–3)

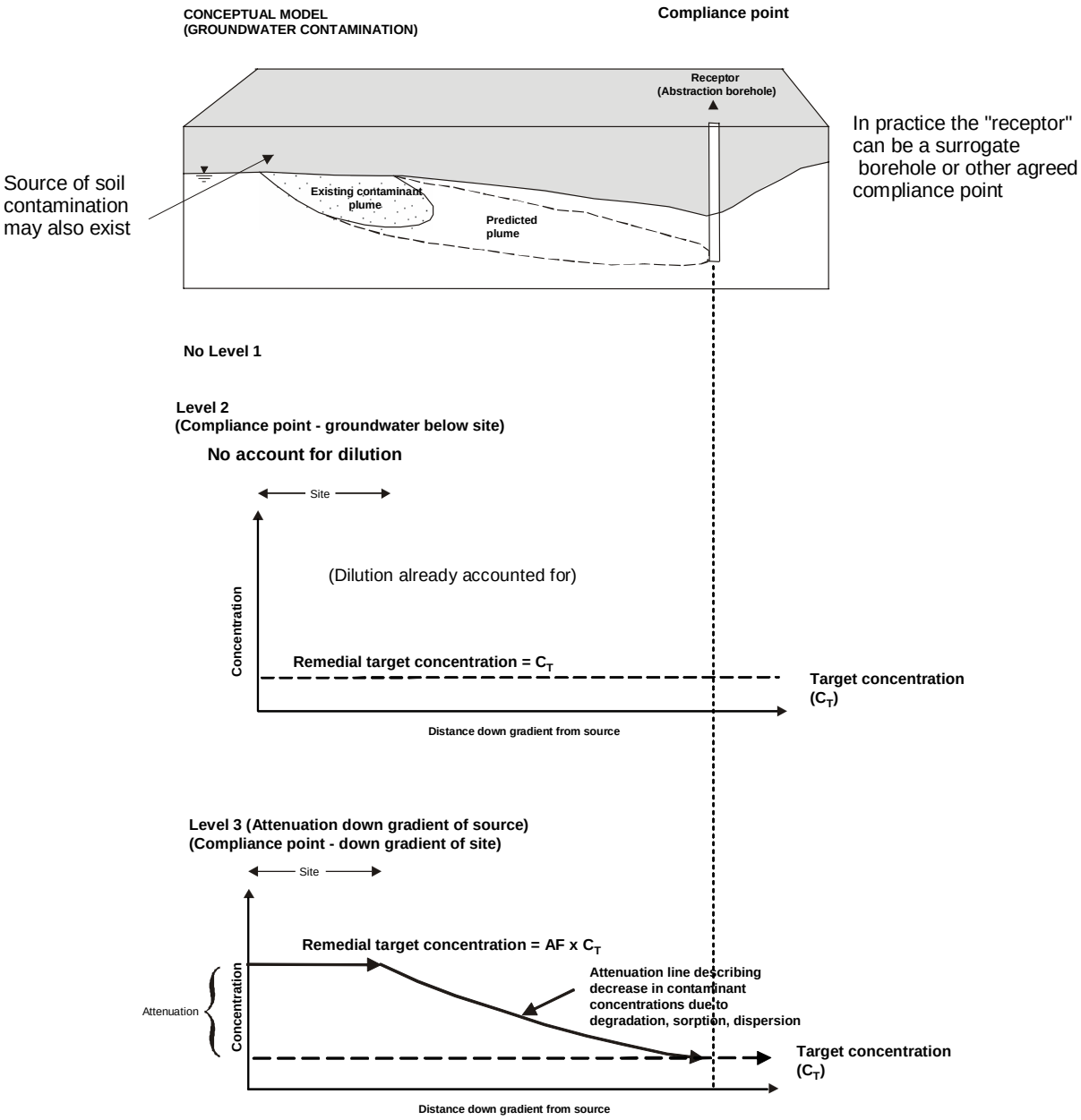


Figure 2.3 Summary of remedial target assessment for groundwater (Levels 2–3)

2.4 Timescale and remedial actions

Decisions regarding the urgency of any remedial actions will depend on the time:

- before an impact is observed at the receptor;
- to carry out any further investigations and remedial target assessment;
- to implement and demonstrate the effectiveness of remedial measures.

Such information needs to be determined on a site-by-site basis. Table 2.4 gives general guidelines that are likely to be appropriate to protect groundwater resources.

Table 2.4 General guidelines regarding the urgency of remedial action

Location based on screening assessment	Possible action (if risk is identified)
Site located within a 50 day travel time of a potable source (Source Protection Zone I) or sensitive dependant ecosystem or within 50 m of any other potable supply.	Interim or emergency action.
Site located over an aquifer where groundwater vulnerability is high or within a 400 day travel time to a potable source (Source Protection Zone II) or sensitive dependant ecosystems.	Remedial action to be determined by remedial target assessment but need to conduct early phases of assessment quickly and reappraise response, taking into account travel time to the receptor.
Site located over an aquifer where groundwater vulnerability is low or outside any Source Protection Zone II. Sensitive dependent ecosystems not in close proximity or immediately downgradient of site.	Need for remedial action to be determined by remedial target assessment.
Site located over unproductive strata (groundwater confirmed as being of no usable resource by local hydrogeologist from the Environment Agency and not in hydraulic continuity with other environmentally sensitive receptors).	Priority is to assess surface water and other receptors.

For example, for a contaminant source located within an Inner Source Protection Zone and with a potentially severe impact, interim measures are likely to be needed as there will be insufficient time to complete thorough investigations and remedial target assessment.

The likelihood of serious or irreversible harm should be assessed at an early stage to determine whether interim or emergency action is warranted, based on the precautionary principle.

There will often be an inverse relationship between the risks to surface water and groundwater. Thus, where the ground is less permeable, risks to surface water will tend to increase. A complementary assessment of the risks to surface water will therefore be needed to determine the urgency of any remedial action. If present, such risks will generally be more immediate and the pathways and travel times more obvious. However, the presence of factors such as land drains will need to be taken into account.

Short-term risks can often be dealt with by breaking the pathway in the form of blocking off drains, temporary pumping, etc. and this may give sufficient time to undertake a full remedial target assessment. However, there may be complex interactions between shallow drainage and groundwater that might make a rapid assessment difficult. Empirical evidence such as additional (short-term) monitoring data may then be needed to provide necessary supporting evidence.

The above refers only to the action appropriate to protect water resources and associated dependant ecosystems. As noted in Chapter 1, risk to other receptors (e.g. human health) may still require remedial action.

2.5 ConSim and other assessment tools

This report presents a series of equations and calculations that can be used to derive remedial targets. These are not intended as a complete list and, depending on the sensitivity

and complexity of the situation, other mathematical methods may be more appropriate (see Section 8.1).

The Environment Agency has developed a spreadsheet tool (Remedial Targets Worksheet v3.1) to help risk assessors follow the framework set out in this document. This worksheet can be downloaded from the Environment Agency's website (www.environment-agency.gov.uk). A user manual (Environment Agency 2006a), which can also be downloaded from the website, describes the worksheet and gives guidance on its use. The manual stresses that the worksheet is only a tool, and that the equations and assumptions behind it may not be appropriate to the site being considered.

The use of this spreadsheet or any other model must be justified as part of the risk assessment (see Section 8.1). Further guidance on the selection and use of subsurface contaminant fate and transport models is given in other Environment Agency reports (Environment Agency 2001b, 2001c, 2001d and 2001e).

The Environment Agency has also promoted the development of a computer software package, ConSim (Environment Agency 2003b), designed to assist the assessment of risks to water quality from land contamination. The ConSim model (www.consim.co.uk) can be used to help in:

- soil and groundwater risk assessments;
- predicting the impact on groundwater from soakaway discharges and land-spreading activities.

Other approaches (e.g. ASTM 2002) are also available that can be adapted for use in the overall framework presented in this report.

The main difference between the two approaches is that ConSim starts with a concentration in the soil/ground and predicts an impact down the pathway at an identified receptor, whereas the remedial targets methodology defines an acceptable environmental standard at a receptor and works back along the pathway to determine what would be an acceptable concentration of a contaminant at the source.

Table 2.5 provides a comparative summary of the two approaches and also explains the difference between the terminology adopted in the original version of the Remedial Targets Methodology (Environment Agency 1999a) and the version presented in this document.

Table 2.5 Comparison of ConSim Levels and Remedial Targets Methodology

Tier/ Level	ConSim: Levels	Remedial targets method (this document): Levels	Remedial targets method (Environment Agency 1999a): Tiers
1	Comparison of contaminant source with receptor	As ConSim	As ConSim
2	Unsaturated zone travel time, transport processes, biodegradation and effects of dilution in the aquifer	As ConSim	Dilution in the receiving groundwater or surface water
3	Saturated zone transport, attenuation and retardation processes	As ConSim	Attenuation in the unsaturated and saturated zones. Simple analytical models
4		Dilution in the receptor (e.g. surface water)	As Tier 3 but more sophisticated numerical models

The calculations within ConSim are performed using the same analytical solutions to groundwater flow and contaminant transport equations as described in this report but, where appropriate, these are coupled with probabilistic Monte Carlo simulations. The output from ConSim thus takes the form of probabilistic plots expressed as frequency or cumulative curves and/or tabular summaries. In practice, different elements of ConSim can be run to assist in the various assessment Levels and the varying approaches should not inhibit the assessment process.

It is important that ConSim and any other model or analytical package should be regarded as a tool in the assessment process. Professional judgement will always be needed to integrate the results from such tools with:

- other technical and professional guidance;
- cost-benefit considerations;
- policy, planning and legislative requirements.

3. Receptors, conceptual model and pollutant linkages

3.1 Receptors

The objective of the assessment is to determine whether the observed soil and groundwater contamination poses an unacceptable risk to groundwater and surface water receptors (pollution of water) and whether remedial work is required to protect these receptors.

The main receptors include:

- groundwater as a resource within aquifers (including all current abstractions from groundwater and any feasible future uses);
- discharges from groundwater, e.g. springs and baseflow to rivers;
- surface watercourses, lakes and ponds;
- wetlands and groundwater-dependent ecosystems;
- estuaries and foreshore environments.

The sensitivity of the receptor, the timescale necessary for the assessment and the consequences of any impact need to be taken into account in the assessment and any course of action.

The **sensitivity** of the site is determined by its location in relation to:

- aquifer designation, i.e. principal or secondary aquifer;
- proximity to critical potable groundwater supplies as defined by Source Protection Zones;
- groundwater vulnerability (e.g. is there a thick cover of low permeability clay protecting the underlying aquifer?);
- the proximity, type and degree of hydraulic continuity with surface water systems.

The concepts of vulnerability and risk to groundwater are considered in more detail in a further Environment Agency report (Environment Agency 2006b).

In addition to location, it is also necessary to consider the existing condition of, and future objectives for, water resources including:

- surface water and groundwater status under the WaterFD (when determined);
- existing surface water or groundwater quality;
- planned objectives for the waters.

3.2 Conceptual model and pollutant linkages

At an early stage in the assessment, it is essential to draw up a conceptual model of the soil and groundwater system that:

- is based on all the physical, hydraulic and chemical data available;
- draws on local knowledge of the site and the surrounding area.

This conceptual model will form the framework for undertaking the remedial target assessment and making decisions on the need for remedial action. If the basic physical and hydraulic data are substantially inadequate, incorrect conclusions may be drawn from the chemical data.

The conceptual model should continue to be developed throughout the risk assessment and should reflect the level of understanding required to support each Level of assessment.

The information obtained during the initial site characterisation should be used to construct a preliminary conceptual model of pollutant linkages in order to determine whether:

- no further action is required as there is no receptor present or a pathway cannot be identified;
- a risk assessment needs to be undertaken to derive remedial targets to determine the need for remedial action;
- urgent or emergency action is required as the source has already resulted in contamination of the receptor or is in close proximity to the receptor, i.e. it is in imminent danger of causing serious or irreversible harm.

The initial assessment phase requires only a qualitative assessment based on existing data (geological maps, geological memoirs and borehole records) and site investigation results. If a further risk assessment is needed, then more data will be required depending on the level of assessment and whether a numerical model is used for the analysis.

The most important data required for the assessment are summarised in Appendix A. These data should be sufficient to allow an initial assessment of:

- contaminant source and release history (historical or ongoing source);
- contaminants of concern including their subsurface distribution in different phases, e.g. free phase (non-aqueous phase liquid; NAPL), dissolved phase, gaseous phase;
- contaminant type (e.g. inorganic, organic) and properties (e.g. solubility, mobility);
- contaminant concentration and distribution;
- groundwater flow and geochemical regime (e.g. aerobic, anaerobic) at the site, including any temporal variation;
- processes affecting contaminant fate and transport such as sorption, degradation and volatilisation;
- groundwater and surface water receptors;
- plausibility of pollutant linkages.

The conceptual model is a simplified representation or working description of how the real system is believed to behave, based on a qualitative analysis of field data. The development of the conceptual model must be an iterative process, continually being challenged and updated as new data become available or as understanding of the system improves.

Good practice guidance on developing conceptual models is provided in:

- *Guide to good practice for the development of conceptual models and the selection and application of mathematical models of contaminant transport processes in the subsurface* (Environment Agency 2001b);
- *Model procedures for the management of land contamination* (Defra and Environment Agency 2004).

The conceptual model must identify uncertainties in the data, the understanding of the site and assumptions or simplifications made in the assessment process. For example, the application of analytical equations usually involves making assumptions regarding the contaminant flow path. Such assumptions should be borne in mind when making decisions on the need for, and extent of, remedial measures.

4. Derivation of target concentrations and compliance point

4.1 Introduction

It is necessary to determine both the target concentration and the compliance point at which this target will be set. This determination should take account of:

- fundamental requirements of EU and UK legislation, e.g. compliance with the Groundwater Directive 80/68/EEC, the Water Framework Directive (when fully implemented), Part IIA of EPA 1990, etc.;
- the background quality of water resources (the local groundwater and/or rivers), whether natural or the result of existing pollution, and the wider expectations for future improvement in water quality;
- all current active (e.g. borehole abstractions) and passive (e.g. springs, river baseflow) uses of the resource and all feasible future uses.

The ideal (and most precautionary) remediation standard is natural background quality – namely, there should be no significant deterioration in the quality at the receptor (i.e. it should not be discernible against natural background variations). This may not always be achievable or cost-effective and is often not a fundamental legislative requirement (in contrast to the need to prevent pollution).

Where the hydrogeological environment is complex and/or the type of contaminant is not amenable, pump-and-treat groundwater remediation schemes in the USA, continental Europe and the UK have had limited success in cleaning groundwater to background conditions. As a result, target concentrations may be:

- based on environmental standards appropriate for the intended use;
- set to ensure that objectives for a groundwater or associated water body are met.

In such circumstances, the Environment Agency will seek to achieve the best environmental solution possible given site-specific circumstances while taking account of environmental costs and benefits (see Section 9.2).

In deriving remedial targets for contaminated soils where contamination of groundwater has not occurred, a stringent target concentration may initially be set in order to prevent groundwater contamination. The cost and benefits of undertaking remediation (see Section 9.2) then need to be assessed and, if the balance is unacceptable, a less stringent target may be set and the process repeated. The aim should always be to secure the best net environmental outcome that can reasonably be achieved and, as a minimum, to prevent pollution (or discernible entry of List I substances to groundwater).

In summary, the main objectives in deriving remedial targets are:

a) Where groundwater contamination has not yet occurred:
    - no discernible entry of List I substances into groundwater;
    - no new risk of pollution of groundwater by List II substances;

- no pollution/damage of dependent surface water bodies or groundwater-dependent terrestrial ecosystems.

b) Where groundwater contamination, including entry by List I substances, already exists:

- minimise further entry of List I substances to groundwater;
- minimise expansion of the groundwater contaminant plume to prevent further pollution (protect groundwater uses, avoid damage to dependent surface water bodies or groundwater-dependent terrestrial ecosystems, etc. and, *when applicable, meet WaterFD objectives as noted below)*.

c) When the WaterFD is fully implemented:

- *no deterioration in status of the groundwater body;*
- *no input of pollutants to groundwater that could cause an environmentally significant and sustained upward trend in groundwater quality.*

Note: in most cases if a) and b) above are met then c) will be met, though there may be a time lag between implementing remedial actions and these actions being fully effective, particularly in deep or slow groundwater systems.

The approach used to set target concentrations and compliance points is described below. Subsequent chapters elaborate on remedial target analysis.

4.2 Target concentration

The basis of this methodology is that a target concentration is set for the identified receptor and that this target concentration should not be exceeded. The target concentration is used in Level 1–4 calculations to derive a remedial target to which soil or groundwater concentrations are compared so to determine the need for remedial action. The choice of the target concentration is, therefore, critical to the determination of a remedial target.

At the outset, a basic understanding of the natural system in question is required, including knowledge of:

- natural background quality;
- groundwater flow;
- interactions with associated surface water receptors;
- the effects of any other anthropogenic activities on the system.

The general approach to setting a target concentration is summarised in Figure 4.1.

For soil contamination, the target concentration should initially be set at background levels, but with the recognition that this may need to be changed to an appropriate environmental standard if remediation to background is not achievable or affordable.

For List 1 or WaterFD priority or prevent substances, the assessment should determine whether attenuation in the unsaturated zone is sufficient to prevent the discernible entry of contaminants into groundwater. For these substances, the target concentration should initially be set as the limit of detection. But if groundwater contamination has already occurred, an appropriate environmental standard should be used.

Background quality should be based on either monitoring data obtained from up-hydraulic gradient of the site or regional groundwater quality monitoring. Existing background quality may differ from natural background quality due to, for example, diffuse pollution from agricultural or industrial sources. In some instances, existing water quality may be sufficiently poor to prevent its use without significant treatment. In this case, there should be further consideration of the need for, and viability of, remediation of any groundwater pollution. As part of site characterisation, the assessment should aim to determine whether upgradient

quality reflects natural groundwater quality or has been impacted by diffuse and/or point sources of pollution.

Data on natural background groundwater chemistry and the geochemical controls on water chemistry in a wide range of British and European aquifers is becoming more widely available (e.g. BGS and Environment Agency 2004).

Where groundwater contamination has been identified, the general approach is to use an environmental standard (assuming the background quality is better than this) because remediation to background quality is unlikely to be achievable. This standard should be relevant to the current or intended use of the aquifer (strategic potable water resource, baseflow support to river flow, wetland habitat).

Note: in all cases care should be taken that any standard used is fit for purpose. A standard is not simply a number but is always associated with compliance criteria (for example, used as an average, maximum, 95%ile and applied or over a specific period of time – daily, annual etc.). Use of a numeric standard outside its original context will usually result in a different impact from that originally intended.

Standards that may be applicable are:

- UK Environmental Quality Standards (EQS) for the protection of aquatic life (in both freshwater and saline environments);
- UK quality standards for saline water required to support fish and shellfish, e.g. Surface Waters (Fish life) (Classification) Regulations 1997;
- UK quality standards for fresh and saline waters used for bathing and contact water sports. e.g. Bathing Waters (Classification) Regulations 1991;
- river water quality objectives;
- EC Water Quality Standards;
- *when applicable, Environmental Standards developed to achieve WaterFD objectives, including the proposed Groundwater Daughter and Priority Substances Directives (these may replace some of the existing standards noted above);*
- UK Water Supply (Water Quality) Regulations 2000;
- UK Private Water Supplies Regulations 1991;
- UK quality standards for water to be used for direct abstraction to potable supply, e.g. Surface Water (Abstraction for Drinking Water) (Classification) Regulations 1996.

Other possible relevant standards and/or objectives include:

- avoidance of groundwater pollution as defined in the Groundwater Regulations 1998;
- ADAS water quality standards for water used for irrigation and livestock watering;
- World Health Organization (WHO) guidelines for drinking water quality;
- Environmental Health criteria including the protection of mineral, spring and other bottled water sources.

For some contaminants, no relevant standards may exist. The assessment should therefore be based on background quality. For synthetic chemicals, the target concentration should initially be set as the limit of detection.

Environmental standards for some contaminants (e.g. pesticides) can be very low and their use ensures that there is unlikely to be any deterioration in background quality. For other contaminants, the standard may be significantly above background quality; for example, the standard for chloride would be the drinking water maximum acceptable concentration of 250 mg/l, which is much higher than the background concentration which is often <50 mg/l.

If setting the target concentration as a quality standard such as a drinking water standard is less onerous than achieving background quality, then deriving the remedial target in this way may mean that some deterioration in groundwater quality could occur. The acceptability of this should be assessed in relation to:

- the sensitivity of the receptor at risk;
- the current or potential use of the water resource;
- whether higher standards of remediation (based on background quality) are achievable, reasonable and cost-effective;
- the degree to which downgradient quality will deteriorate as a result of the observed soil or groundwater contamination. This may involve use of the risk assessment model to predict the impact of the observed contamination on groundwater or surface water quality at the receptor.

For good quality aquifers which are extensively developed for potable supplies or provide a significant flow component to surface water (e.g. principal aquifers), the target concentration may need to be set at a level between an appropriate environmental standard and the background level in order to provide sufficient protection to water quality.

If background quality exceeds an environmental standard, the assessment should consider:

- whether the existing quality prevents utilisation of resources and if remediation is warranted;
- the degree to which background quality will deteriorate as a result of the observed soil or groundwater contamination. This may involve the use of a model such as ConSim, which allows the contaminant concentration in the compliance point or receptor to be determined;
- whether background quality is natural or has been impacted by upgradient point or diffuse sources of pollution.

In such circumstances, the target should be set initially at a value higher than the background concentration, taking account of natural variation in background and precision in measurement. The value should be sufficiently high that it can be clearly distinguished from natural or trivial variations in quality, but also sufficiently low that the resource value is protected. A value of 10 per cent higher than natural background may be appropriate but will need to be justified and discussed with the regulator.

When designing the site investigation, including the sampling and monitoring programme, it is important to ensure that detection limits are appropriate to the target concentration selected.

4.3 Selection of compliance points

This section sets out an overall methodology on selecting compliance points. An additional appendix giving guidance on identifying compliance points in specific aquifer settings is in preparation and will be published as a supplementary document in 2007.

A compliance point can be located at the receptor itself or at any point along the contaminant pathway between the source and the receptor. The choice of compliance points will depend on the assessment Level (Figures 2.2 and 2.3).

At Levels 1 and 2, a precautionary approach is adopted and the compliance point (and receptor) will be either the soil zone (Level 1) or groundwater below the site (Level 2). For Level 2, the compliance point will typically be a hypothetical borehole receptor located immediately downgradient of the source. This means that the assessment takes account only of dilution by groundwater flow and attenuation in the unsaturated zone. If the contaminant is

a List 1 substance (i.e. one whose entry into groundwater must be prevented), then the base of the unsaturated zone should be set as the compliance point.

Provided that the target concentration will afford adequate protection to receptors as described below, at Level 3 the compliance point may be located at a likely, planned or existing receptor or at any other point downgradient of the source.

At Level 4, the compliance point is always at the receptor itself since this level takes additional account of dilution within the abstraction or in surface water (see below).

The following steps should be undertaken when setting a compliance point:

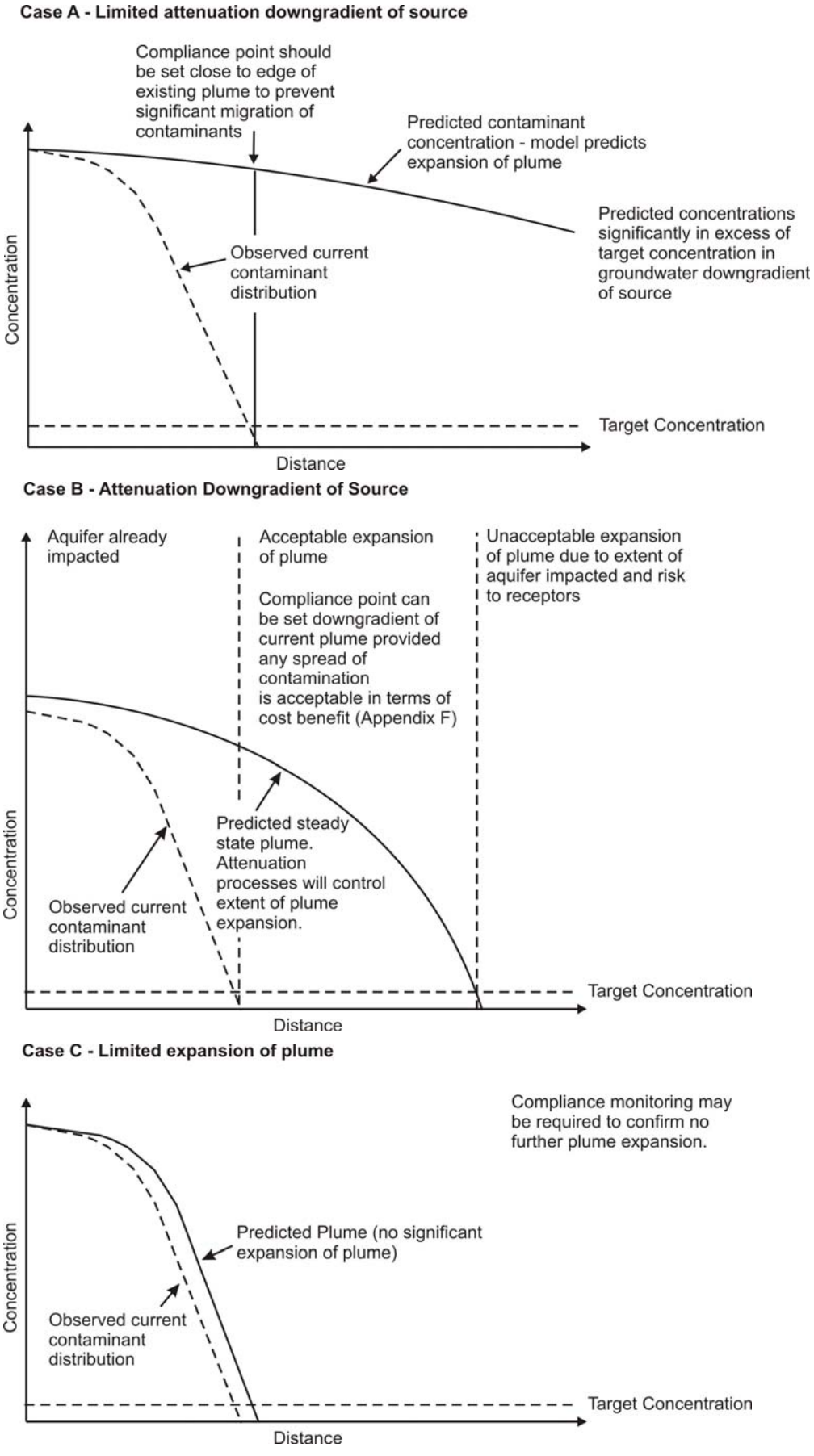
1. Identify all existing or planned downgradient receptors, e.g. abstraction boreholes and surface water bodies (see Section 3.1).
2. Assess the potential (plausible) future use of the aquifer taking account of:
    - existing and future land use, e.g. an area designated for use as domestic housing with mains supplies might reasonably be regarded as a constraint in the ability to develop that area of the groundwater resource;
    - land ownership – there may be factors (e.g. private estates, park land, major infrastructure development) governing the long-term control of the land or access to adjacent land that constrain the potential for future water abstraction;
    - topography – steep or inaccessible land or areas with unsuitable access may reasonably influence the identification of sites for the development of groundwater resources;
    - the potential yield of the aquifer and background quality, which may affect current or future use of the aquifer.
3. Identify the contaminants of concern from the site and determine the extent of any groundwater contamination, e.g. draw a map of the distribution of contaminants in groundwater.
4. Predict the likely impact on groundwater quality from the contaminant source, including whether any existing groundwater contaminant plume would be expected to expand.
5. Assess the potential significance of attenuation in reducing contaminant concentrations.
6. Identify an appropriate compliance point.
7. Derive remedial targets (Chapters 5–7).
8. Evaluate whether the compliance point and remedial target are reasonable (in terms of protection of receptors), practical and affordable.

Attenuation can have a significant effect on contaminant concentrations and the calculated remedial target, particularly if the compliance point is located several hundreds of metres down-hydraulic gradient of the source. It is possible that no remediation may be required, even for high levels of source contamination. This is acceptable provided all the receptors are adequately protected and that the extent of any contaminant plume remains within policy constraints (for example, attenuation can be relied upon, no constraint on resource use etc.).

The potential significance of natural attenuation is illustrated in Figure 4.2:

- For Case A, there is limited attenuation and expansion of the plume would be expected. In this case, it would be appropriate to set the compliance point close to the source.
- For Case B, some expansion of the plume is predicted. However, this will be limited by attenuation and it may be appropriate to locate the compliance point further downgradient of the source. The important factors will be whether there is sufficient confidence in the attenuation rates used and whether the predicted expansion of the plume is acceptable.
- For Case C, no significant expansion of the plume is predicted and the assessment needs to consider whether remediation of the existing groundwater pollution is warranted (e.g. beneficial, affordable and achievable).

Figure 4.2 Attenuation and compliance point



The assessment can be undertaken for a 'hypothetical' compliance point located between the source and the receptor. A typical case is where it has not been possible to construct an off-site monitoring point. In this case, the assessment will need to be confirmed by reference to on-site groundwater monitoring boreholes (see Section 9.3).

The location of a downgradient compliance point should be discussed with the Environment Agency and will need to be justified in terms of:

- the confidence that can be attached in the risk assessment, i.e. can attenuation of contaminants be demonstrated using site data (Environment Agency 2000a);
- the sensitivity of receptors at risk, and potential implications if the assessment is appreciably incorrect. For poorly permeable or unproductive aquifers and where receptors are remote, then a case can be made for locating the compliance point away from the source. For principal aquifers where receptors are often nearby, then the compliance point will need to be located close to the source
- the observed extent of any existing groundwater contamination;
- the extent groundwater deterioration is likely to occur. Model predictions should be made to assess the extent to which groundwater quality downgradient of the source could deteriorate (see Section 5.4). In general and provided there are no reasons to set a compliance point nearer to the source, the assessment should seek to demonstrate that the remedial works will limit plume expansion. In the absence of any other criteria, one approach would be to limit the expansion of the front of the plume to no more than 10 per cent of the distance to the nearest specific receptor, which can be either a defined receptor or other compliance point, or by 100 metres (whichever is the lesser);
- the ability to locate groundwater monitoring boreholes downgradient of the receptor such that a groundwater monitoring scheme can be implemented to demonstrate that any changes in contaminant concentration are consistent with the risk assessment (see Sections 8.5 and 9.3).

Surface waters

If surface water is the main potential receptor, the assessment will need to consider whether the compliance point should be the surface water body or an adjacent groundwater monitoring point. The main issue is whether dilution in the river can be taken into account in determining the remedial target concentration (Level 4 assessment, see Section 5.7).

The precautionary approach is to:

- set the compliance point within the groundwater body immediately upgradient of the watercourse;
- fix the target groundwater concentration as equal to the target concentration in the watercourse (e.g. the relevant environmental standard).

This means that the environmental standard cannot be compromised regardless of how much groundwater enters the watercourse. A second iteration (**only** if fully justified) would be to consider:

- the potential interaction between the groundwater body and the watercourse;
- the effects of attenuation in the riparian and hyporheic zones;
- any subsequent dilution within the watercourse.

Any assessment that considers dilution must consider background quality, low flow conditions and other potential pollutant inputs to the watercourse (see Section 5.7). In most cases, the remedial target should be derived for low flow conditions and the target condition

set as a proportion of the appropriate environmental standard (to take account of the influence of other possible pollutant sources).

Any compliance criteria set to protect a surface water receptor must also take account of potential uses of the groundwater between the contaminant source and the surface water. This is less likely to be an issue when the surface water is relatively close to the source.

4.4 Water Framework Directive

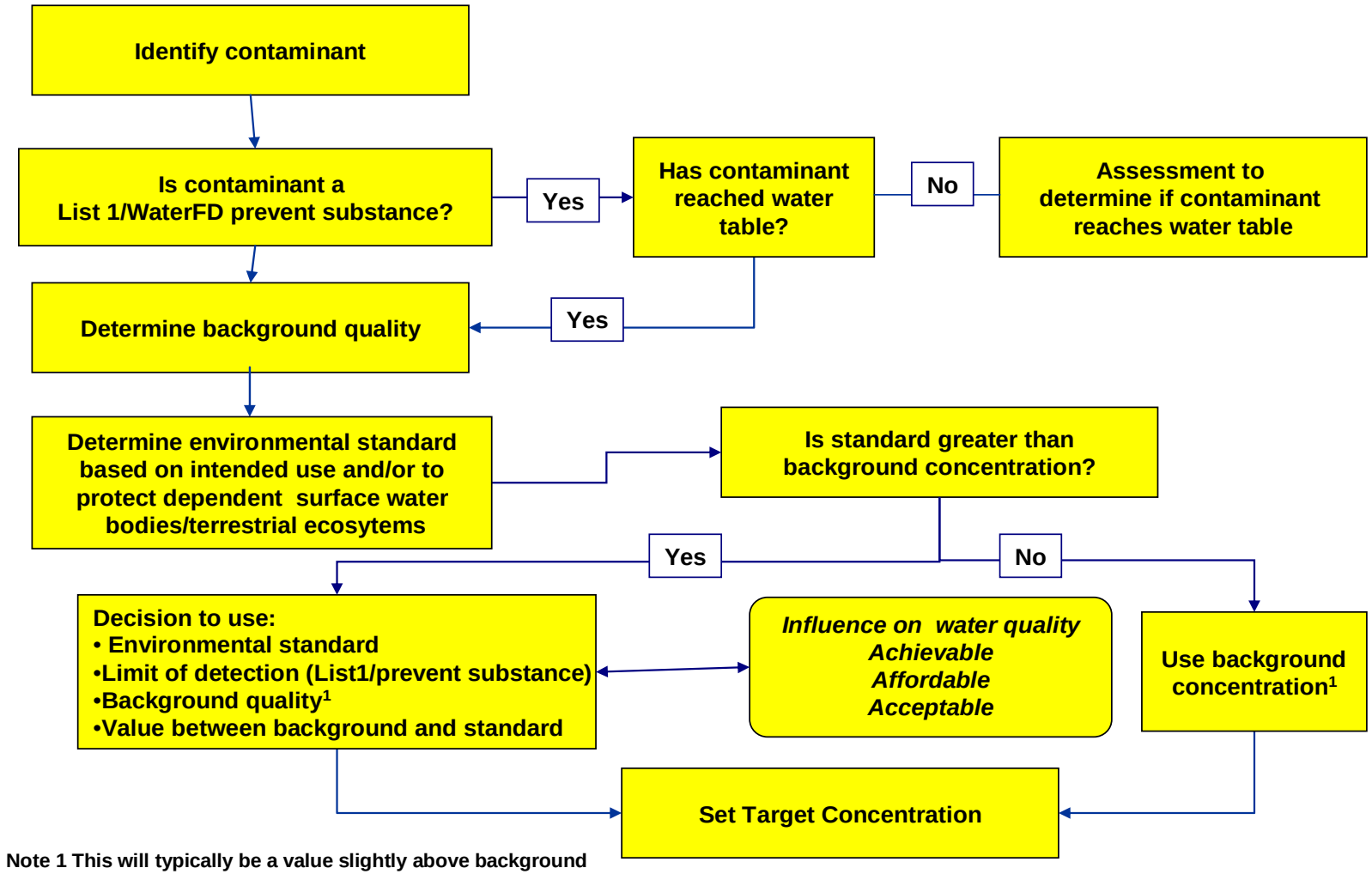
In determining compliance points, selecting target concentrations and setting objectives for the remedial assessment, the Environment Agency should be consulted to check whether the site poses a risk to meeting the objectives of the Water Framework Directive. Such a situation may arise where:

- groundwater contamination has or is likely to result in increasing concentrations in groundwater (expanding plume) downgradient of the site;
- contaminant loading to associated surface water bodies has or is likely to result in a measurable impact on surface water quality;
- groundwater contamination has or is likely to result in the need for additional treatment at a drinking water abstraction point;
- contaminant loading has or could result in significant damage to a groundwater-dependent terrestrial ecosystem.

In practice, this is only likely to apply to ‘larger’ sites where there has been major contamination of groundwater (e.g. the contaminant plume is several hundred metres long) or at sites located close to associated surface water bodies or wetlands.

In addition, it will be necessary to consider the contaminants in relation to the ‘prevent or limit’ requirements of the WaterFD. In the case of substances deemed to be hazardous, as with Groundwater Directive List I substances, there should be no discernible input to groundwater and the compliance point is at the base of the unsaturated zone.

Figure 4.1 Derivation of target concentration



Note 1 This will typically be a value slightly above background

5. Remedial target assessment - soils

5.1 Introduction

This chapter provides a description of each of the four Levels of assessment (see Table 2.3) for the derivation of soil remedial targets (Figure 2.2).

The assessment considers whether leaching of contaminants from the soil zone poses a risk to the identified groundwater or surface water receptor. The approach relies on the assessment of the contaminant concentration of water (pore water – as defined in Table 2.2) in contact with the contaminated soil.

The pore water concentration is determined, in order of preference, from:

1) Analysis of pore water quality or perched water quality.

2) Results of leaching tests on the contaminated soil. For preference and where it is appropriate, the test should be undertaken according to BS EN 12457 (see Appendix B). This replaces the Environment Agency R&D Note 301 leaching test methodology issued by its forerunner, the National Rivers Authority, in 1994 (NRA 1994a).

3) Theoretical calculation of the pore water concentration that would be expected from contact with the soil or a discrete contaminant phase. This calculation is based on the measured soil contaminant concentration and equations describing the partitioning of contaminants between water and the soil matrix or discrete contaminant phase (see Table 5.2). For the remedial target assessment, a soil remedial target concentration can be calculated as given in Table 5.1 based on soil–water partitioning.

All these methods for deriving pore water quality in soil have their own limitations (see Section 5.2).

The need for remediation of soils to protect the identified receptor is established by comparing the results of leaching tests, direct measurements of pore water quality or measured soil concentrations with the remedial target (see Table 5.1). The methodology is illustrated by worked examples included in this chapter. The precise methodology to be adopted at each Level (particularly at Levels 3 and 4) is not fixed and may need to be varied on a site-by-site basis.

Table 5.1 Calculation of remedial target concentrations (Levels 1–3)

Level	Pore water remedial target concentration	Soil remedial target concentration
	The pore water concentration should not exceed the remedial target concentration RT_l defined below:	*The total measured soil concentration should not exceed the soil remedial target concentration RT_s defined below:*
1	$RT_l = C_T$	$RT_s = C_S = C_T\left(K_d + \frac{\theta_w + \theta_a H}{\rho}\right)$
2	***(dilution only)*** RTl = CT × DF	RTs = Cs × DF
3	***(dilution and attenuation)*** RTl = CT × DF × A	RTs = CS × DF × AF
	Attenuation in the unsaturated zone can also be included in the assessment at Level 2 (see Section 5.3). Dilution in the receptor (such as an abstraction or groundwater-dependent surface water) can be included in the assessment at Level 4 (see Section 5.7).	
	Definitions RT_l = pore water remedial target concentration for in-situ soils (mg/l) C_T = target concentration for water (mg/l) AF = attenuation factor (dimensionless) DF = dilution factor (dimensionless)	 RT_s = soil remedial target concentration for in-situ soils (mg/kg) C_S = calculated total soil concentration (mg/kg) K_d = soil water partition coefficient (l/kg) θ_w = water-filled soil porosity (fraction) θ_a = air-filled soil porosity (fraction) $\theta_w + \theta_a$ = total soil porosity H = Henry's Law constant (dimensionless)* ρ = bulk density (g/cm^3)

* The dimensionless Henry's Law constant (H) may be converted from the Henry's Law constant in atm-m^3/mol by multiplying by 42.3 (unit conversion for 15°C).

Table 5.2 Soil–water partitioning

The equation typically used to calculate pore water quality based on soil concentration is:

$$C_p = \frac{C_s}{\left(K_d + \frac{\theta_w + \theta_a H}{\rho} \right)}$$

where:

C_S	=	soil concentration (mg/kg)
C_p	=	pore water concentration (mg/l)
K_d	=	soil–water partition coefficient (l/kg)
θ_w	=	water-filled soil porosity (fraction)
θ_a	=	air-filled soil porosity (fraction)
ρ	=	bulk density (g/cm^3)
H	=	Henry's Law constant (dimensionless)

NB This equation assumes linear partitioning. For some soils and contaminants, partitioning is best described by a non-linear equation.

5.2 Level 1 (soil zone)

For this Level, the compliance point is taken as the soil zone and the remedial target is set as equivalent to the target concentration. No allowance is made for processes such as dilution and attenuation that might affect contaminant concentrations along the pathway between the soil and the identified receptor.

At Level 1, the soil remedial target is set as either (Table 5.1):

- a **pore water remedial target concentration** (if leaching tests or pore water data are available) equal to the target concentration for the identified receptor;

or

- a **soil remedial target concentration** equal to a calculated soil concentration (if only soil analysis data are available) using empirical equations that describe soil–water partitioning (see Table 5.2) . These calculations are sensitive to the value of the partition coefficient.

The partition coefficient describes the partitioning of a chemical between different phases such as the soil and water phase. This parameter is contaminant-specific and is likely to vary according to the:

- soil properties (mineral content, surface area);
- site-specific conditions (e.g. soil pH);
- contaminant concentrations in water.

Standard analytical equations that can be used to calculate a partition coefficient for organic compounds, based on the fraction of organic carbon content of the soil and published values for properties of the contaminant, are given in Table 5.3.

Table 5.3 Calculation of partition coefficient for organic chemicals

The partition coefficient for organic compounds can be calculated using the following equations.

Partition coefficient for non-polar organic chemicals (e.g. aromatic hydrocarbons such as benzene and toluene):

$$K_d = K_{oc} . f_{oc}$$

Partition coefficient for ionic organic chemicals (e.g. phenol):

$$K_d = f_{oc} . \left[K_{oc,n} \left(1+10^{pH-pKa}\right)^{-1} + K_{oc,i} \left(1-\left(1+10^{pH-pKa}\right)^{-1}\right)\right]$$

where:

K_d = soil–water partition coefficient (l/kg)
K_{oc} = organic carbon partition coefficient (l/kg)
f_{oc} = fraction of organic carbon (fraction)
$K_{oc,n}$ = sorption coefficient for neutral species (l/kg)
$K_{oc,i}$ = sorption coefficient for ionised species (l/kg)
pH = pH value
pKa = acid dissociation constant

NB These equations assume linear partitioning. For some soils and contaminants, partitioning is best described by a non-linear equation.

Data requirements for Level 1

The data required for a Level 1 assessment are summarised in Table 5.4. Site investigations will usually involve soil testing and leaching tests. If the pore water concentration is calculated based on partitioning relationships, the recommended approach is to obtain site-specific values for soil pH and the fraction of organic carbon (for organic contaminants).

Literature values for the soil parameters (e.g. porosity and bulk density) may be used provided they are appropriate to the soil conditions observed on-site. For example, the partition coefficient for metals and ionisable organics can vary with soil pH and it is therefore important to choose literature values that are consistent with the measured soil pH. The air-filled and water-filled porosity of a soil can be estimated from the soil moisture content, soil bulk density and particle density (Table D1, Appendix D).

Literature values for the partition coefficient can be acceptable for chemicals where this coefficient is well defined (for example, a small range of published values and values are appropriate to the soil type and pH value) or if the chemical is characterised by a high partition coefficient. Site-specific measurements should be obtained when the partition coefficient is poorly defined in the literature (for example, a wide range of published values) or where greater certainty is required to support decisions regarding the need to undertake remediation.

The Environment Agency has published guidance on the methodology for determining partition coefficients (Environment Agency 2000b, 2005a). This guidance covers:

- ammonium;
- anions;
- metals;
- pesticides;

- volatile organic carbons (VOCs), e.g. chlorinated solvents;
- semi-volatile organic carbons, e.g. naphthalene.

In the case of VOCs, it is important that the test is undertaken with no headspace to prevent losses due to volatilisation.

The test procedure is not appropriate for highly hydrophobic organics (i.e. organics characterised by low solubility and high sorption coefficients) as these compounds are not readily leached and tend to sorb to test equipment (e.g. filter paper, containers). The recommended approach for hydrophobic contaminants is to calculate a soil remedial target based on soil–water partitioning relationships (see Table 5.3).

Literature values for Henry's Law constant and the organic partition coefficient are usually adequate.

It is essential that all soil and/or leachate analyses are conducted by suitably accredited laboratories (e.g. United Kingdom Accreditation Service; UKAS) using validated methods.

Table 5.4 Data requirements for Level 1

Parameter*	**Site-specific data essential**	**Site-specific data preferable**
Pore water concentration, e.g. leaching test, direct measurement	Y	
Or, if assessment based on **theoretical calculation** (see Table 5.1), each of the following:		
Measured total soil concentration	Y	
Water-filled porosity		Y
Air-filled porosity		Y
Soil bulk density		Y
Henry's Law[2]		
Partition coefficient of contaminants to soil	Y	
Fraction of organic carbon of soil (organic contaminants only)[1]	Y	
Organic carbon partition coefficient[1,2]		
Soil pH value (particularly for metals)	Y	
Contaminant properties including solubility and density[2]		

[1] For organic contaminants, the partition coefficient can be calculated from the fraction of organic carbon and the organic partition coefficient (see Table 5.3).
[2] Literature value will normally be sufficient.
* Parameters that are likely to have a major affect on the assessment due to the sensitivity of the calculation and/or because they may be characterised by a large range in parameter values are highlighted in bold.

Evaluation of results for Level 1

As subsequent analysis relies on the value(s) determined for pore water quality, it is important that the results of the Level 1 assessment are evaluated in respect to:

- the method for measurement of pore water and whether this is:
  - appropriate to the contaminant;
  - representative of site conditions.
- the reliability of the test results, e.g. were adequate measures undertaken to prevent volatile loss for leaching tests undertaken for VOCs;
- whether the observed concentrations reflect naturally high values (in which case remediation is likely to be inappropriate);
- the contaminant properties, in particular whether the calculated or measured concentrations exceed effective solubility limits (see also Section 6.3);
- whether the contaminant has by-passed the soil zone by flow along preferential pathways (e.g. fissures) and the main contamination is at, or below, the water table;
- whether hot spots of contamination are significant with respect to water resources. This will generally involve calculation of the mass loading of contaminant(s) at the water table (Level 2 assessment).
- the degree to which the remedial target concentration is exceeded. This may give an initial indication of whether Level 2 and 3 assessments are likely to conclude that remediation is required.
- whether the contaminated soil represents a long-term contaminant source, e.g. repeat leaching test results may indicate that contaminant concentrations reduce with time such that a declining source term could be considered (see Section 6.3);
- whether the contaminant is a List 1 substance such that the assessment may need to determine whether attenuation in the soil zone is sufficient to prevent the contaminant reaching the water table.

Although a direct comparison between pore water/leaching test data and the target concentration at the receptor requires little data, there can be wide variations in practice between the results of leaching tests, direct pore water analysis and calculated concentrations. The equations used to describe soil–water partitioning tend to be conservative and assume that all of the soil contaminant mass can take part in soil–water partitioning. It is preferable, therefore, to use more than one method of assessment and for the results to be compared in an attempt to:

- gain an understanding of the potential and actual contaminant mobility in the environment;
- improve the quality of the assessment.

Pore water contaminant concentrations, as measured from leaching tests, can be compared with the theoretical pore water concentration calculated using the equation given in Table 5.2. This comparison may be useful in evaluating the results obtained from these two methods.

A Level 1 assessment is conservative as no account is taken of dilution and attenuation, which may reduce contaminant concentrations along the flow path. Thus, soil contaminant concentrations often exceed the Level 1 remedial target. When interpreting the results of the assessment, it is important to consider whether exceedances are a result of historic polluting activities or reflect natural conditions. Concentrations of some inorganics – notably metals and ammonium – can be naturally high. It is recommended, therefore, that analyses should also be obtained for natural or uncontaminated soils.

An example of a Level 1 assessment is given in Table 5.5.

Table 5.5 Level 1 assessment – worked example

Soil contamination was identified at a former industrial site. Analysis of soil samples obtained from 10 trial pits identified elevated copper and zinc concentrations as follows:

Contaminant	**Soil concentration (mg/kg)**		
	Average	**Minimum**	**Maximum**
Copper	160	40	280
Zinc	24	5	35

The Environment Agency indicated that the site was located directly over an aquifer and within the Outer Source Protection Zone to a potable groundwater abstraction. In view of the potential risk to this source, a Level 1 assessment was undertaken.

Target concentrations based on the maximum admissible drinking water concentrations were agreed with the Environment Agency as given in the table below. No leaching tests were carried out and the remedial targets were calculated using a theoretical equation describing soil–water partitioning (see Table 5.1). Site-specific partition coefficients were derived by laboratory testing. The parameter values used to calculate the Level 1 remedial targets are also given in the table below.

Parameter			**Copper**	**Zinc**	**Source**
Target concentration	**C_T**	**mg/l**	**2**	**5**	Drinking water standard
Bulk density	ρ	g/cm^3	1.65	1.65	Soil measurement
Porosity: air-filled	θ_a	fraction	0.18	0.18	Based on particle size analysis
Porosity: water-filled	θ_w	fraction	0.05	0.05	Based on particle size analysis
Soil pH value			7.0	7.0	Soil measurement
Henry's Law constant	H		0	0	Not volatile
Partition coefficient	K_d	l/kg	4 000	420	Laboratory analysis following method given in Environment Agency 2005a

Example calculations to determine remedial targets (see Table 5.1)*:*

Remedial target concentration $= C_T\left(K_d + \frac{\theta_w + \theta_a H}{\rho}\right)$

RT_{copper} = $2\times\left(4000+\left(\frac{0.05+(0.18\times 0)}{1.65}\right)\right)$ = **8 000 mg/kg**

RT_{zinc} = $5\times\left(420+\left(\frac{0.05+(0.18\times 0)}{1.65}\right)\right)$ = **2 100 mg/kg**

Summary
The measured soil concentrations for copper (40–280 mg/kg) and zinc (5–35 mg/kg) are below their calculated remedial target concentrations of 8 000 mg/kg and 2 100 mg/kg respectively. No further action was considered necessary.

5.3 Level 2 assessment (attenuation in the unsaturated zone and dilution by groundwater flow below the source)

At Level 2, the analysis considers whether dilution of contaminants leached from the soil by groundwater flow below the site and attenuation of pollutants within the unsaturated zone are sufficient to reduce contaminant concentrations to acceptable levels.

The remedial target (RT) is determined by multiplying the target concentration by a dilution factor (DF) and/or unsaturated zone attenuation factor (AF_u), as given below:

$$RT = AF_U \times DF \times C_T \text{ (attenuation in unsaturated zone + dilution)}$$

or

$$RT = AF_U \times C_T \text{ (attenuation in unsaturated zone only)}$$

or

$$RT = DF \times C_T \text{ (dilution only)}$$

where:

DF = dilution factor

AF_U = attenuation factor (unsaturated zone)

C_T = target concentration

The assessment is likely to first consider the influence of dilution and may include attenuation only if remedial targets are exceeded. Excluding attenuation in the unsaturated zone from the assessment will result in a more conservative assessment and, if remedial targets are exceeded, this should be taken into account when deciding whether remediation is necessary.

The Level 2 calculation provides a remedial target for the soil which is less conservative than that derived at Level 1. The pore water or measured soil concentration is compared with this remedial target to establish the need for remediation to protect the identified receptor (see Table 5.1).

For Level 2, the compliance point is taken as groundwater beneath the source area (see Figure 2.3).

Dilution factor at the water table

The **dilution factor (DF)** can be calculated as the ratio between groundwater flow below the site (the source area) and infiltration through the contaminated soil. Table 5.6 gives examples of the equations that can be used to calculate the dilution factor.

Calculation of the dilution factor requires the conceptual model to incorporate an understanding of infiltration through the source zone and groundwater flow below the site. The model should also take account of the current situation and whether this may change as a result of site development (e.g. the effect of removing or adding areas of hardstanding).

Calculation of a dilution factor in a Level 2 assessment is included in the worked example shown in Table 5.7.

Attenuation factor (unsaturated zone)

Attenuation processes (retardation, biodegradation, etc.) may also affect the contaminant as it migrates down through the unsaturated zone to the water table.

The **unsaturated zone attenuation factor (AF_u)** is defined as the ratio of the pore water contaminant concentration in the soil and the predicted concentration at the base of the unsaturated zone as follows:

$$AF_u = \frac{C_p}{C_{uns}} = \frac{\text{pore water concentration}}{\text{contaminant concentration at base of unsaturated zone}}$$

The travel time for a contaminant to move down through the unsaturated zone can be significant, particularly for low infiltration rates and for a thick unsaturated zone where by-pass flow is limited. For contaminants that are readily sorbed onto the soil matrix, travel times can be of the order of hundreds or even thousands of years. For degradable contaminants, biodegradation may prevent any impact at the water table.

The conceptual model for the site should consider whether:

- processes within the unsaturated zone are likely to affect contaminant concentrations;
- such effects should be included in the assessment.

Numerical models are available which allow contaminant fate and transport in the unsaturated zone to be represented. For example, the ConSim model (Environment Agency 2003b) takes account of contaminant movement through the unsaturated zone, including the time for contaminants to reach the water table and degradation of contaminants. However, it is essential to be able to justify the modelling approach adopted and whether this provides an adequate representation of conditions at the site (see also Section 8.1).

If the unsaturated zone is considered in the assessment, then it is important to provide some validation through, for example:

- field data – to demonstrate a decrease in contaminant concentrations with depth. For most sites, this is likely to be limited to measurements of soil concentration with depth. Other approaches include pore water profiling;
- checks on groundwater monitoring data – the absence of a contaminant in groundwater may provide evidence that attenuation in the unsaturated zone is significant, though consideration should be given to whether the contaminant has yet to reach the water table.

Data requirements for Level 2

The data requirements for calculating a dilution factor are shown in Table 5.8. The calculation requires site-specific data on:

- hydraulic conductivity
- hydraulic gradient
- mixing zone thickness.

The hydraulic gradient can usually be defined with reasonable confidence from groundwater level monitoring boreholes. The aquifer thickness can also usually be defined from investigation boreholes. For thick aquifers, however, the mixing thickness is typically less than the total aquifer thickness. The mixing zone thickness can be defined where multiple depth monitoring boreholes have been constructed through the plume; otherwise, the

thickness may need to be estimated based on hydrogeological data or estimated using empirical equations (see Table 5.6).

The main uncertainty in the calculation of the dilution factor is likely to relate to hydraulic conductivity. This parameter can show marked vertical and lateral variation, with measured values often ranging by more than an order of magnitude. Hydrogeological expertise is, therefore, required to determine a realistic range of values to derive the dilution factor based on site measurements. One simple check is that the calculated groundwater flow is consistent with the amount of rainfall that could infiltrate to the water table over the groundwater catchment to the site.

The data requirements for determination of travel time and attenuation in the unsaturated zone are summarised in Table 5.8.

Table 5.6 Basic equations for calculating dilution factor (DF) for groundwater flow below the source

Standard analytical equations that can be used are given in the table below. This is not intended to be a definitive list, as other equations are available which may be more appropriate to a given situation.

DF calculated based on target concentration	DF calculated based on concentration of contaminant in contaminated discharge	Comment
$DF_{GW} = \frac{(K.i.M_z + L.Inf)C_T - (K.i.M_z.C_u)}{L.Inf.C_T}$	$DF = \frac{(K.i.M_z + L.Inf)C_C}{K.i.M_z.C_U + L.Inf.C_C}$	Background concentration included
$DF = 1 + \left(\frac{K.i.M_z.}{L.Inf}\right)$	$DF = 1 + \left(\frac{K.i.M_z}{L.Inf}\right)$	No allowance for background concentration

Mixing zone thickness

For a thin aquifer (typically <10 m), the mixing zone thickness (M_z) can be taken as the actual aquifer thickness. This is likely to be an unrealistic assumption for thick aquifers and the mixing depth may need to be based on field investigations or experience of similar sites, or estimated using the following equation (US EPA 1996):

$$Mz = \sqrt{0.0112.L^2} + da\left[1 - \exp\left(\frac{-L.Inf}{K.i.da}\right)\right]$$

(NB If M_z > da, then M_z = da)

where:

M_z = mixing zone thickness (m)
L = length of contaminant source in direction of groundwater flow (m)
da = aquifer thickness (m)
Inf = infiltration (m/d)
K = hydraulic conductivity (m/d)
i = hydraulic gradient
A = area of contaminant source (m^2) (A = L.w)
w = width of site (m)
C_C = concentration of contaminant in contaminated discharge (e.g. leaching test concentration) (mg/l)
C_T = target concentration (mg/l)
C_U = background concentration of contaminant in groundwater (mg/l)
exp = exponential

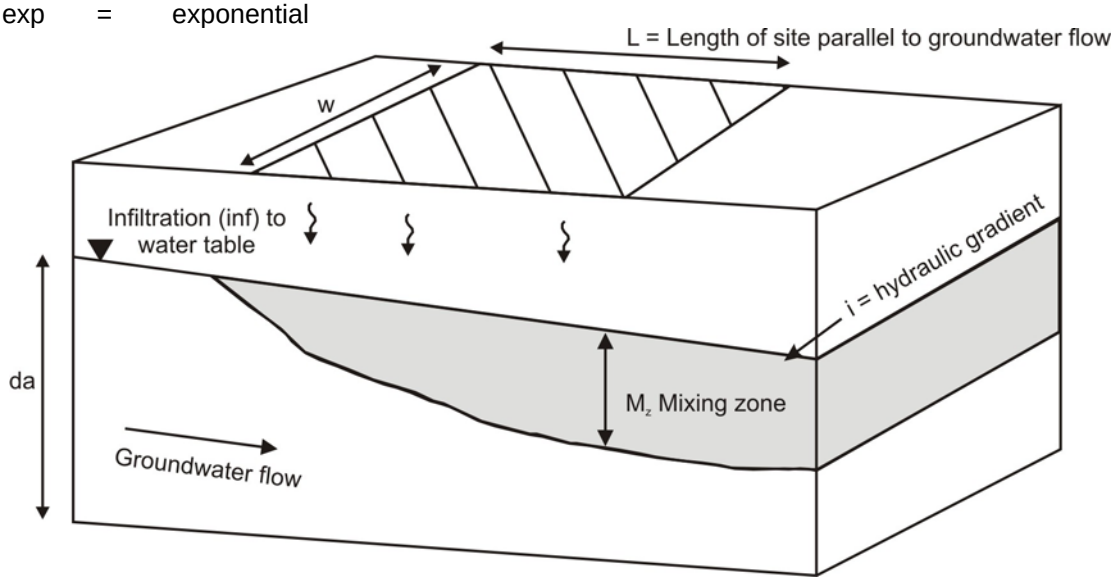


Table 5.7 Level 2 assessment - worked example for calculating dilution factor

Soil contamination was encountered at a former chemical works. Analyses of soil samples found elevated concentrations of the chlorinated solvent, tetrachloroethene (PCE), in part of the site. Soil leaching tests undertaken on five soil samples give contaminant concentrations of 0.1, 1.2, 0.3, 0.4 and 0.2 mg/l respectively.

The site is underlain by alluvial sands and gravels. There were no nearby licensed groundwater abstractions, but a good quality river was located about 80 m away. It was agreed with the Environment Agency that this river was at possible risk due to the leaching of PCE by water infiltrating through the soil down to the water table.

Level 1 assessment
A target concentration of 0.01mg/l (EQS for tetrachloroethene) was selected for the Level 1 assessment. All the leaching tests exceeded this target concentration, so there was a need either to upgrade the Level analysis or to implement remedial action. The estimated cost of remediation was significantly higher than the cost of further investigations and a Level 2 assessment was therefore undertaken.

Level 2 assessment (dilution)
Further investigations were undertaken to provide the necessary information to calculate groundwater dilution and to determine if any groundwater contamination had occurred. Five monitoring boreholes were drilled in and around the site. No evidence of groundwater contamination was identified. Aquifer parameters determined from the further investigations are given in the table below. The effective rainfall for the site was obtained from the Met Office. Approximately 25 per cent of the site is covered by hardstanding, with run-off routed to foul drains. The site drains were assumed to be 80 per cent efficient at preventing leakage and the infiltration factor was therefore taken as 80 per cent (i.e. 75 per cent plus 20 per cent of 25 per cent).

Parameter		Unit	Value	Source
Target concentration mg/l	C_T		**0.01**	EQS
Saturated aquifer (mixing zone) thickness	M_z	m	6	Field measurement
Hydraulic conductivity	K	m/d	140	Field measurement
Hydraulic gradient	i		0.005	Field measurement
Effective rainfall		m/d	0.0006	Met Office
Infiltration factor			80 %	Field data
Infiltration rate	Inf	m/d	0.00048	Calculated
Length of contaminated site, parallel to direction of groundwater flow	L	m	60	Field measurement

Example calculation

Dilution factor $$DF = 1 + \frac{K.i.Mz}{Inf.L} = 1 + \frac{140 \times 0.005 \times 6}{0.00048 \times 60}$$ = 147

Remedial target $$RT_{PCE} = DF.C_T = 147 \times 0.01$$ = **1.5 mg/l**

Summary

The dilution factor was calculated as 147, giving a Level 2 remedial target of 1.5 mg/l. All the leaching tests results fell below this target. Although this analysis indicated that no remedial action was necessary to protect the river, there is still a potential for groundwater below the site to be contaminated. As chlorinated solvents are classified as List 1 substances, continued monitoring is considered necessary to confirm that no deterioration in groundwater quality occurs, with the provision to implement remedial measures if required.

Table 5.8 Data requirements for Level 2 assessment

Parameter*	Site-specific data essential	Site-specific data preferable
DILUTION FACTOR		
Infiltration		
Area of contaminated soil	Y	
Effective rainfall	Y	
Percentage run-off due to, for example, presence of hardstanding	Y	
Groundwater flow		
Hydraulic conductivity	Y	
Hydraulic gradient	Y	
Saturated aquifer/mixing zone thickness	Y	
Source dimension relative to groundwater flow	Y	
Background groundwater quality	Y	
UNSATURATED ZONE		
Unsaturated zone thickness	Y	
Partition coefficient	Y	
Fraction of organic carbon (organic contaminants) in unsaturated zone	Y	
Degradation characteristics of contaminant	Y	
Bulk density of unsaturated zone material		Y
Water filled porosity		Y
Hydraulic conductivity		Y
Rock type	Y	

* Parameters that are likely to have a major affect on the assessment due to the sensitivity of the calculation and/or because they may be characterised by a large range in parameter values are highlighted in bold.

5.4 Level 3 assessment (attenuation down-hydraulic gradient of the source)

At Level 3, the assessment considers whether attenuation of pollutants down-hydraulic gradient of the source is sufficient to reduce contaminant concentrations to acceptable levels.

The remedial target is determined by multiplying the Level 2 remedial target concentration by a saturated zone attenuation factor (AF) (see Table 5.1)**.** This provides a remedial target for the soil which is less conservative than that derived at Level 2. The pore water or measured

soil concentration is then compared with this remedial target to establish the need for remediation to protect the identified receptor.

For Level 3, the compliance point is located between the source and the identified receptor; see Figure 2.2 and Section 5.4.

For some contaminants and aquifer settings, the time for a contaminant to reach the compliance point can be considerable (thousands of years). This time can be taken into account in the assessment as described in Section 5.5.

Attenuation factor (saturated zone)

Attenuation of contaminants can occur as a result of:

- degradation of contaminants, e.g. biological breakdown of organic substances;
- sorption of contaminants onto soil particles and the aquifer matrix;
- ion exchange;
- precipitation of inorganic compounds due to a change in the chemical environment;
- volatilisation of semi-volatile or volatile contaminants;
- dispersion of contaminants as they move through the aquifer.

The effect of these processes is to decrease contaminant concentrations along the pathway (Appendix C). Only degradation and volatilisation result in a reduction in the mass of contaminants in groundwater. In some cases, natural attenuation may be sufficient to protect the identified receptor without need for any remedial action.

The **attenuation factor** is defined as the ratio of the contaminant concentration in groundwater below the source to the calculated concentration at a point down-hydraulic gradient of the site (see Figure 5.1) as follows:

$$AF = \frac{C_0}{C_{ED}} = \frac{\text{contaminant concentration in groundwater below source}}{\text{predicted concentration of contaminant at compliance point}}$$

Examples of analytical equations that can be used to calculate the attenuation factor are given in Appendix D. These equations consider dispersion, retardation and degradation. Other analytical or numerical solutions may be equally, or more valid for certain hydrogeological situations (Domenico 1987, Environment Agency 2001b). The assessment should justify the basis for selecting the numerical solution (see Section 8.1).

The remedial target should be determined for steady-state conditions, such that for time variant analytical solutions, time should be set as a large number to represent steady state.

For many analytical solutions, the contaminant concentration, C_o, does not need to be known as the attenuation factor is determined as the ratio C_o/C_{ED}. Alternatively, the concentration can be calculated by dividing the soil pore water concentration (derived during the Level 1 assessment) by the dilution factor.

For degradable contaminants, the calculation of an attenuation factor is sensitive to the assumed rate of degradation. Thus it is essential that:

- the conceptual model for the site provides evidence that degradation is occurring;
- a realistic or conservative value is used and, where possible, this is based on field data (Environment Agency 2000a).

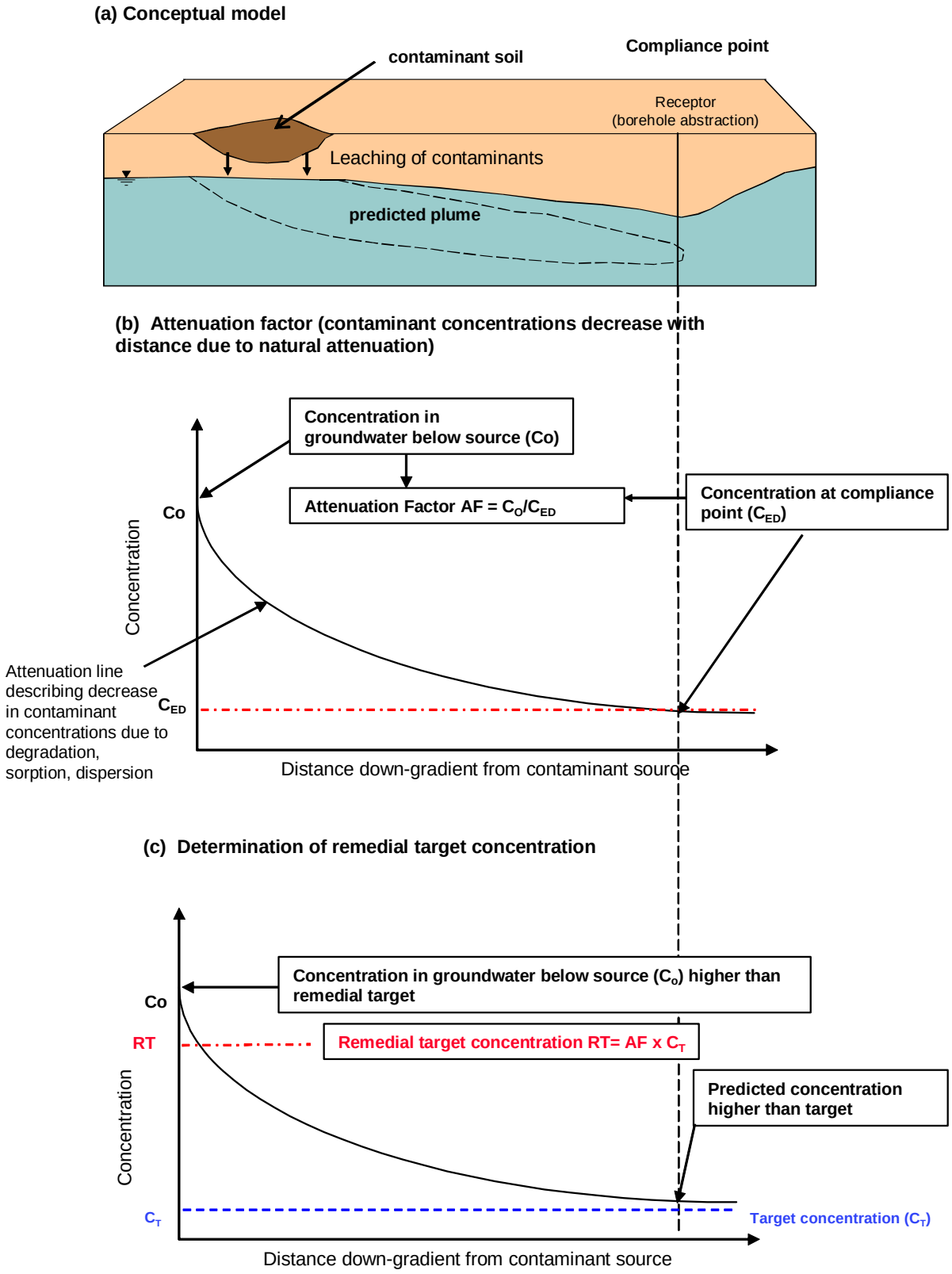


Figure 5.1 Determination of attenuation factor

The conceptual model should also consider the factors that may influence the rate of degradation. These include contaminant concentration, the geochemical environment (e.g. aerobic or anaerobic) and, in the case of degradation of oxidisable contaminants such as

benzene, the availability of oxidants such as dissolved oxygen, nitrate and sulphate (Environment Agency 2000a, 2002a).

Limited data are available on in-situ rates of biodegradation and many of these relate to shallow groundwater systems and may not be applicable to deeper systems. Where a literature-based decay rate is used, the rate should be:

- based upon a field observation from a natural system similar to the one in question;
- reviewed and agreed upon by the appropriate parties.

This is to safeguard against the use of too rapid a rate of biodegradation, which may result in overestimated remedial target concentrations and hence insufficient aquifer protection. For example, published values may relate to degradation under aerobic aquifer conditions, whereas the aquifer environment may be anaerobic. In that case, a different set of organisms are likely to be active and different degradation rates will apply. In the absence of approved degradation rates, degradation should be assumed to be negligible.

The majority of sources of information on degradation rates are for studies in North America and for shallow sand and gravels. These rates may not be appropriate to UK aquifers or to UK climate conditions (e.g. temperature). However, they provide an initial indication of a plausible range in degradation rates and whether the contaminant would be expected to degrade. Literature values should also be checked as to whether the degradation rate refers to laboratory experiments where degradation may have been determined only for the dissolved phase or to field-based studies.

Guidance on assessing natural attenuation degradation is given in Environment Agency (2000a). Rates of degradation for some contaminants are published in other Environment Agency reports for a range of geochemical environments and aquifer settings (Environment Agency 2002a, 2003c, 2004). Again, the degradation rate used in the assessment must be justified.

Most analytical models assume that degradation can be represented as a first order reaction (e.g. exponential decay of contaminant degradations). This assumption will need to be justified based on the conceptual understanding of the site and particularly where degradation may be inhibited due to the geochemical environment. In some cases, a first order reaction is not appropriate for representing the degradation of organics as degradation may be rate-limited and dependent on contaminant concentration and/or the availability of electron acceptors. An example of an analytical solution that relates degradation to the availability of oxidants (dissolved oxygen, nitrate and sulphate) is included in Appendix D.

The assessment must also consider any breakdown products and whether these pose an additional risk to receptors. If so, remedial targets should also be derived for these breakdown products. For example, vinyl chloride is a breakdown product of tetrachloroethene.

The contaminant may also be retarded as it migrates from the source to the receptor. Depending on the hydrogeological setting and contaminant properties, the time for breakthrough at the receptor can be considerable. This issue is considered in Section 5.5.

The worked example shown in Table 5.9 includes the calculation of an attenuation factor.

Table 5.9 Level 3 assessment (attenuation) – worked example

Organic liquor had previously been stored in two unlined storage lagoons covering an area of 5,000 m^2. This practice was discontinued and the lagoons drained. Sampling of soils below these lagoons found high levels of contamination by benzene, with soil concentrations of 400–3 200 mg/kg. The lagoons are located over a sand and gravel aquifer, with groundwater flow to a good quality river located 100 m from the site.

Level 1 assessment
Soil leaching tests were undertaken on 12 samples, with toluene concentrations in the leachate ranging from 5 to 65 mg/l (average concentration 30 mg/l). The EQS for benzene of 0.03mg/l was set as the target concentration. The leaching test results all exceeded this value. It was agreed with the Environment Agency that dilution and attenuation would potentially be significant processes in reducing contaminant concentrations as groundwater moves from the site towards the river. Therefore, the assessment was upgraded to include both Level 2 and Level 3.

Level 2 and 3 assessment
Further site investigations (including construction of monitoring boreholes) were undertaken to determine the direction of groundwater flow, the hydraulic gradient, the saturated thickness and hydraulic conductivity of the sand and gravel aquifer. Sampling of the monitoring boreholes indicated that some groundwater contamination had occurred. The remedial target concentration was derived taking account of attenuation and dilution as shown in the example calculations below. The parameter values used to derive the dilution factor (DF) and the attenuation factor (AF) are given in the table below:

Parameter		Unit	Value	Source
Target concentration	**C_T**	**mg/l**	**0.03**	**EQS**
Source length	L	m	40	Field measurement
Source width	S_z	m	125	Field measurement
Infiltration	Inf	m/d	0.003	Met. Office
Mixing zone/initial plume thickness	M_z/Sy	m	5	Field measurement
Hydraulic conductivity	K	m/d	25	Field measurement
Hydraulic gradient	i		0.01	Field measurement
Porosity	n		0.15	Estimated
Bulk density	ρ	g/cm^3	1.65	Laboratory measurement
Decay constant	λ	d^{-1}	0.0019	Calculated using literature value for half life of 365 days
Distance to compliance point	x	m	100	Field measurement
Dispersivity (longitudinal)	a_x	m	10	Assumed 10 % of pathway length
Dispersivity (transverse)	a_z	m	1	Assumed 10 % of longitudinal dispersivity
Dispersivity (vertical)	a_y	m	0.0001	Set as small value as thin aquifer
Partition coefficient	K_d	l/kg	5.7	Average of five batch test results

Note: the initial concentration C_o does not need to be known for this example as the attenuation factor can be calculated from the ratio C_o/C_{ED}

Dilution factor (refer to Table 5.6)

$$DF = 1 + \frac{K.i.M_z}{Inf.L} = 1 + \frac{25 \times 0.01 \times 5}{0.003 \times 40} = 11.4$$

Level 2 remedial target

$$= DF \times C_T = 11.4 \times 0.03 = 0.34 \text{ mg/l}$$

Benzene concentrations derived from the soil leaching tests (5–65mg/l) exceed this remedial target, so the assessment proceeded to Level 3.

Table 5.9 (continued)

Attenuation factor (refer to Tables D2 and D3, Appendix D)

The calculation steps are as follows:

Retardation factor, $R_f = \left(1 + \frac{K_d . \rho}{n}\right) = 1 + \frac{5.7 \times 1.65}{0.15} = 63.7$

Rate of contaminant movement, $u = \frac{K.i}{n.R_f} = \frac{25 \times 0.01}{0.15 \times 63.7} = 0.026 m/d$

Calculated concentration (C_{ED}) at compliance point using the Domenico equation (Table D3):

$$C_{ED} = C_0 \exp\left\{\frac{x}{2a_x}\left(1 - \sqrt{\left[1 + \frac{4\lambda a_x}{u}\right]}\right)\right\}.erf\left\{\frac{S_y}{2\sqrt{a_y x}}\right\}.erf\left\{\frac{S_z}{4\sqrt{a_z x}}\right\}$$

$$C_{ED} = C_0 \exp\left(\frac{100}{2 \times 10}\right)\left[1 - \sqrt{\left(1 + \frac{4 \times 0.0019 \times 10}{0.026}\right)}\right] \times \text{erf}\left(\frac{5}{2\sqrt{0.0001 \times 100}}\right) \times \text{erf}\left(\frac{125}{4\sqrt{1 \times 100}}\right) = 0.0076 \times C_0 mg/l$$

Since attenuation factor (AF) = C_0/C_{ED}

= $C_0/(0.0076 \times C_0)$ (substituting for C_{ED} from the Domenico equation)

AF = 1/0.0076

AF = **131**

The Level 3 remedial target (RT) was calculated as follows:

RT = AF × DF × C_T

= 131 × 11.4 × 0.03 = **44.8 mg/l**

Summary

The remedial target value of 45 mg/l (leachable benzene in soils) lies within the observed range of benzene concentrations from leaching tests (5–65 mg/l). Consequently, remedial action was considered necessary to treat the most contaminated areas of the site. In addition, a groundwater monitoring scheme was implemented to provide confirmation that residual contamination in groundwater would not pose an unacceptable risk to the river. This was considered more cost-effective than undertaking further detailed investigation and assessment.

Location of compliance point and calculation of attenuation factor

General guidance on the selection of the compliance point is given in Section 4.3.

The location of the **compliance point** has a major impact on the derivation of the attenuation factor and the remedial target concentration. The further the compliance point is set from the site, the greater the attenuation factor and hence the higher the remedial target. This is illustrated in Figure 5.2 and is particularly the case for degradable contaminants. The effect of degradation on the calculated remedial target depends on:

- the distance to the compliance point;
- hydraulic conductivity;

- effective porosity;
- hydraulic gradient.

These parameters determine the time of travel and hence the time for degradation processes to occur.

The recommended approach is to calculate contaminant concentrations at various locations downgradient of the source for different assumed positions of the compliance point.

This information can be used to determine the influence of variations in the position of the compliance point on:

- the remedial target;
- the potential contaminant concentrations in the aquifer.

The results can then be used to agree a compliance point location based on a balance between protecting the resource and setting a target that can be realistically achieved (as discussed in Section 4.3).

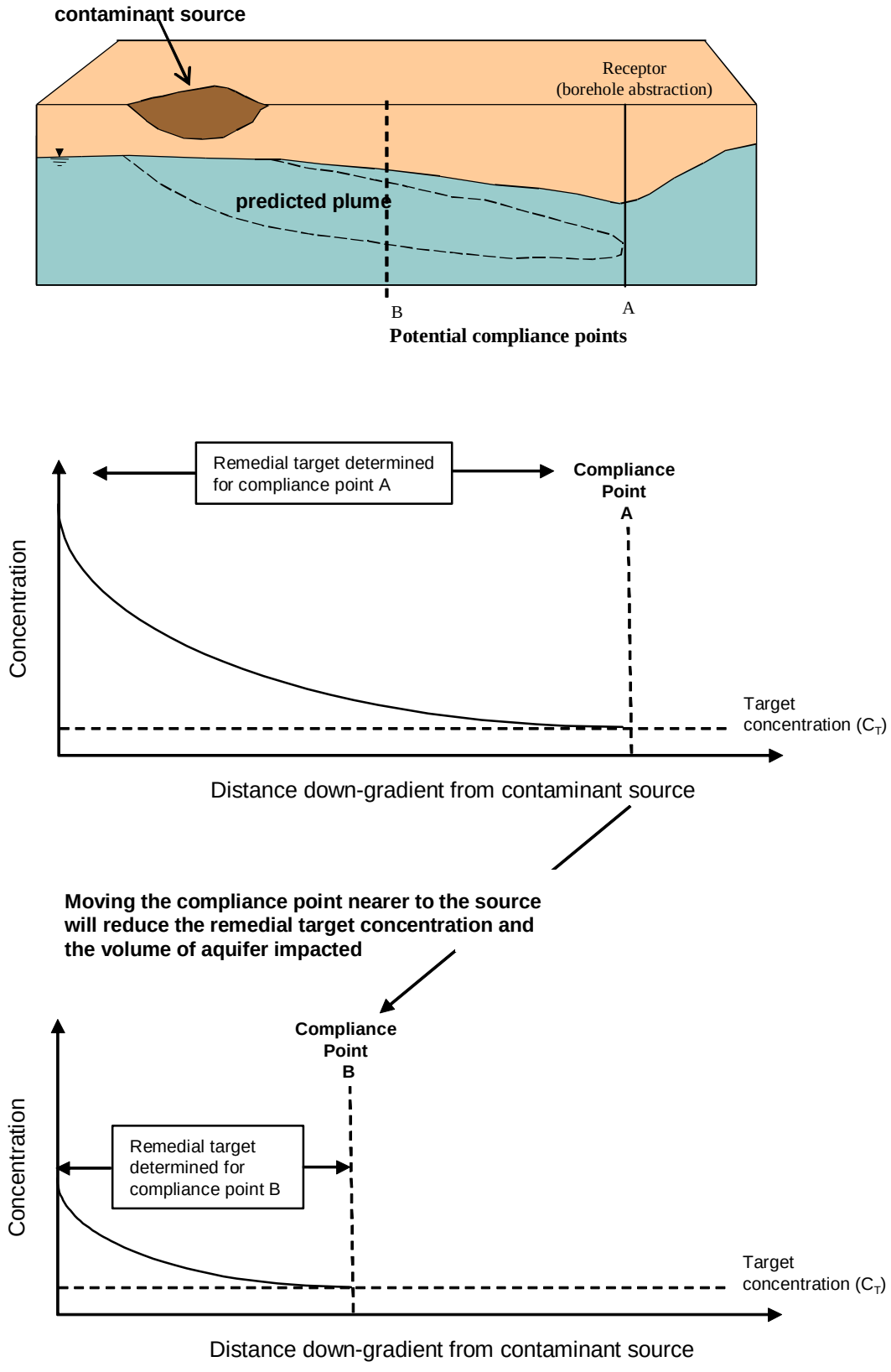


Figure 5.2 Influence of changing location of compliance point on calculated remedial target

Data requirements for calculation of attenuation factor

The data requirements typically required for determination of the attenuation factor are summarised in Table 5.10. However, due to the range of processes that can result in attenuation, this is not a definitive list.

In developing a conceptual model for the site, it is essential to identify:

- what processes are occurring;
- whether these are significant;
- what data are required to characterise the process.

Table 5.10 Data requirements for calculation of attenuation factor

Parameter*	Site-specific data essential	Site-specific data preferable
Source width and depth	Y	
Distance to compliance point	Y	
Degradation characteristics of contaminant (appropriate to site conditions)	Y	
Effective porosity		Y
Dispersivity		Y
Partition coefficient – saturated zone	Y	
Fraction of organic carbon (organic contaminants) in aquifer	Y	
Organic carbon partition coefficient (organic contaminants only)[1]		
Hydraulic conductivity	Y	
Hydraulic gradient	Y	
Bulk density		Y

[1] Literature value will normally be sufficient.
*Parameters that are likely to have a major affect on the assessment due to the sensitivity of the calculation and/or because they may be characterised by a large range in parameter values are highlighted in bold.

5.5 Evaluation of time for contaminant to arrive at the compliance point

Determination of the remedial target concentrations should initially be based on steady-state or equilibrium conditions, i.e. an infinite amount of time is allowed for the contaminant to reach the compliance point.

In practice, there will be a delay for the contaminant to reach the compliance point. This delay will be function of:

- hydraulic conductivity;

- hydraulic gradient;
- effective porosity;
- dispersion;
- retardation of the contaminant due to interaction with the aquifer matrix;
- the distance to the compliance point.

It is recommended that the assessment should also determine:

- the expected time for contaminants to move through the aquifer system to reach the compliance point;
- the time before steady-state conditions are established.

This information is useful in terms of establishing the urgency of any remedial actions and in planning any monitoring programme (see Section 9.3).

For some low flow groundwater systems and for contaminants which are characterised by a high partition coefficient (e.g. some polycyclic aromatic hydrocarbon (PAH) compounds), the rates of contaminant movement can be slow (centimetres per year). Thus, there may be a considerably delay (tens or even thousands of years) before the contaminant reaches the compliance point.

In these cases, it may be acceptable for no action to be taken even if the remedial target is exceeded. However, this approach is only likely to be acceptable when the impact of the contamination is localised to the area around the source (i.e. within metres or tens of metres of the source). Travel times will normally need to exceed 1,000 years before this case can be considered.

A decision not to implement remediation based on travel time will require the following supporting information:

- estimate of travel time to the compliance point (taking into account dispersion);
- demonstration that no rapid pathways exist, i.e. the pathway is well characterised;
- estimate of peak concentrations at the receptor. In many cases highly sorbed contaminants are characterised by low solubilities such that peak concentrations may be low;
- consideration of any reasonable changes in mechanism of source release, e.g. will this change in the future;
- adequate definition of contaminant properties, e.g. partition coefficient;
- time for breakthrough against longevity of source, e.g. will the source be exhausted before breakthrough occurs;
- demonstration that the impact on the aquifer away from the source is localised, i.e. limited to a few metres or tens of metres;
- sensitivity of aquifer and potential for development of the affected area in the future.

Analytical models and/or numerical models can be used to determine the rate at which a contaminant moves through the aquifer and the time before steady state conditions are established.

5.6 Review of Level 2 and 3 assessment

A summary of the factors that need to be considered in reviewing a remedial target assessment for soils and groundwater is given in Chapter 9. Such a review for Level 2 and 3 should also consider the following additional factors:

- any substances that may result from chemical or biological breakdown of the contaminant;
- time for breakthrough at the compliance point or receptor;
- whether the methods and or numerical solutions adopted are appropriate to the site (see Section 8.1);
- whether setting a remedial target based on a downgradient compliance point offers adequate protection to the receptor;
- whether degradation rates are appropriate to the site and can be justified based on site-specific data;
- whether the assessment has been conservative by excluding attenuation in the unsaturated zone and dilution at the receptor.

A simple check that should be undertaken is that the calculated remedial target does not exceed the solubility limit for the contaminant. In this case, remediation of the soil would be unnecessary to protect water resources, although free product may still represent a risk of forming explosive vapours or unacceptable human exposure.

Where the assessment shows that the remedial target is exceeded only at contaminant hot spots within the site, the risk analysis should be extended to determine if the total contaminant loading from the site would be sufficient to impact on the identified receptor. This analysis may identify that action is not necessary to protect the water resource.

By introducing attenuation into the assessment and moving the compliance down-hydraulic gradient of the source, a Level 3 evaluation implies that groundwater quality down-hydraulic gradient of the site can deteriorate as illustrated in Figure 5.1. One example is that, while there may be no effect at the identified receptor (which may be a groundwater abstraction), groundwater quality may be affected for some distance downgradient of the site. The acceptability of this will need to be assessed in relation to the cost and achievability of remediation against environmental protection (see Chapter 9).

The selection of a compliance point between the receptor and the source can, however, provide a realistic solution in terms of providing a balance between protecting the water resource and making use of natural attenuation processes. Further guidance on the selection of the compliance point is given in Sections 4.3 and 5.4.

5.7 Level 4 assessment (receptor)

Dilution at the receptor

At Level 4, the compliance point is taken as a specific receptor such as an abstraction, a groundwater-dependent surface water body or a spring.

In this case, dilution at the receptor can be taken into account in the assessment. This assumes that the receptor intercepts or receives all of the groundwater flow below the site. The conceptual model should demonstrate that there is a pollutant linkage between the site and receptor.

For receiving streams, attenuation in the hyporheic zone (river bed sediment) can also be taken into account where this is supported by field data. As a minimum, this should be the presence and nature of bed sediment.

Research has shown that increased attenuation of certain pollutants can occur in riparian and hyporheic environments as a result of:

- steep chemical and hydraulic gradients;
- greater organic content (than the adjacent aquifer);
- a dense and more readily replenished microbial population.

The higher organic carbon content in riparian/hyporheic zones may cause oxygen depletion and result in reducing conditions. Studies have shown increased nitrification and reduction of other reducible pollutants (Hill 1996, Puckett 2004, Smith 2005). Similarly, higher organic carbon and clay mineral content in alluvial sediments may increase retardation (sorption) of pollutants (Smith 2005). However, the riparian and hyporheic zones are typically highly heterogeneous and relatively thin. Pollutant movement times may be small and variable. Investigations of natural attenuation processes at the groundwater surface water interface will need to establish (Brunke *et al.* 1997, Smith 2005):

- the attenuation process;
- the effects of heterogeneous flow on pollutant residence time;
- the impact on hyporheic and stream ecology

The remedial target is determined by multiplying the target concentration by a dilution factor appropriate to the receptor and an attenuation factor as follows:

$$RT = AF \times DF_R \times C_T \text{ (attenuation along flow path + dilution in receptor)}$$

or

$$RT = DF_R \times C_T \text{ (dilution in receptor only)}$$

where:

DF_R = dilution factor for receptor (dilution by groundwater flow cannot be taken into account);

AF = attenuation factor (this may include attenuation in unsaturated zone, saturated zone and/or hyporheic zone);

C_T = target concentration.

The dilution factor is determined by the ratio of infiltration through the contaminated soil to either the groundwater abstraction or the stream flow (see Table 5.11). This approach provides a less conservative remedial target, particularly for a large abstraction or a high stream flow. This represents a special case.

Dilution in the receptor can **only** be taken into account where:

- the impact of groundwater contamination on the aquifer between the source and the receptor has been assessed;
- the impact does not prevent current or future use of the aquifer;
- the predicted impact on the receptor does not result in:
  - any measurable deterioration in water quality;
  - exceedance of environmental standards;
  - failure to achieve objectives.

The assessment should be supported by a cost-benefit assessment (see Section 9.2). This needs to demonstrate that the remediation measures that could be required by setting a lower remedial target because dilution at the receptor has been excluded from the assessment are prohibitive in relation to the resulting environmental benefit, i.e. no significant improvement in water quality.

Cases where taking dilution in the receptor into account is unlikely to be acceptable are where:

- groundwater between the source and receptor has not yet been impacted;
- the aquifer has a high resource value;
- the current level of groundwater or surface water contamination is unacceptable.

For receiving streams, the dilution factor should be calculated for low flow – typically the flow exceeded 95 per cent of the time (Q95 flow). In addition, the assessment should also consider:

- the total contaminant loading to the stream;
- if there is any evidence of an impact on surface water quality that could be attributed to the site. This should include consideration of the site proximity, history and whether an impact is expected to have already occurred.
- whether any impact would be detectable, i.e. the contaminant loading is low in relation to flow in the stream;
- upstream surface water quality (this may reduce the amount of dilution available in the stream);
- impact on surface water quality of other contaminant sources. If a environmental standard such as an EQS is used as a basis for setting the target concentration, then setting the target concentration as 10 per cent of the standard is recommended as this would provide a more conservative assessment.
- the significance of the attenuation of contaminants in river sediments and the variability in the type of sediments present.

Although dilution in a groundwater abstraction can be taken into account when assessing the significance of groundwater pollution, dilution in this receptor should not be used to derive remedial targets. This is because the calculated dilution factor will depend on the abstraction rate, i.e. it could decrease.

A ‘do nothing’ outcome from a Level 4 assessment implies that dilution of contaminants in the environment is sufficient to mitigate adverse effects. This is not necessarily applicable in all cases as certain substances may accumulate in sediments and biota (or aquifer-based particles) forming a sink for future contaminant leaching and, possibly, adverse ecological or human health effects.

Table 5.11 Basic equations for calculating dilution factor (DF) for receptor

Standard analytical equations that can be used are given below. This is not intended to be a definitive list, as other equations are available which may be more appropriate to a given situation.

DF calculated based on target concentration	DF calculated based on concentration of contaminant in contaminated discharge	Comment
Receiving stream		
$DF_{River} = \frac{(Inf.A + Q_u)C_T - (Q_u.C_u)}{Inf.A.C_T}$	$DF = \frac{(Inf.A + Q_U)C_C}{Inf.A.C_C + Q_U.C_U}$	Background concentration included
	$DF = \frac{Inf.A + Q_U}{Inf.A}$	No allowance for background concentration
Spring or groundwater abstraction		
$DF_{Abs} = \frac{Q_A.C_T - C_u(Q_A - Inf.A))}{Inf.A.C_T}$	$DF = \frac{Q_A.C_C}{Inf.A.C_C + C_U(Q_A - Inf.A)}$	Background concentration included
	$DF = \frac{Q_A}{Inf.A}$	No allowance for background concentration

where:

Inf = infiltration (m/d)
Q_A = spring discharge or abstraction rate (m^3/d)
A = area of contaminant source (m^2)
Q_U = surface water flow upstream of discharge point under low flow conditions (m^3/d)
C_C = concentration of contaminant in contaminated discharge (e.g. leaching test concentration) (mg/l)
C_T = target concentration (mg/l)
C_U = background concentration of contaminant in receiving water (mg/l)

6. Remedial target assessment - groundwater

6.1 Introduction

This chapter provides a description of each of the assessment Levels used to derive remedial targets for contaminated groundwater in order to protect the identified groundwater or surface water receptor.

It is assumed that the soil does not present a problem, i.e. the contaminant has by-passed the soil zone or the original soil contamination has been removed. Thus, the only processes of significance are attenuation, dispersion and dilution in the saturated zone between the identified source of contaminated groundwater and the receptor.

Some of the steps described in the previous chapter on the assessment for soils are repeated. These are not described in detail (references are given to the appropriate parts of Chapter 5). Chapter 7 outlines how to deal with both contaminated soil and groundwater.

The approach in this chapter relies on comparing contaminant concentrations in groundwater with the remedial target to establish the need for remediation (see Figure 2.3).

In setting a remedial target for groundwater, it is important to consider whether remediation to this standard is achievable or cost-beneficial. Experience with pump-and-treat systems indicates that it is not generally possible to return groundwater to background quality. For this reason, the target concentration is usually set at an environmental standard appropriate to the use of the aquifer rather than as background quality (see Section 4.2, Figure 4.1).

This chapter also describes the approach that should be adopted for:

- free product or non-aqueous phase liquids (NAPLs);
- for the case where the assessment needs to take account of a decline in the contaminant source term.

6.2 Level 2 (groundwater below source)

At Level 2, the remedial target is set as the target concentration at the receptor (see Figure 2.3). Observed contaminant concentrations in monitoring boreholes within the plume of contaminated groundwater are compared with this target concentration to determine the need for further action.

The compliance point will typically be groundwater below the site but, in some cases, the plume of contaminated groundwater will have migrated beyond the site boundary. This possibility needs to be considered in the assessment, particularly if the off-site plume is suspected of containing higher contaminant concentrations.

Definition of the contaminant plume forms an important part of the assessment in determining maximum contaminant concentrations. This work will be a function of:

- the number, location and construction of the monitoring boreholes;
- the complexity of the hydrogeological regime (the plume may be diving such that the boreholes may miss the centre of the plume);

- the nature and distribution of the contaminant. For example, if the contaminant is a light non-aqueous phase liquid (LNAPL), are the boreholes screened at the water table and is the risk associated mainly with movement of the free product or due to dissolution and migration by groundwater?
- the history of contamination and contaminant movement. For example, the plume may have already moved beyond the site boundary or a number of separate contaminant pollution releases may have occurred.

The observation borehole network should be sufficient density to:

- allow the geometry of the contaminant plume to be defined with confidence;
- ensure that the maximum contaminant concentration relates to a point in the centre rather than the perimeter of the plume.

It will be necessary to justify the basis for the monitoring network and whether it is of sufficient density to define the problem or whether further boreholes are required.

In practice, the geometry of contaminant plumes can be complex and, for many sites, there will be insufficient boreholes to define the contaminant plume with certainty – particularly when borehole locations are constrained by existing buildings and services.

Expert judgement is required in determining the distribution of contaminants in groundwater. This assessment can be aided through the application of mathematical models to help understand the likely extent of a contaminant plume.

In general, the maximum observed groundwater concentration in the plume should be compared with the remedial target.

- If the concentration exceeds the target, remedial action or Level 3 assessment will be required (probably including further site investigation).
- If the concentration is below the target, further monitoring will be necessary to show that it is not exceeded in the future.

The next stage in the assessment is to determine what proportion of the plume exceeds the remedial target. Assessments can then be made of the volume of groundwater requiring treatment or whether attenuation along the flow path is sufficient to protect the identified receptor (e.g. Level 3 assessment).

The assessment requires a high level of technical expertise in:

- interpreting the field data;
- deciding if further information are required;
- determining a realistic maximum contaminant concentration for comparison with the remedial target concentration.

6.3 Level 3 (attenuation downgradient of source)

At Level 3, the assessment takes account of the potential attenuation as contaminated groundwater moves off-site to the receptor. The Level 3 remedial target concentration for groundwater is derived by multiplying the target concentration at the receptor or compliance point by the attenuation factor (see Figure 5.1). Observed contaminant concentrations within the plume of contaminated groundwater are compared with this remedial target.

The **attenuation factor (AF)** is defined as the ratio of the contaminant concentration in groundwater to the calculated concentration at a point down-hydraulic gradient of the source, as follows:

$$AF = \frac{C_0}{C_{ED}} = \frac{\text{contaminant concentration in groundwater below source}}{\text{target concentration of contaminant at compliance point}}$$

The compliance point is located down-hydraulic gradient of the source. This may be:

- an identified receptor (e.g. a groundwater abstraction);
- an actual or virtual borehole located between the source and the receptor.

The procedure for setting a compliance point is described in Sections 4.3 and 5.4.

The general approach to calculating the attenuation factor is described in Section 5.4. It involves the use of an appropriate analytical or a numerical fate and transport model to predict contaminant concentrations downgradient of the source as a result of dispersion, retardation and degradation. Examples of analytical solutions are given in Appendix D; however, other solutions or models may be more appropriate to the problem. In addition, the choice of modelling approach will need to be justified (see Section 8.1).

As part of the assessment and to verify the analysis, contaminant concentrations in groundwater downgradient of the site should be compared with modelled concentrations. Model parameter values should be modified (within a range consistent with field measurements) to provide the closest fit with the observed data. Agreement between model and observed data will allow greater confidence to be attached to the remedial target. This type of analysis is important for degradable contaminants to provide field confirmation of the rate of degradation used in the assessment.

If the monitoring network is adequate and variations in contaminant concentration with time have been measured, the significance of degradation can be assessed according to the type of plume (see Figure 6.1):

1) **Shrinking plume** where contaminant concentrations in monitoring boreholes decrease with time. In this case, the rate of contaminant movement is exceeded by the rate of degradation, and indicates depletion in the contaminant source. The observed groundwater contamination is unlikely to represent a risk to downgradient receptors and further remediation is unlikely to be required.

2) **Stable plume** where contaminant concentrations in monitoring boreholes do not change with time. The rate of contaminant movement is balanced by the rate of degradation. The assessment should concentrate on determining whether additional measures are required (e.g. treatment of the source or contaminated groundwater) to reduce contaminant concentrations in groundwater to an acceptable level. Remedial targets may need to be derived.

3) **Expanding plume** where contaminant concentrations in monitoring boreholes increase with time. In this case, the rate of contaminant movement exceeds the rate of degradation and the plume will continue to expand and may therefore pose a risk to the receptor. Remedial targets will need to be derived to determine the level of remediation required.

For the majority of the sites, there is likely to be insufficient information to determine plume behaviour (several years of monitoring data are normally required) and remedial targets will need to be derived.

Unless the assessment needs to consider a declining source term (see below), the remedial target should be calculated assuming a steady-state condition.

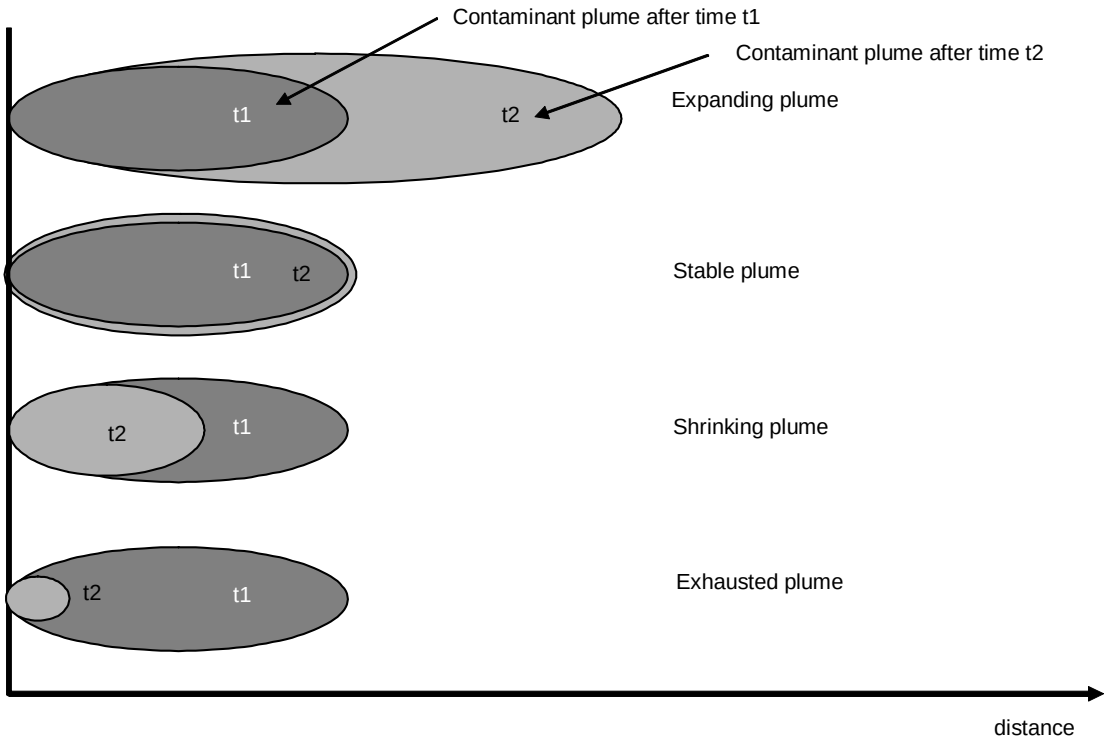


Figure 6.1 Types of plume behaviour

Free product or NAPL

A common problem is where the source of contamination is free product that is:

- floating on the water table (LNAPL);
- residual NAPL in the aquifer;
- denser material present below the water table, i.e. dense non-aqueous phase liquid (DNAPL).

The free product may represent:

- a direct risk to the receptor via its movement through the saturated zone;
- an indirect risk due to the solution of organics and their subsequent transport (dissolved phase) to the receptor.

The assessment will need to consider both cases. If free product is considered to represent a direct risk to an identified receptor, then remedial action will generally be required. Where solution and transport by groundwater needs to be assessed, then a remedial target is determined for groundwater in direct contact with the free product.

The assessment should consider whether the concentrations of contaminants in the dissolved phase are of sufficient magnitude to pose a risk to downgradient receptors. If the remedial target is exceeded, then remediation is likely to require a combination of NAPL recovery and groundwater control and/or treatment.

The dissolved concentration in groundwater can be determined by one of the following methods:

- observed concentration in groundwater immediately downgradient of the free product (representative sampling of groundwater through a layer of free product is difficult);
- measured concentration from leaching tests undertaken on NAPL samples;

- calculated using Raoult's Law (see Table 6.1).

Table 6.1 Raoult's Law

Raoult's Law allows the dissolved phase concentration of an organic in water in contact with the NAPL sample to be calculated as follows:

$$C_d = S \times X$$

where:

C_d	=	dissolved phase concentration in groundwater (mg/l)
S	=	pure phase (liquid) solubility of organic compound (mg/l) (usually obtained from literature sources)
X	=	molar fraction of organic contaminant in free product or NAPL (obtained from laboratory analysis of free product)

Alternative mathematical techniques (e.g. ASTM 2002) are available to determine the dissolved phase concentrations of organics in groundwater that is in contact with NAPL.

At Level 2, the dissolved contaminant concentrations (as determined above) are compared with the target concentration.

At Level 3, attenuation of the dissolved phase is taken into account (degradation is likely to be a significant factor for organic contaminants) and the attenuation factor calculated as described in Section 5.4.

The Level 3 assessment should also consider depletion of the source (see below). For example, if the source of the free product (e.g. a leaking solvent tank) has been removed, then the volume of free product would be expected to reduce with time due to dissolution into groundwater. But for large spills, this may take many years to occur and other processes such as volatilisation and degradation of the free product are probably more significant. For low solubility substances such as coal tar, source depletion will take many years and other processes may be negligible.

Particular care should be taken in interpreting data relating to the presence of NAPL due to the difficulties associated with:

- representative sampling and laboratory analysis;
- the presence of co-solutes;
- non-equilibrium conditions between the NAPL and water phases. The concentration of organics in the NAPL phase and hence in the dissolved phase can vary with time as a result of preferential solution of the more soluble organics.

Close liaison between those undertaking sampling, analysis and the assessment itself is particularly important when free product is involved.

Further guidance on dealing with NAPLs is given in Environment Agency R&D Publication 133 (Environment Agency 2003d).

Constant or declining source term

The assessment should initially assume a constant source term. Provided no further contamination occurs, this will represent a conservative assumption. However, there are cases where the source term may change including:

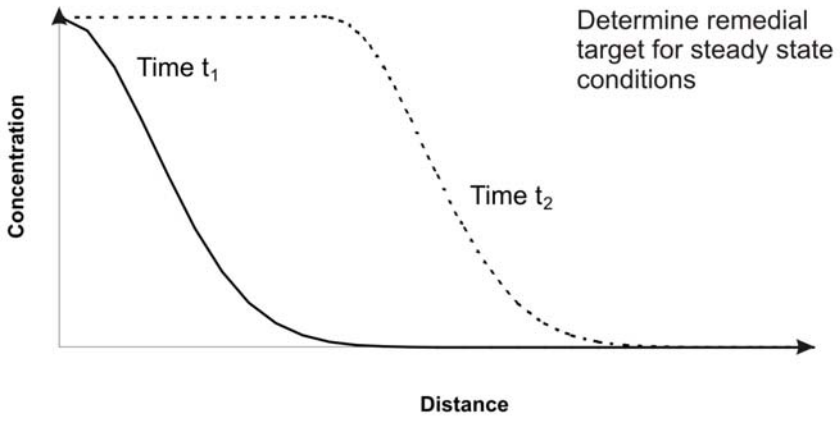
- depletion in the source term with time. For example, once the source of contamination (e.g. a leaking storage tank) is removed, then the concentration of the contaminant in the soil zone will reduce with each successive flushing by rain water infiltrating through the soil. Repeated soil leaching tests on soil samples may demonstrate a decline in the contaminant source with each flushing.
- the contaminant source was of finite volume, e.g. single fuel spill;
- physical removal of the source term;
- degradation of the source;
- change in the volume of water infiltrating through the soil, e.g. due to placement of a low permeability layer over the area of contamination.

If a decline in the source term can be demonstrated (e.g. through repeat leaching tests or mass balance calculations), then a declining source term can be incorporated into the assessment.

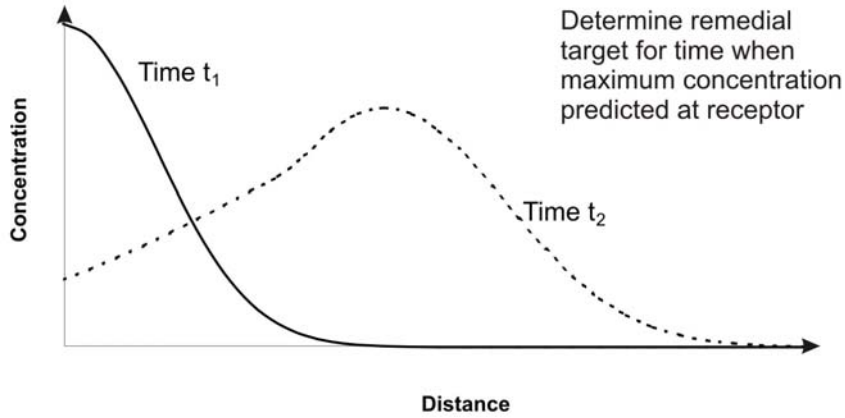
The equations described in Appendix D assume a **constant source term** (see Figure 6.2) for the contaminant. Some analytical techniques (Environment Agency 2003b) and most numerical models allow for changes in the source term to be taken into account.

For a **declining source term** (see Figure 6.2), the recommended approach is to calculate the variation in contaminant concentration with time at the compliance point. This would be expected to increase to a maximum value before declining. If calculated concentrations at the compliance point do not exceed the target concentration, no action is required. If the target concentration is exceeded, then action is likely to be required. The attenuation factor can be calculated as the ratio of the contaminant concentration at the source and the peak concentration at the compliance point.

Constant Source Term



Declining Source Term



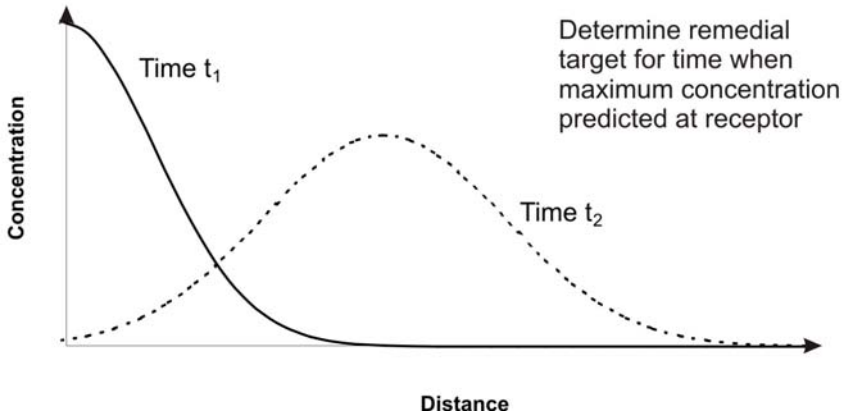


Figure 6.2 Types of source term

The assessment should also consider the period over which the remedial target is exceeded. If this is relatively short and will not result in an unacceptable impact on water quality for the identified receptors, then action may not be required.

6.4 Level 4 assessment

Where the receptor is a stream or a groundwater abstraction, dilution at this point might be considered (see Section 5.7). This assumes that the receptor intercepts or receives all of the contaminated groundwater flow. In this case, the dilution factor (see Table 6.1) is defined as the ratio of the stream flow or the groundwater abstraction to the flow of contaminated groundwater through the centre of the plume.

The remedial target (RT) is determined by multiplying the target concentration by the dilution factor (DF) and/or saturated zone attenuation factor (AF).

This approach allows the actual impact on the receptor to be examined, but takes no account of the acceptability of the impact on groundwater.

Dilution in the receptor is considered to represent a special case and the assessment will need to justify that:

- any impact on the receptor is acceptable (i.e. below the target concentration);
- that remediation of the aquifer is not warranted on cost/benefit grounds (see Section 9.1).

Further guidance is given in Section 5.7.

6.5 Review of the assessment

Groundwater contamination problems are more likely to involve a Level 3 assessment, coupled with a detailed site investigation to define aquifer properties and the extent and degree of contamination. The investigations undertaken should provide field data to verify the risk assessment, particularly where degradation may be a factor.

The assessment should be undertaken by qualified staff, particularly where the hydrogeological regime is complex.

The decision to undertake any remediation will need to balance:

- the need to protect water resources;
- the role of natural attenuation (notably degradation);
- the practicality of any remediation scheme in improving water quality;
- the timescale to implement any measures;
- the cost of remediation.

The review should focus on:

- the extent of groundwater contamination and whether measures are required to reduce the degree of contamination;
- whether adequate data are available to define the extent and degree of groundwater contamination;
- the likely behaviour of the plume in the future and, in particular, whether it is likely to expand;
- the practicality, cost and benefits of implementing remediation.

A difficulty in many groundwater contamination cases is the ability to install downgradient (off-site) monitoring boreholes, particularly at small sites or where access is a problem. In many cases, the risk assessment may indicate that there should not be a significant risk to receptors (as a result of attenuation) based on setting a hypothetical compliance point downgradient of the site, but it is not possible to verify this conclusion using monitoring

boreholes. In such cases, the assessment will need to be confirmed through reference to monitoring boreholes located at the site boundary (see Section 9.3).

Additional factors that will also need to be taken into account are:

- sensitivity of downgradient receptors and the consequences of incorrect assumptions in the risk assessment (e.g. rate of degradation). For example, if the aquifer is a principal aquifer and background groundwater quality is good, then off-site boreholes will be required to confirm the assessment unless strong evidence is presented that natural attenuation processes are occurring.
- confidence in site characterisation, e.g. has a robust conceptual model been developed, which is supported by good quality site-specific data?
- several lines of evidence that demonstrate that the contaminant would be expected to degrade under the conditions observed at the site (Environment Agency 2000a). For example,
  - there are published data that the contaminant can degrade;
  - the conditions are appropriate for degradation (i.e. for oxidisable contaminants, the concentrations of oxidants are sufficient to support degradation);
  - there is field evidence from on-site boreholes of degradation (e.g. decrease in contaminant concentrations with distance from the source);
- the cost of implementing remedial action, particularly where the benefit may be marginal. The assessment should provide an estimate of the costs and describe the predicted impact on groundwater quality down-hydraulic gradient of the site.

Table 6.1 Basic equations for level 4 groundwater assessment

Standard analytical equations that can be used in Level 4 are given in the table below. This is not intended to be a definitive list, as other equations are available which may be more appropriate to a given situation.

Groundwater flow below site: $Q_C = K.i.w.M_z$

DF calculated based on target concentration	DF calculated based on concentration of contaminant in contaminated groundwater	Comment
K.i.w.M		
$DF = \frac{C_T(Q_C + Q_U) - Q_U.C_U}{Q_C.C_T}$	$DF_{River} = \frac{(Q_C + Q_U)C_C}{Q_C.C_C + Q_U.C_U}$	Background concentration included
	$DF = \frac{Q_C + Q_U}{Q_C}$	No allowance for background concentration
Groundwater abstraction		
$DF_{Abs} = \frac{Q.C_T - C_u(Q - Q_c))}{Q_c.C_T}$	$DF = \frac{Q_A.C_C}{Q_c C_C + C_U(Q_A - Q_c)}$	Background concentration included
	$DF = \frac{Q_A}{Q_c}$	No allowance for background concentration

where:

M_z	=	mixing zone thickness (m)
w	=	width of contaminated zone (plume) at right angles to groundwater flow (m)
K	=	hydraulic conductivity (m/d)
i	=	hydraulic gradient
Q_A	=	abstraction rate (m^3/d)
Q_U	=	surface water flow upstream of discharge point (m^3/d)
Q_C	=	groundwater flow below site (m^3/d)
C_C	=	concentration of pollutant in contaminated groundwater (mg/l)
C_U	=	background concentration of contaminant (mg/l)
C_T	=	target concentration (mg/l)
Inf	=	infiltration (m/d)
A	=	area of contaminant source (m^2)

7. Soil and groundwater assessment

When contamination of both soil and groundwater has been identified, the assessment should follow the approach detailed in Chapters 5 and 6, and summarised in Figure 7.1. The objective should be to:

- determine remedial targets for both soil and groundwater (an example of this approach is given in Appendix F);
- establish if remedial action is required for soil and/or groundwater and which should be given priority (refer to Figure 7.1).

The assessment should consider:

- whether remedial action is still required for groundwater after the soil source of contamination has been removed;
- the link between the observed soil and groundwater contamination.

The latter is achieved by calculating the groundwater contaminant concentrations that would be expected from the observed soil contamination and by considering the following cases:

- **Predicted concentrations are lower than observed concentrations.** This could indicate:
  - an additional source of contamination;
  - that contaminants have by-passed the soil zone;
  - dilution and attenuation processes have been overestimated.

  The reason for the higher groundwater concentrations needs to be understood and, if necessary, the source of the contamination defined more accurately so that any remedial action can be targeted appropriately.
- **Observed concentrations are lower than those predicted.** This could indicate that:
  - groundwater concentrations could increase in the future;
  - the assessment has been too conservative, e.g. it has underestimated the significance of attenuation and thus overestimated the remedial target.

  The reason for the lower predicted groundwater concentrations needs to be understood as, in the latter case, this may indicate that no remedial action is required.
- **Predicted and observed concentrations are similar.** This suggests that the conceptual model and analysis are correct and provides verification of the remedial targets determined. Care needs to be taken, however, as there may be more than one combination of parameter values which could be used to obtain a reasonable simulation of the observed groundwater concentrations, but which could result in the determination of very different remedial targets.

Only the soil zone may have been considered in many site investigations. The assessment should therefore be extended to consider whether contamination of groundwater has, or could occur as there could be a need to extend the scope of the investigations. It is also necessary to establish that, if groundwater is remediated in isolation, it will not be recontaminated by contaminated soil or a discrete phase of contaminated material.

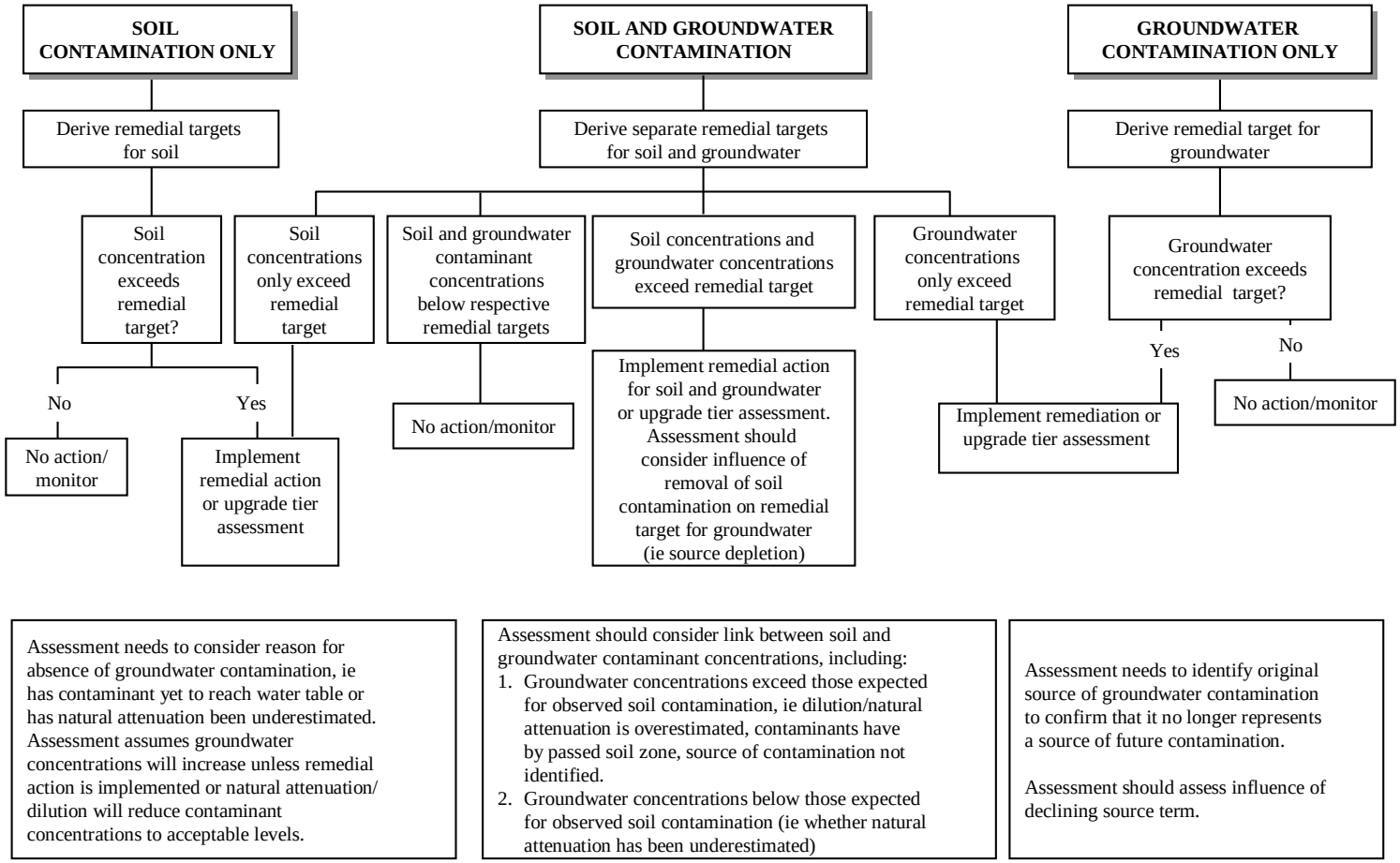


Figure 7.1 Assessment of soil and groundwater contamination

8. Fate and transport models, parameter values, sensitivity analysis and uncertainty

8.1 Model selection

Remedial targets can be derived using analytical or numerical contaminant fate and transport models. Examples of analytical models that can be used to calculate soil–water partitioning, dilution, attenuation and remedial targets are given in this report. The Environment Agency has also developed a spreadsheet model (see Section 2.5) as a tool to derive remedial targets, but this model may not be appropriate to some sites and alternative models may be more appropriate.

What is important is that the mathematical model selected should:

- provide an adequate representation of the site;
- support the derivation of remedial targets.

More detailed guidance on model selection is given in *Guide to good practice for the development of conceptual models and the selection and application of mathematical models of contamination transport processes in the subsurface* (Environment Agency 2001b).

When applying a mathematical model, it is necessary to understand and discuss:

- any limitations in the data used in constructing the model;
- any assumptions made in applying the model, e.g. whether degradation can be represented by first order decay.

Any assumptions need to be considered in relation to how the results of the model will be used. For example, do remedial targets derived using a relatively simple analytical model justify the implementation of a high cost remediation scheme?

Examples of the main assumptions associated with analytical models include:

- the aquifer is intergranular, homogeneous and isotropic, i.e. there is no lateral or vertical variation in parameter values;
- steady-state groundwater flow;
- the only processes that can affect the fate and transport of contaminants are dilution, sorption, degradation, dispersion and volatilisation (Level 1 assessment);
- sorption is linear, instantaneous and reversible;
- degradation can be described by an exponential function (first order decay);
- the contaminant source can be represent as a constant term (see Section 6.3).

Additional assumptions may apply according to the analytical model used.

The use of a mathematical model in the derivation of remedial targets needs to be justified in terms of whether it adequately represents the conceptual model. If the mathematical model is inappropriate, then a more sophisticated modelling approach may be required – probably supported by further data collection.

An essential part of the assessment is to understand how the mathematical model works and how input parameters affect the model output, i.e. its calculated remedial target. For

example, hydraulic conductivity is used in the calculation of the dilution factor and the attenuation factor. Increasing the value of hydraulic conductivity will increase the dilution factor, but it can also reduce the attenuation factor. This is because the time for the contaminant to reach the compliance point reduces and the significance of some attenuation mechanisms (degradation) therefore decreases.

8.2 Uncertainty

When deriving remedial targets and determining the need for soil/groundwater remediation, it is essential to consider the degree of uncertainty with respect to:

- the conceptual understanding of the system, e.g. will natural degradation decrease contaminant concentrations away from the source and what processes control this degradation?
- whether the mathematical model adequately describes the system behaviour. Application of a mathematical model will require a number of assumptions about the system behaviour (e.g. the remedial targets spreadsheet mentioned in Section 2.5 assumes that sorption can be described by a linear isotherm).
- definition of parameter values (this may be a product of the natural variability of the system, the number of measurements made and the reliability of these measurements). For example, uncertainty may be associated with measurement of a parameter value (e.g. potential errors in measurements or test results) or knowledge of the natural variation in a parameter value.

Most parameters have some natural variability. Hydraulic conductivity, for example, will vary spatially within an aquifer and this variability will be reflected in test results. Both natural variability and uncertainty need to be considered when assigning values to input parameters.

It is important to understand the effect of uncertainty when reviewing the assessment. For example, is the level of uncertainty acceptable in calculating the remedial target? In many cases, further investigations may be required if development of the conceptual model and mathematical model have shown inconsistencies and/or shortfalls in the definition of system behaviour.

Further guidance on dealing with uncertainty is given in:

- *Guidance on assigning uncertain parameters in subsurface fate and transport models* (Environment Agency 2001e).

8.3 Data requirements and selection of parameter values

Summaries of the typical data requirements for deriving remedial targets are given in Chapter 5 and Appendix A. This information will be determined in increasing detail with each successive Level of assessment. It will also vary from site to site depending on the nature of the source and contaminant, and the hydrogeological and geochemical environment.

The amount of data will depend on:

- the complexity of the site;
- the required degree of confidence in making decisions about the need to remediate. This will in turn be influenced by the sensitivity and risks associated with a site.
- the level of uncertainty associated with the parameters under investigation, e.g. highly unpredictable contaminant fate and behaviour will require considerable data collection;
- the costs of obtaining additional data balanced against the associated benefits of reducing uncertainty and using less conservative safety factors in the assessment.

Site-specific values should be obtained as part of the derivation of remedial targets, particularly those that are crucial to the assessment and which exhibit the greatest levels of uncertainty. Literature data can be used:

- as part of an initial assessment (provided they are used conservatively);
- if the parameter is well constrained in the literature and is appropriate to site conditions (i.e. temperature, geochemical environment, aquifer/soil type). For example, degradation rates derived from North America where aquifer type and groundwater temperatures are different to the UK should be used with extreme caution.
- if a sensitivity analysis indicates that the parameter does not affect the calculated remedial target appreciably.

The reasons and assumptions behind the selection of literature values should be documented.

An important part of the assessment will be selecting parameter values for input to the mathematical model. Guidance on the selection of parameter values is given in Environment Agency (2001e). In choosing a parameter value, consideration should be given to:

- the range in parameter values (as defined from field, laboratory measurements);
- accuracy of measurements;
- uncertainty in parameter values.

Normally, the input parameters will not be a single value but will consist of a range of values.

The use of a single value implies (almost invariably incorrectly) a high degree of certainty in the input parameter, i.e. it can be defined by a single value and/or its variability is known everywhere. For example, if values for hydraulic conductivity of 1.5, 17, 22 and 25 m/d had been derived from field testing, the remedial target derived using the lower value of 1.5 m/d would be an order of magnitude smaller than if the average value had been used. This does not present a problem where the observed concentrations are below the remedial target concentration derived using any one of these values. It presents a potential difficulty when, for example, the observed concentrations exceed the remedial target calculated using the minimum value of hydraulic conductivity. In reality, the conceptual model will need to consider whether this range of values provide an indication of the natural variability of the system or includes a value that is unrepresentative of the aquifer and should not be used in calculating the remedial target. This example illustrates that the assessment requires an element of expert judgement in deciding what value should be used and whether further investigations are necessary.

For sites where a parameter is poorly defined, then further data are likely to be required – particularly if this parameter is critical to decisions regarding the need to remediate.

Two types of mathematical model can be used in a risk assessment: deterministic and probabilistic. For **deterministic models**, a single parameter value is defined and the model calculates a single result. For **probabilistic models**, parameter values are defined by a distribution and the model result is described by a range of values. Probabilistic models are used to take account of the uncertainty in defining or measuring parameter values (e.g. due to sampling or analytical errors) or to represent the variability of a parameter (e.g. the variation of hydraulic conductivity in a heterogeneous aquifer). The worked examples in earlier chapters have assumed single parameter values (deterministic) to illustrate the methodology. ConSim (Environment Agency 2003b) is an example of a probabilistic model.

The limitation of using single values, therefore, is that the effect of parameter uncertainty may not readily be taken into account and thus a high level of confidence needs to associated with the parameter values used. The alternative approach is to use a probabilistic model such as ConSim.

Several approaches are possible in selecting parameter values for deterministic models. The precautionary approach of using conservative parameter values offers greatest protection to the receptor, but could lead to combinations of unrealistic values with consequent implications for cost and achievability and could be challenged.

The alternative is to re-run the model using different parameter values to determine the effect of uncertainty associated with the definition of a parameter value on the calculated remedial target. For example, best estimate, minimum and maximum values can be used to obtain an estimate of the range in possible answers (Environment Agency 2001c). However, there can be problems with this approach as:

- implausible results may be obtained by combining minimum or maximum parameter values (i.e. a result that exceeds what is known about a system);
- minimum or maximum values may be based on a limited dataset that may not describe adequately the real range in a parameter value, such that the result may be misleading;
- the process is time-consuming;
- the range of variation in the results is so large that it is unhelpful in decision-making.

Rather than use an unrealistic combination of worst case values, the preferred approach is to select realistic values and then consider a safety margin based on the sensitivity analysis (see Section 8.4).

Where possible, site monitoring data should be used to confirm the assessment, e.g. by comparing calculated concentrations in groundwater with observed concentrations. This may allow parameters values to be constrained and thus greater confidence to be attached to the remedial target.

More detailed guidance on the selection of parameter values and dealing with uncertainty is given in *Guidance on assigning values to uncertain parameters in subsurface fate and transport models* (Environment Agency 2001e).

Probabilistic models provide a better tool for dealing with uncertainty in the definition of a parameter value. Important factors in the use of these models are:

- whether there are sufficient data to define the distribution;
- what distribution should be used to define the variation in the parameter value (e.g. normal or log-normal distribution);
- the values used to define the distribution (e.g. mean, standard deviation).

The output from the model will be a range of results typically represented as the probability that a given concentration will be exceeded. In this case, the remedial target will be chosen based on the probability of exceeding a given value, for example the 95th percentile value.

8.4 Sensitivity analysis

A sensitivity analysis should be undertaken as part of the application of a risk model to determine which parameters have the greatest influence on the model results.

A sensitivity analysis is usually undertaken by:

- varying each parameter in turn by a given percentage (e.g. 20 per cent);
- calculating how this changes the model result (i.e. the remedial target concentration).

This analysis allows the most sensitive parameters to be identified and a reasoned judgement to be made on whether further data to better constrain the parameter are needed. This provides greater confidence to be attached to decisions based on the model results.

Two factors need to be considered:

1) The sensitivity analysis provides information on the sensitivity of the model (i.e. the equations used to represent the site) and does not necessarily reflect the sensitivity of the real environment.

2) The range in the parameter values used should reflect the range as determined from field and laboratory testing. For example, in calculating the rate of contaminant groundwater movement using the following equation, the calculation is as sensitive to a change in the value of bulk density as it is to a change in the value of hydraulic conductivity.

Contaminant velocity, $u = \left(\frac{k.i}{n + K_d.\rho} \right)$

where:

K_d	=	partition coefficient (l/kg)
ρ	=	bulk density (g/cm^3)
n	=	effective porosity
i	=	hydraulic gradient
k	=	hydraulic conductivity (m/d).

However, the value of bulk density determined for a soil is only likely to vary from 1.6 to 2.0 g/cm^3, whereas the value of hydraulic conductivity determined from field testing can often vary by more than an order of magnitude. Clearly there is no benefit in demonstrating the sensitivity of the model by using parameter values which exceed the known range of feasible values.

8.5 Validation of the model using field observations

Confidence in the assessment can improved if the mathematical model can be shown to provide a good simulation of observed conditions. This can be achieved by comparing model predictions with observed measurements, i.e. contaminant concentrations in monitoring boreholes around the site. The closer the match, the higher the confidence that can be attached to any decisions made using the model. This is particularly true when degradation has been included in the derivation of remedial targets and a combination of field data and modelling results provide support for the rates of degradation used in the assessment.

9. Cost-benefit assessment, monitoring and final review

9.1 Exceedance of remedial target and decision to remediate or undertake higher level assessment

The results of the remedial target assessment should be used to determine whether:

- further data and/or a higher level assessment are required;
- remediation is required subject to cost-benefit assessment (see Section 9.2);
- no action is required other than further monitoring;
- no action or monitoring are required.

Decisions should be based on:

- whether the observed soil and/or groundwater concentrations exceed the remedial target;
- the conceptual understanding of the site.

Decisions must be recorded, with any significant uncertainties described (see also Section 9.5).

Where observed concentrations are significantly below or higher than the target, decisions will be relatively straightforward. Where observed concentrations lie close to the remedial target, then decisions regarding the need for remedial action should consider:

- the number of measurements used to define the extent and degree of contamination, e.g. do exceedances represent localised 'hot spots' or are they indicative of more widespread contamination that has been missed by the investigation?
- the confidence that can be attached to parameter values and the method used to derive the remedial target, e.g. are parameters overly optimistic or pessimistic?
- the degree of confidence required to support decision-making;
- the sensitivity of the receptors at risk;
- the location of the compliance point (Levels 3 and 4) and whether this is realistic in terms of aquifer protection and attenuation processes;
- the costs and benefits of implementing remedial measures.

These factors may identify that further site characterisation is required.

The decision to implement remedial measures should take into account all these factors and other wider policy considerations. This report considers the need for remediation only from a technical perspective. The Environment Agency should be consulted to determine any wider considerations, e.g. how WaterFD objectives and exemptions are to be applied within a River Basin District. As a consequence, the final remedial target that is applied at a site may not be the same as the output from the assessment tools described in this report.

9.2 Environmental benefit and cost

When evaluating whether to implement remedial measures where contamination has resulted from historical activities, the environmental benefit should be considered in relation to the cost of the scheme. The following should be taken into account:

- the cost of implementing the scheme and whether this is disproportionate in relation to the environmental benefit;
- whether remediation is technically feasible;
- the practicality of implementing the scheme;
- the improvement in surface water or groundwater quality that would result from remediation;
- the degree of reduction in risk of future pollution;
- the wider environmental costs (disposal of waste products, energy etc. as well as site remedial costs).

This report does not provide guidance on how to undertake such a cost-benefit assessment. Instead, guidance is given in:

- *Costs and benefits associated with groundwater remediation* (Environment Agency 1999b);
- *Costs and benefits associated with groundwater remediation: framework for assessment* (Environment Agency 2000c);
- *Model procedures for the management of land contamination* (Defra and Environment Agency 2004).

9.3 Compliance Monitoring

A monitoring programme will be necessary unless investigations have demonstrated that:

- the observed contamination represents no risk;
- the proposed measures (e.g. removal of the source) will be effective in protecting the receptor(s).

The objectives of compliance monitoring are to:

- determine when remediation should cease, i.e. when concentrations fall consistently below the remedial target;
- determine the effectiveness of the remediation scheme with a view to implementing corrective action if the remedial objectives have not been met.

For soil contamination, any monitoring boreholes should be located at the edge of the source area to demonstrate that no significant contamination has occurred at this point or to trigger further action.

For contaminated groundwater problems, the boreholes will normally be located between the source and the identified compliance point or receptor to provide confirmation that the predicted or assumed attenuation processes are effective (e.g. no unacceptable expansion of the plume). The decision factors to be adopted in determining the position of a compliance monitoring borehole are summarised in Figure 9.1.

The number, location and construction of monitoring boreholes required are determined on a site-specific basis. However, they will be a function of:

- size of the contaminant source;
- type and distribution of contaminant (e.g. if LNAPLs are present, then monitoring should include sampling at the water table);
- complexity of the hydrogeological regime and pathways;
- cost of long-term monitoring;
- access – including presence of existing buildings and services, land ownership and security of installation;
- sensitivity of the receptor at risk;
- regulatory requirements.

It is essential that the borehole locations should be agreed with an experienced hydrogeologist.

In general, the **minimum** requirements for monitoring boreholes are:

- one borehole located up-hydraulic gradient of the contaminant source to determine background quality;
- at least two boreholes located either at the downgradient edge of the contaminant source or the contaminant plume, with at least one of these being the compliance point. A single downgradient borehole is not considered satisfactory due to the uncertainty in ensuring that this borehole is in the line of contaminant movement.
- at least one borehole located directly on the flow path between the source and the identified receptor to act as a sentinel or early warning borehole.

Depending on the complexity of the aquifer setting and the plume geometry, further boreholes may be required to demonstrate that:

- the monitoring network provides adequate protection to downgradient receptors;
- any remedial works are effective.

Boreholes located away from the contaminant source should be sited to take into account the fact that the contaminant plume might move via discrete pathways or may dive within the aquifer. The certainty that the borehole is sited correctly will reduce with increasing distance from the plume, even though the size of any plume is likely to increase as a result of dispersion. The safest approach is to locate the compliance borehole at the edge of the known contaminant plume. This provides greatest certainty that monitoring is undertaken at the correct location.

The monitoring scheme will normally involve setting control and/or trigger levels at key monitoring locations.

A control level should be used to provide an early warning that an impact may occur or that the scheme is not working to expectations. Further monitoring and investigation should be undertaken if a control level is exceeded.

Trigger levels can be used in two ways:

1. Exceedance of a trigger level indicates that there is a risk of deterioration in water quality at the receptor and that additional mitigation measures need to be implemented to protect it.
2. A trigger level may be used to indicate when remediation can cease, i.e. the remediation scheme results in an improvement in groundwater quality and contaminant levels fall below the trigger level such that there is no longer a risk to the receptor.

The trigger level will vary according to the location of the monitoring point in relation to the source or compliance point/receptor as shown in Table 9.1.

Table 9.1 Derivation of trigger levels

Location of monitoring point	Trigger level
At the source	The remedial target should be used
Between the source and the compliance point[1]	Calculated to ensure the target concentration is not exceeded at the compliance point (see Figure 9.2)
At the compliance point[1]	The target concentration should be used. For some sites, monitoring at the compliance point may not be possible or a 'virtual' compliance point may have been used. In this case, compliance monitoring should be based on a borehole between the source and the compliance point (typically located at the site boundary) and a trigger level derived on that basis.

[1] The compliance point may be at the receptor or at some point upstream from it.

A monitoring programme should be agreed with the Environment Agency in terms of:

- the number, location and construction details of the boreholes;
- the methodology used to obtain representative samples;
- the number and type of samples;
- range of determinants for analysis. This should include:
  - the main contaminants identified;
  - appropriate analytical methods and their limits of detection
  - breakdown products (where appropriate).
- the cost-effectiveness of the sampling/analytical strategy;
- frequency and duration of monitoring;
- the basis for determining that measured concentrations exceed the trigger level. For example, the use of the mean value or to prescribed statistical threshold (e.g. 95th percentile) so as to account for likely variation in water quality as a function of sampling and analytical procedures.

The monitoring data should be reviewed to assess whether:

- the scheme is operating as expected;
- further measures need to be implemented if the trigger or control levels are exceeded. These measures may include:
  - additional investigations and monitoring to better understand plume behaviour;
  - an update of the risk assessment or implementation of additional mitigation measures.

  The precise actions should to be determined on a site-specific basis and agreed with the Environment Agency.
- monitoring can cease as contamination no longer represents a risk.

9.4 Final review

The assessment should be subject to a final review based on the following important questions:

- Have pollutant linkages been identified?
- Is emergency action required to protect the receptor, e.g. is there sufficient time to undertake the risk assessment?
- Has the site been characterised adequately, e.g. are further data needed?
- Is the target concentration appropriate in protecting receptors and ensuring that pollution does not occur?
- Where multiple contaminants are present, has the assessment been carried out for the key contaminant in terms of environmental sensitivity?
- Are the methods used in the analysis appropriate to site conditions?
- Are the parameter values used in the assessment defined adequately?
- In assessing soil contamination, have contaminants by-passed the soil zone?
- Are remedial targets realistic in relation to background?
- Is the plume of contamination increasing or decreasing?
- Have key uncertainties been addressed in determining the proposed actions?
- Is the receptor protected adequately?
- Have other sources of contamination been considered?
- Is the remedial target concentration and the proposed remedial measures appropriate, achievable and cost beneficial? For example, remediation of groundwater to background levels may not always be achievable either technically or cost-effectively.
- Are the timescales for implementation of the remediation scheme appropriate with respect to:
  - the capabilities of those undertaking the remediation;
  - the principle of sustainable development;
  - the risk of further contamination of water resources while the scheme is being planned and implemented?
- If no remedial action is required, is monitoring required?

In evaluating the target and remedial target concentrations, together with any remedial measure(s), consideration should be given as to whether there will be a short- or medium-term increase in the volume of groundwater contamination between the source of contamination and the receptor. Whether this is acceptable will be a balance between protecting the environmental target and the cost and practicality of doing so. In exceptional circumstances (e.g. if the predicted duration of the impact at the receptor is very short), it may be more effective to treat or isolate the receptor than to remediate groundwater per se.

In some cases (e.g. in an industrial complex), more than one source of contamination may exist – both inside and outside the site. Groundwater flowing below the site may already have been contaminated. In these cases, the assessment should take account of:

- the different sources of contamination;
- the quality of groundwater up-hydraulic gradient of the site.

This is likely to result in a lower (more stringent) remedial target concentration being set for the site. This is because the calculated dilution factor will be lower where background quality and/or multiple contaminant sources are taken into account.

In the case of multiple contaminant sources, the appropriate parties and the Environment Agency will need to agree whether it is reasonable to require remediation at the site in isolation of the other sources. For example, the site may represent only a small potential impact on the identified receptor compared with other contaminant sources. This is an example of where wider policy considerations and catchment objectives can come into play.

Throughout the process of deriving remedial targets and deciding on the need for remedial action, regular liaison with the Environment Agency will help to ensure agreement on important stages in the assessment.

9.5 Reporting

As a minimum, the report detailing the remedial target assessment should include:

- the study objectives, e.g. purpose of undertaking the assessment;
- site description and history;
- site investigation and monitoring results (including all data collected as part of the investigation);
- the conceptual model and pollutant linkages;
- a description of the remedial targets and the mathematical models used, including justification that the model used is applicable to the site;
- description and justification of the parameter values used in the assessment;
- results of the remedial target assessment;
- conclusions from the study including the need for further investigation, monitoring, remedial action or whether no further action is required;
- copies of mathematical model(s), including input and output files.

Figure 9.1 Determining the position of compliance monitoring boreholes

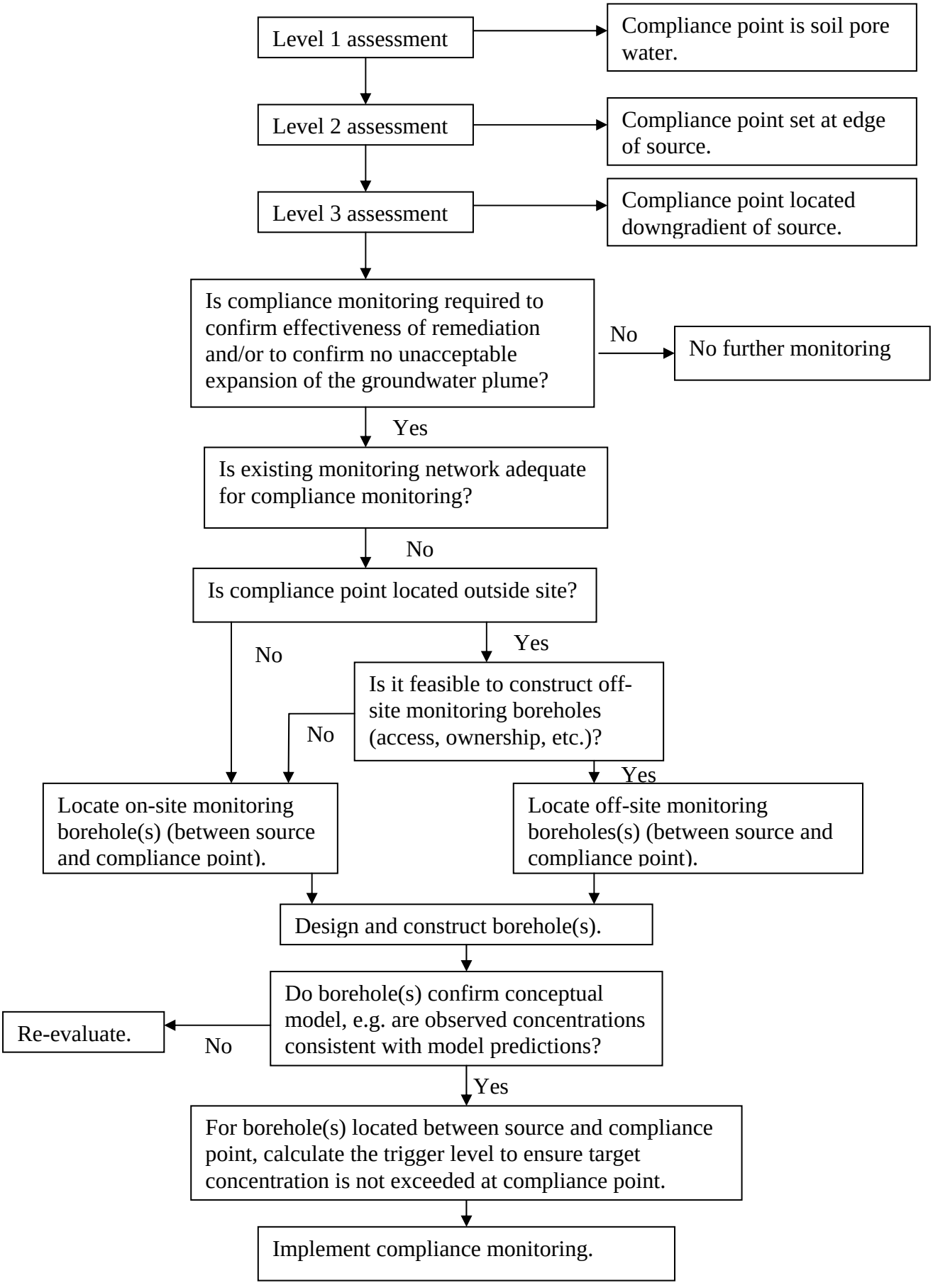
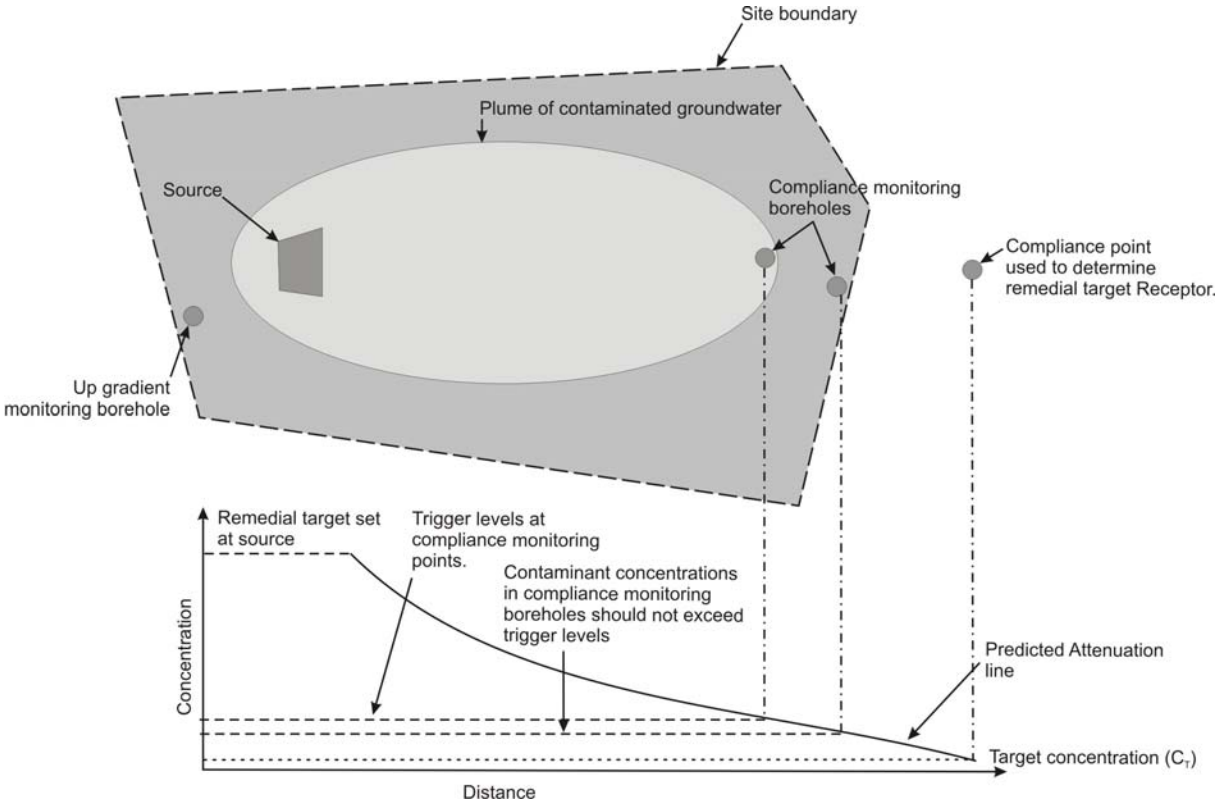


Figure 9.2 Compliance monitoring



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11. Glossary

Absorption	The incorporation of a chemical within a solid or liquid.
Adsorption	The attachment of a chemical to the surface of a solid or liquid.
Advection	Mass transport caused by the bulk movement of flowing groundwater.
Aquifer	A permeable geological stratum or formation that is capable of both storing and transmitting water in significant amounts.
Attenuation	Reduction in contaminant concentration through biological, chemical and physical processes as it passes through a medium.
Biodegradation	The breakdown of a substance or chemical by living organisms, usually bacteria.
Contamination	The presence of any substance, microorganism or energy at a concentration or level above the normal (expected) natural background range, as a consequence of natural or anthropogenic processes.
Compliance point	Negotiated location where the remedial target concentration must be achieved.
Conservative pollutants	Pollutants that can move readily through the aquifer with little reaction with the rock matrix and which are unaffected by biodegradation (e.g. chloride).
Controlled waters	All rivers, canals, lakes, ground waters, estuaries and coastal waters to three nautical miles from the shore (defined by Water Resources Act 1991, Part III, Section 104).
Dense non-aqueous phase liquid (DNAPL)	A liquid immiscible with water that has a density greater than water and so sinks in water.
Diffusion	Migration of substances by natural movement of their particles.
Dilution	Reduction in concentration brought about by the addition of water.
Dispersion	Irregular spreading of solutes due to aquifer heterogeneity at pore-grain scale (mechanical dispersion) or at field-scale (macroscopic dispersion).

Eluate	A solution resulting from the mixing of soil and water in order to remove sorbed substances.
Effective rainfall	The amount of rain available for recharge to the aquifer after evapotranspiration (length units).
Equilibrium	No net transfer between two phases.
Free phase contamination	Product (e.g. petrol, diesel) that is present in its original state and at a high saturation. May also include coal tars.
Groundwater	All water that is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil [Regulation 1(2) of the EC Groundwater Directive 80/68/EEC].
Groundwater Source Protection Zone (SPZ)	An area designated around a groundwater abstraction, the maximum extent of which is the catchment area for the source. Within this area the Agency wishes to see limits to processes and activities or focus protection measures in order to prevent or limit inputs of pollutants to groundwater and thus protect the abstraction source.
Henry's Law constant	Coefficient that represents the equilibrium partitioning factor between a solute in the water and vapour phases.
Hydraulic conductivity	A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity.
Hydraulic gradient	The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.
Hydraulic head	The sum of the elevation head, the pressure head and the velocity head at a given point in the aquifer.
Hyporheic zone	Zone beneath and adjacent to a river or stream where groundwater and surface water mix.
Intergranular	Occurring between the grains of a rock or soil.
Light non-aqueous phase liquid (LNAPL)	A liquid immiscible with water that is less dense than water and so floats on water.
List I substance	EC Groundwater Directive 80/68/EEC classifies groups and families of substances as within List I or List II. List I substances are the most toxic substances and must be prevented from entering groundwater. They include pesticides, sheep dip, solvents, hydrocarbons, mercury, cadmium and cyanide.
List II substance	EC Groundwater Directive 80/68/EEC classifies groups and families of substances as within List I or List II. List II

	substances are less dangerous but must be controlled to prevent pollution of groundwater. They include substances such as ammonia.
Non-aqueous phase liquid (NAPL)	Liquids that are immiscible with water.
Non-polar molecule	A molecule not susceptible to permanent charge, usually one without ionisable groups attached.
Partitioning	The process by which a contaminant, released originally in one phase (e.g. adsorbed to soil grains) becomes distributed between other phases (i.e. vapour and dissolved phases).
Partition coefficient	In a heterogeneous system of two or more phases in equilibrium, the ratio of the activities (or less accurately the concentrations) of the same molecular species in the phases is a constant at constant temperature. This constant is termed the partition coefficient.
Pathway	A route along which a particle of water, substance or contaminant moves through the environment.
Perched water	A discontinuous layer of saturated strata formed above the main water table due to a layer of low permeability material intercepting water moving downwards through the unsaturated zone.
Permeability	Measure of the ability to transmit water. Defined as the volume of water passing through 1 m^2 of aquifer under unit hydraulic gradient. Units: m^3/m^2 d or m d^{-1}.
Polar molecule	A charged molecule that is affected by changes in pH.
Pollution (of groundwater; Groundwater Directive)	The discharge by man, directly or indirectly, of substances or energy into groundwater, the results of which are such as to endanger human health or water supplies, harm living resources and the aquatic ecosystem or interface with other legitimate uses of water.
Pollution (EPA 1990)	Pollution of the environment due to the release (into any environmental medium) from any process of substances which are capable of causing harm to man or any other living organism supported by the environment.
Pollution (Water Framework Directive)	The direct or indirect introduction, as a result of human activity, of substances or heat into the air, water or land which may be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems, which result in damage to material property, or which impair or interfere with amenities and other legitimate uses of the environment.

Pore water	Any free water (i.e. not adsorbed within the matrix of a soil or rock and incapable of participating in contaminant movement) contained within the primary pore space or within fissures either in the unsaturated or the saturated zone.
Porosity	The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.
Principal aquifer	These are geological strata that exhibit high permeability and usually provide a high level of water storage. They are capable of supporting water supply on a strategic scale and are often of major importance to river base flow. (Formerly known as major aquifer).
Priority substance	Substance or group of substances shown to be of major concern for European waters and which have been identified in accordance with Article 16(2) and listed in Annex X of the Water Framework Directive.
Receptor	An entity/organism or a controlled water that is being or could be harmed by a potential pollutant.
Recharge	The water that reaches the saturated zone of an aquifer, which is calculated as rainfall, deliberate recharge and unintentional leakage (e.g. from leaking water supply pipes), less runoff, evapotranspiration and soil storage.
Remedial target	The goal of remedial activity set at the compliance point, in the form of a desired concentration in the soil or groundwater.
Retardation	A measure of the reduction in solute velocity relative to the velocity of the groundwater caused by sorption processes.
Saturated zone	The zone in which the voids of the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.
Secondary aquifer	These include a wide range of geological strata with a correspondingly wide range of permeability and storage. Depending on the specific geology, these subdivide into permeable formations capable of supporting small to moderate water supplies and baseflows to some rivers, and those with generally low permeability but with some localised resource potential. (Includes the former minor aquifers but also some of the former non-aquifers).
Sorption	The process whereby substances are absorbed into, or adsorbed onto, solid surfaces such as soil or aquifer mineral surfaces.
Target concentration	Maximum acceptable concentration of a substance at a compliance point.
Total soil concentration	The total concentration of a contaminant within the soil matrix, whether it be adsorbed, absorbed or in free phase.

Unproductive strata	These are geological strata with low permeability that have negligible significance for water supply or river base flow. (Formerly formed part of the non-aquifers).
Unsaturated zone	The zone between the land surface and the water table. It includes the root zone, intermediate zone and capillary fringe. The pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Saturated bodies (e.g. perched groundwater) may exist in the unsaturated zone. Also called zone of aeration or vadose zone.
Virtual borehole	A point where a borehole might be located between the source and the receptor at which a target concentration may be defined.
Volatilisation	The process by which the pure liquid phase turns to the gaseous phase, or boils.

12. Appendices

Appendix A Sources of information

Table A1 lists sources of information when drawing up the conceptual model and Table A2 those for parameters for Levels 1-4. The list given in Table A1 is for guidance only and will be dependent on site-specific conditions.

Table A1 Details to be covered by the conceptual model

Topic	Specific information	Data source	Comments
Site description and history	Grid references, site plan, site boundary, area of site	Site plans, OS maps, site staff, public registers	
	Relevant site history including activities that may have given rise to contamination (also include land adjacent to the site)		
	Current use (including site layout)		
	Proposed future use of site (including development of site)		
	Details of abstraction licences, discharge consents, authorisations, etc.		
	History of pollution incidents, including prosecutions, Notices, etc.		
	Drainage systems, soakaways		
	Topography		
Characterisation of site geology	Local and regional setting	BGS maps, memoirs, borehole records, site investigations, Soil Survey (NSRI) records	
	Solid and drift geology and soil details		
	Lithological description		
	Geometry (thickness and lateral extent) of the main lithologies		
	Stratigraphy including borehole logs		
	Structure including faulting, fissuring		
Characterisation of hydrology and climate	Surface water drainage	OS maps Flow gauging Environment Agency Climate data (rainfall, evaporation) Land-use, soil type, Met Office CEH	
	Surface water flows, including low flows		
	Groundwater/surface water interaction		
	Surface water quality		
	Abstractions and discharges		
	Surface water catchments		
	Rainfall, potential and actual evaporation		
	Infiltration through soil and surface water run-off		

Table A1 (continued) Details to be covered by the conceptual model

Topic	Specific information	Data source	Comments
Receptors	Groundwater below or adjacent to site.	Environment Agency, local authority, OS maps	
	Existing and potential users of groundwater, abstractions.		
	Surface water (springs, streams, ponds, wetlands and dependent ecology, Habitats Directive designated sites)		
	Distance from site to receptors		
	Sensitivity of receptors		
Characterisation of groundwater flow system	Groundwater occurrence	Environment Agency, groundwater vulnerability maps, groundwater monitoring, site investigations Geological maps	
	Groundwater vulnerability		
	Location of Source Protection Zone (SPZ)		
	Direction of groundwater flow		
	Hydraulic gradients (horizontal and vertical)		
	Variations (seasonal and long-term) in groundwater levels and flow direction		
	Flow mechanism (fissure/intergranular flow)		
	Single or multilayered aquifer and significance of aquitards		
	Influence of geological structures (faults) on flow		
	Aquifer properties – porosity, pore size	Laboratory measurements Grain size Pumping tests Literature (e.g. aquifer properties manuals – BGS and Environment Agency 1997, 2001)	Important to differentiate between total and effective porosity.
	Aquifer properties - hydraulic conductivity	Rising/falling head tests Packer tests Pumping tests Literature (e.g. aquifer properties manuals – BGS and Environment Agency 1997, 2001)	Hydraulic conductivity may vary laterally and vertically (anisotropy).
	Lateral and vertical variation in aquifer properties		
	Groundwater interaction with surface water bodies (rivers, lakes, canals etc.)	Climate data, land use Flow gauging Environment Agency	
	Artificial influences on the groundwater regime, e.g. fracturing of strata due to collapse of underground mine workings		
	Recharge and indirect recharge		
	Discharge to springs and streams		
	Groundwater abstractions		
	Historical, current and future aquifer management which may affect the groundwater regime, e.g. rising groundwater levels in response to a cessation of abstraction		
Characterisation of groundwater flow system	Aquifer thickness and effective thickness	Boreholes Geophysical logging Packer testing	Flow may be in discrete zones such that aquifer depth may differ from the total depth of the

Table A1 (continued) Details to be covered by the conceptual model

Topic	Specific information	Data source	Comments
			formation.
	Mixing depth	Monitoring results Geophysical logging Groundwater level variation	Can be estimated using empirical equations. Often limited by bedding structures in sedimentary sequences.
Source/ contaminant characteristics	History of contamination (volume of spills, number of releases, location(s), dates, frequency(ies) and method(s) of release and duration)	Site records, stock keeping Laboratory analysis Chemical databases DoE Industry Profiles (×47) (available on Environment Agency website) Chemical reference textbooks	
	Contaminants present/identified		
	Likely contaminant form (e.g. DNAPL, LNAPL, dissolved, particulate)		
	Contaminant phase (solid, sorbed phase, residual phase, free phase, dissolved phase, vapour phase)		
	Contaminant distribution (soil zone, unsaturated zone, saturated zone)		
	Contaminant concentration (soil zone, unsaturated zone, saturated zone)		
	Continuous, plug or declining contaminant source		
	Contaminant properties (solubility, partition coefficient, density, recalcitrance etc)		
Likely pathways	Unsaturated zone pathways		
	Saturated zone pathways		
	Geological, structural and topographic controls		
	Influences of preferential flow via fissures, drainage systems, soakaways, man made structures, foundations, old mines, boreholes etc.		
Contaminant migration characteristics	Intergranular porosity/dual porosity/fracture flow	Literature (e.g. geological memoirs; BGS and Environment Agency 1997, 2001)	
	One, two or multi-phase flow		
	Density controlled flow		

Table A1 (continued) Details to be covered by the conceptual model

Topic	Specific information	Data source	Comments
	Degradation kinetics	Analysis of observed changes in Contaminant concentrations Microbiological studies Laboratory trials Literature	Breakdown products with different properties Chemical environment Typical represented as first or second order decay kinetic reaction. May be controlled by available electron acceptors (oxygen, nitrate, sulphate, ferric iron).
	Sorption characteristics, partition coefficients	Literature Tracers Laboratory experiments	Lithology, bulk density, pH-dependent. Competition between different species, chemical reactions, solubility, polarity, changes in media properties.
	Volatilisation (Henry's Law)	Literature	Volatile contaminants only
	Dispersion processes	Tracer studies Literature Laboratory experiments Empirical values (one tenth of distance plume has migrated) as approximation	The value of the dispersion coefficient is scale-dependent. Values reported in field experiments are often several orders of magnitude greater than those from laboratory experiments.
Characteristics of soil/rock in relation to contaminant transport	Fraction of organic carbon.	Laboratory measurement Literature	Standard test methods for CEC and Kd determination published by Environment Agency (Environment Agency 2000c, 2005a). See also US EPA 1999.
	Cation exchange capacity (CEC)		
	Mineralogy (e.g. clay content, Fe/Mn oxides, $CaCO_3$ content, etc.).		
	Bulk density		
	Grain size distribution.		
	Moisture content		
	Significance of preferential pathways		
	Permeability		
	Porosity		
	Fracture size and spacing in rock		

Table A1 (continued) Details to be covered by the conceptual model

Topic	Specific information	Data source	Comments
Contaminant behaviour	Plume shrinking, stable, expanding Plume diving (due to density effects recharge or vertical hydraulic gradient)	Field sampling and monitoring	
	Seasonal and long-term changes in contaminant concentrations		
	Processes affecting contaminant transport (e.g. advection, dispersion, sorption, degradation)		
	Presence of breakdown products, if applicable		
	Influence of reactions/competition between contaminants		
	Influence of biochemical environment on contaminant processes (e.g. pH on metal mobility)		
	Significance of natural attenuation processes, and evidence in support of natural attenuation	Environment Agency 2000a, Wiedemeier *et al.* 1999	
	Influence of future changes on contaminant behaviour (e.g. effect of remediation scheme)		
Bio-geochemical environment	Background quality	Field sampling and monitoring	
	Aerobic/anaerobic		
	pH, temperature, salinity, redox potential (Eh), indicators such as dissolved oxygen, alkalinity, NO_3^-/ NO_2^-, Fe^{3+}/Fe^{2+}, SO_4^{2-}/S^{2-}, CO_2/CH_4, H_2O/H_2		
	Microbiology		

BGS = British Geological Society

CEH = Centre for Ecology and Hydrology

OS = Ordnance Survey

Table A2 Data sources for parameters used in Levels 1–4

Parameter	Data Source	Comments
Soil porosity	Laboratory measurement Grain size analysis Literature	Important to differentiate between total and effective porosity. In soil and unsaturated zone only partial saturation. Water-filled porosity can be estimated from moisture content. Aquifer properties manuals useful for georeferenced data (BGS and Environment Agency 1997, 2001)
Henry's Law constant	Literature	Volatile contaminants only
Bulk density	Laboratory measurement Literature	Dry bulk density
Fraction of organic carbon	Laboratory measurement Literature	BGS and Environment Agency are preparing a geochemical properties manual.
Sorption/partition coefficient	Laboratory experiments Literature Tracer tests	Lithology, bulk density, pH dependent. Competition between different species, chemical reactions, solubility, polarity, changes in media properties. Kd test method (Environment Agency 2000b and 2005a)
Hydraulic conductivity	Rising/falling head tests Packer tests Pumping tests Literature Laboratory tests Particle size	Porous or fissured aquifer. Hydraulic conductivity may vary laterally and vertically (anisotropy). Unsaturated zone hydraulic conductivity dependent on saturation. Aquifer properties manuals useful for georeferenced data (BGS and Environment Agency 1997, 2001)
Hydraulic gradient	Observation boreholes	Pressure gradient where density is a factor.
Aquifer thickness	Boreholes Geophysical logging Geological memoirs	Flow may be in discrete zones such that aquifer depth may differ from the total depth of the formation.
Mixing depth	Borehole logging Multi-level sampler monitoring results	Often constrained by lithological structure (e.g. bedding plane separation). Likely to be restricted to higher permeability zone near water table (if present). Likely to be less than saturated aquifer thickness for thick aquifers. Can be estimated using empirical equations.
Direct recharge	Climate data (rainfall, evaporation), land-use, soil type	Variable recharge due to low permeability cover.

Table A2 (continued) Data sources for parameters used in Levels 1–4

Parameter	Data Source	Comments
Indirect recharge (leakage or discharge to sewers, drains, water mains)	Flow gauging Sewerage undertaker records	
Stream flow	Environment Agency, SEPA Stream gauging CEH	
Dispersion coefficient	Tracer test studies Literature Laboratory experiments Empirical values	The value of the dispersion coefficient is scale dependent. Values reported in field experiments are often several orders of magnitude greater than from laboratory experiments. Literature (e.g. Xu and Eckstein 1995)
Biodegradation	Interpretation of field data Literature	Recommendations for field assessment presented in R&D Publication 95 (Environment Agency 2000a) and US EPA (2002). Useful reviews in Environment Agency 2002a, 2003c and 2004 Breakdown products with different properties. Chemical environment. Typical represented as first or second order decay kinetic reaction. Alternatively may be linked to available electron acceptors (oxygen, nitrate, sulphate, ferrous iron).
Aquifer porosity	Pumping tests Grain size analysis Laboratory tests Literature	Pumping tests may not be of sufficient duration to define specific yield. Effective porosity may differ from total porosity. Aquifer properties manuals useful for georeferenced data (BGS and Environment Agency 1997, 2001)

Appendix B Soil leaching tests

Soil leaching tests essentially consist of agitating a mass of contaminated soil with a volume of water (eluate) and measuring the concentration of contaminants in the eluate.

Tests may vary in terms of:

- the mass of soil;
- the volume of eluate;
- the period of agitation;
- preparation of the soil (e.g. screening out larger particles);
- environmental controls (pH, temperature).

The recommended procedure for undertaking leaching tests is described in BS EN 12457 (BSI 2002).

The basic test procedure involves:

- removing of material greater than 4 mm in size (this should not exceed 5 per cent of the total sample);
- drying a sub-sample to determine natural moisture content;
- mixing the sample with de-ionised water;
- agitation of the soil/water mix for 24 hours;
- filtering the sample through a 0.45 µm filter;
- measuring contaminant concentrations in the eluate;
- measuring pH, conductivity and, optionally, redox potential at the end of test;
- calculating the weight in mg of contaminant leached per kg of soil at natural moisture content.

The test results are typically expressed as:

- mg of contaminants per litre of leachate (mg/l);
- mg of contaminant leached per kg of soil at natural moisture content (mg/kg).

The first result is directly applicable to the Level 1 assessment. The second result is used in soil waste classification (Environment Agency 2005b).

BS EN 12457 has three parts describing a number of different test types for materials with a particle size below 4 mm (with and without size reduction):

- Part 1 – one-stage test using a liquid to solid ratio of 2:1 l/kg;
- Part 2 – one-stage test using a liquid to solid ratio of 10:1 l/kg;
- Part 3 – two-stage test using a liquid to solid ratio of 2:1 in the first stage and a liquid to solid ratio of 8:1 in the second stage. The results are combined to determine a total mass of contaminant leached from the soil sample.

Part 4 describes a one-stage test using a liquid to solid ratio of 10:1 l/kg for materials with a particle size below 10 mm (with and without size reduction).

Additional tests include:

- maximum availability leaching test (NEN 7341) to determine the maximum amount of contaminant that can be leached from a soil sample (NEN 1995);
- pH dependence test (CEN/TS 14429) to determine influence of pH on soil leaching (CEN 2005);
- upflow percolation test (CEN/TS 14405) to determine leached concentrations for different liquid to solid ratios (CEN 2004).

The choice of test will depend on whether:

- the test results can be used for other purposes such as choice of soil remediation technique (e.g. soil washing) or waste classification for disposal to landfill (Environment Agency 2005b);
- information is needed on:
  - the influence of pH on contaminant leaching;
  - variation in leachate concentrations with volume of eluate;
  - effect of repeat tests on soil leaching;
  - maximum amount of contaminant that can be leached from the soil.

Depending on the test, soil:water ratios range from 2:1 to 10:1 l/kg. These represent higher ratios than would typically be observed under field conditions and there is, therefore, the potential that the measured concentrations are diluted. Thus, pore water concentrations determined for samples where a 2:1 liquid/solid ratio is used are preferable.

Note:

1. The test procedure has been verified for inorganics. Caution should be used for testing for organics. For volatile organics, it is essential that all precautions are taken during sample preparation and testing to prevent volatile loss.
2. The test is not recommended for hydrophobic contaminants due to:
   - the poor leachability of these organics;
   - potential problems of sorption of the contaminant to the test apparatus.

   The recommended approach for hydrophobic contaminants is to calculate theoretical soil remedial targets.

Appendix C Summary of processes that may influence the attenuation factor

Process	Description	Dependencies	Effect
Sorption	Reaction between aquifer matrix and solute whereby contaminants become sorbed on organic carbon or clay minerals. Sorption can be represented by linear or non-linear equations.	Dependent on aquifer properties (organic carbon, clay mineral content, bulk density, specific surface area and porosity) and the hydrophobicity of the pollutant.	Removes solutes from groundwater via sorption to the aquifer matrix. Reduces apparent rate of solute movement (i.e. retards contaminants relative to groundwater). Contaminants can desorp back into groundwater from the aquifer matrix.
Retardation	Reduction in rate of contaminant migration to processes including sorption, ion exchange, precipitation/dissolution and fissure/pore water diffusion.	Dependent on aquifer and contaminant properties.	Reduction in apparent rate of solute movement.
Biodegradation	Microbial degradation of contaminants.	Dependent on: • contaminant concentration (degradation may be inhibited at high concentration – toxicity effect); • supply of electron acceptors (oxygen, nitrate, sulphate), i.e. if insufficient supply, then degradation will be inhibited; • geochemical environment, e.g. BTEX compounds (benzene, toluene, ethylbenzene and xylene) will degrade at faster rate under aerobic conditions.	Results in a loss of contaminant mass and reduction in contaminant concentration.
Abiotic degradation	Chemical transformations (e.g. hydrolysis) that degrade contaminants.	Dependent on contaminant properties and groundwater geochemistry.	Results in a loss of contaminant mass and reduction in contaminant concentration. Rates typically much slower than biodegradation.

Process	Description	Dependencies	Effect
Volatilisation	Volatilisation of contaminants dissolved in groundwater into the vapour phase (soil gas).	Dependent on the chemical's vapour pressure (Henry's Law constant) and air-filled porosity.	Removes contaminants from groundwater and transfers them to soil gas.
Dispersion	Spreading of a contaminant plume as a result of groundwater moving at different rates/following different pathways through the aquifer. Dispersion is typically represented by empirical equations (derived from analysis of plume dimensions).	Dependent on aquifer properties and scale of observation. Independent of contaminant properties.	Results in longitudinal, transverse and vertical spreading of the contaminant plume as it moves through the aquifer. Reduces contaminant concentrations.
Diffusion	Spreading of contaminant due to molecular diffusion.	Dependent on contaminant properties and concentration gradients. Generally unimportant relative to dispersion except at very low groundwater velocities. Diffusion significant in dual porosity systems in controlling contaminant movement between fissure water and pore water.	Diffusion of contaminant from area of relatively higher concentration to areas of lower concentration. Reduces contaminant concentrations. For dual porosity aquifers, can result in a decrease in the rate at which a contaminant can migrate through the aquifer.

Appendix D Analytical models

This appendix provides examples of the analytical solutions that can be used to derive remedial targets. A number of simplifying assumptions are associated with the use of the equations (particularly those given in Tables D3–D5) including:

- the aquifer system can be represented by relatively simple analytical models;
- the aquifer is intergranular, homogeneous and isotropic, i.e. there is no lateral or vertical variation in parameter values;
- steady-state groundwater flow;
- the only processes which can affect the fate and transport of contaminants are dilution, sorption, degradation and dispersion;
- the dispersion coefficient can be expressed as a product of groundwater velocity (*v*) and dispersivity (*a*);
- molecular diffusion can be assumed to be negligible;
- sorption is linear, instantaneous and reversible;
- degradation can be described by an exponential function (first order decay);
- the contaminant source can be represent as a constant term.

An additional analytical solution is included in Table D6 where degradation is represented as an oxidant mixing-limited process.

It is emphasised that analytical solutions represent idealised conditions and only approximate the controlling processes.

Details of the papers cited are given at the end of this appendix.

Table D1 Air-filled and water-filled porosity

The air-filled and water-filled porosity of a soil can be calculated from the soil moisture content and bulk density as follows:

Total porosity = $1 - \frac{\rho_{dry}}{\rho_{part}}$

Air-filled porosity = $\theta_a = \theta_T . \frac{(100.MC.\rho_{part})}{(\rho_{part} / \rho_{dry} - 1)}$

Water-filled porosity = θ_T - θ_a

where:

θ_w	=	water filled soil porosity (fraction)
θ_a	=	air filled soil porosity (fraction)
θ_T	=	total soil porosity (fraction)
MC	=	moisture content (wt/wt)
ρ_{dry}	=	dry bulk density (g/cm^3)
ρ_{wet}	=	wet bulk density (g/cm^3) = $\rho_{dry} \times (100 + MC)/100$
ρ_{part}	=	particle density (g/cm^3)

Table D2 Summary of basic equations for calculating the rate of contaminant movement, retardation and advection

Advection and retardation

Rate of groundwater flow $v = \frac{Ki}{n}$

Retardation factor $R_f = 1 + \frac{K_d.\rho}{n}$

Rate of contaminant movement due to retardation $u = \frac{K.i}{n.R_f}$

where:

R_f	=	retardation factor
K_d	=	partition coefficient (l/kg)
v	=	rate of groundwater flow (m/d)
u	=	rate of contaminant movement due to retardation (m/d)
ρ	=	bulk density (g/cm^3)

Dispersion and dispersivity

Dispersion $D = a_x.v + D^*$

For relatively high rates of groundwater flow, molecular diffusion is small in comparison with dispersion and can be ignored.

Dispersivity (*a)* is often derived from empirical equations which relate the value to distance (x) as illustrated by the following equations.

1. $a_x = 0.1x$, $a_z = 0.01x$, $a_y = 0.001x$

or

2.* $a_x = 0.83(\log x)^{2.414}$

$a_z = a_x /10$, $a_y = a_x /100$ are assumed

where:

a_x, a_y, a_z	=	longitudinal, vertical and lateral dispersivity (m)
v	=	rate of groundwater flow (m/d)
x	=	distance to compliance point (m)
D	=	dispersion (m^2/s)
D^*	=	effective molecular diffusion coefficient (m^2/s)
x	=	distance to compliance point (m)

* Xu and Eckstein 1995

Table D3 Basic analytical equations for calculating attenuation factor

Calculation of concentrations downgradient of the site (steady-state) using the Domenico equation. This is a simplified version of the Ogata Banks equation given in Table D5.

$$C_{ED} = C_0 \exp\left\{\frac{x}{2a_x}\left(1-\sqrt{\left[1+\frac{4\lambda a_x}{u}\right]}\right)\right\}.erf\left\{\frac{S_y}{2\sqrt{a_y x}}\right\}.erf\left\{\frac{S_z}{4\sqrt{a_z x}}\right\}$$

Attenuation factor $AF = \frac{C_{ED}}{C_0}$

where:

C_{ED}	=	concentration of contaminant at distance x (mg/l)
C_0	=	initial contaminant concentration in groundwater (mg/l)
λ	=	decay constant = 0.693/half life for degradation of contaminant in days
a_x, a_y, a_z	=	longitudinal, vertical and lateral dispersivity (m)
S_z, S_y	=	width and thickness of plume at source (in the saturated zone) (m)
u	=	rate of contaminant movement due to retardation (Table D2)
	=	$u = \frac{K.i}{n.R_f}$
R_f	=	retardation factor (Table D2)
n	=	effective porosity
i	=	hydraulic gradient
K	=	hydraulic conductivity (m/d)
x	=	distance to compliance point (m)
erf	=	error function
exp	=	exponential

Note: For certain cases or choices of parameter value, the Domenico equation can give slightly different calculated values to the Ogata Banks equation. This is a function of the simplifications made in the Domenico solution.
Plume thickness at source, Sy, is equal to mixing zone thickness (M_z) used in calculating the dilution factor.
This solution assumes that vertical dispersion occurs in one direction only.

Table D4 Basic equations for calculating attenuation factor (Level 3)

Calculation of concentration downgradient of site using the Domenico equation (simplified version of the Ogata Banks equation, see Table D5).

$$C_{ED} = \frac{C_0}{2}\exp\left\{\frac{x}{2a_x}\left(1-\sqrt{\left[1+\frac{4\lambda a_x}{u}\right]}\right)\right\}.erfc\left\{\frac{1}{2\sqrt{a_x ut}}.\left(x-ut\sqrt{\left[1+\frac{4\lambda a_x}{u}\right]}\right)\right\}.erf\left\{\frac{S_y}{2\sqrt{a_y x}}\right\}.erf\left\{\frac{S_z}{4\sqrt{a_z x}}\right\}$$

Attenuation factor $AF = \frac{C_{ED}}{C_0}$

where:

C	=	concentration of contaminant at point x and time t (mg/l)
C_0	=	initial contaminant concentration in groundwater (mg/l)
λ	=	decay constant = 0.693/half life for decay of contaminant in days
a_x, a_y, a_z	=	longitudinal, vertical and lateral dispersivity (m)
S_z, S_y	=	width and thickness of plume at source (in saturated zone) (m)
u	=	rate of contaminant movement due to retardation (Table D2)
	=	$u = \frac{K.i}{n.R_f}$
R_f	=	retardation factor (Table D2)
n	=	effective porosity
i	=	hydraulic gradient
K	=	hydraulic conductivity (m/d)
x	=	distance to compliance point (m)
erfc	=	complimentary error function
erf	=	error function
exp	=	exponential
t	=	time since contaminant entered groundwater (days)

Note: Plume thickness at source, Sy, is equal to mixing zone thickness use in calculating the dilution factor.
In order to calculate the remedial target, time (t) should be set as a large number (i.e. 10^{-99} d) and the lateral and vertical offset should be set as zero.
This solution assumes that vertical dispersion occurs in one direction only.

Table D5 Basic equations for calculating attenuation factor (Level 3)

Calculation of concentrations downgradient of the site (time variant) using the Ogata Banks equation (Table D3 gives the steady-state solution of this equation. Table D4 gives the simplified Domenico time-variant version of this equation).

$$C_{ED} = \frac{C_0}{8}\exp\left\{\frac{x}{2a_x}\left(1-\sqrt{\left[1+\frac{4\lambda a_x}{u}\right]}\right)\right\}.erfc\left\{\frac{1}{2\sqrt{a_x ut}}.\left(x-ut\sqrt{\left[1+\frac{4\lambda a_x}{u}\right]}\right)\right\}$$

$$+\exp\left\{\frac{x}{2a_x}\left(1+\sqrt{\left[1+\frac{4\lambda a_x}{u}\right]}\right)\right\}.erfc\left\{\frac{1}{2\sqrt{a_x ut}}.\left(x+ut\sqrt{\left[1+\frac{4\lambda a_x}{u}\right]}\right)\right\}$$

$$.\left[erf\left\{\frac{z+\frac{S_z}{2}}{2\sqrt{a_z x}}\right\}-erf\left\{\frac{z-\frac{S_z}{2}}{2\sqrt{a_z x}}\right\}\right].\left[erf\left\{\frac{y+S_y}{2\sqrt{a_y x}}\right\}-erf\left\{\frac{y-S_y}{2\sqrt{a_y x}}\right\}\right]$$

Attenuation factor $AF = \frac{C_{ED}}{C_0}$

where:

C	=	concentration of contaminant at point x and time t (mg/l)
C_0	=	initial contaminant concentration in groundwater (mg/l)
λ	=	decay constant = 0.693/half life for decay of contaminant in days
a_x, a_y, a_z	=	longitudinal, vertical and lateral dispersivity (m)
S_z, S_y	=	width and thickness of plume at source (in saturated zone) (m)
u	=	rate of contaminant movement due to retardation (Table D2)
	=	$u = \frac{K.i}{n.R_f}$
R_f	=	retardation factor (Table D2)
n	=	effective porosity
i	=	hydraulic gradient
K	=	hydraulic conductivity (m/d)
n	=	effective porosity
i	=	hydraulic gradient
k	=	hydraulic conductivity (m/d)
x	=	distance to compliance point (m)
z	=	distance (lateral) to compliance point perpendicular to flow direction (m)
y	=	distance (depth) to compliance point perpendicular to flow direction (m)
erf	=	error function
exp	=	exponential
erfc	=	complementary error function
t	=	time (in days) since contaminant entered groundwater

Note: Plume thickness at source, Sy, is equal to mixing zone thickness.
In order to calculate the remedial target time (t) should be set as a large number (i.e. 10^{-99} d) and the lateral and vertical offset should be set as zero.
This solution assumes that vertical dispersion occurs in one direction only.

Table D6 Basic analytical equations for calculating attenuation factor (Level 3)

Biodegradation controlled by oxidant mixing-limited process. The following analytical solutions are a modification to original work by Domenico and Robbins (1985) in order to represent biodegradation as an oxidant mixing-limited process.

a) Time-variant solution

$$C_{ED} = \frac{C_{ED_{max}}}{2} \text{ erfc}\left(\frac{x - v t}{2\sqrt{a_x v t}}\right) \text{erf}\left(\frac{S_Y}{4\sqrt{a_y x}}\right) \text{erf}\left(\frac{S_Z}{4\sqrt{a_z x}}\right) \left(1 + \frac{C_{EA_{max}}}{C_{ED_{max}}}\right) - C_{EA_{max}}$$

b) Steady-state solution

$$C_{ED} = C_{ED_{max}} \text{ erf}\left(\frac{S_Y}{4\sqrt{a_y x}}\right) \text{erf}\left(\frac{S_Z}{4\sqrt{a_z x}}\right) \left(1 + \frac{C_{EA_{max}}}{C_{ED_{max}}}\right) - C_{EA_{max}}$$

Attenuation factor $AF = \frac{C_{ED}}{C_0}$

where:

C_{ED}	=	concentration of contaminant at point x and time t (meq/l)
C_{EDmax}	=	maximum concentration of electron donor in groundwater (meq/l)
C_{EAmax}	=	maximum concentration of electron acceptors in groundwater (meq/l)
a_x, a_y, a_z	=	longitudinal, vertical and lateral dispersivity (m)
S_z, S_y	=	width and thickness of plume at source (in saturated zone) (m)
v	=	groundwater velocity (m/d) (no retardation)
	=	$\frac{K.i}{n.}$
n	=	effective porosity
i	=	hydraulic gradient
K	=	hydraulic conductivity (m/d)
x	=	distance to compliance point (m)
erfc	=	complimentary error function
erf	=	error function
t	=	time since contaminant entered groundwater (days)

Note: The analytical solutions listed above calculate concentration CED in units of electron equivalents (meq/l). To convert back to units of mg/l, multiply concentrations in meq/l by the contaminant-specific molecular weight (g/mol) and divide by the number of electrons donated in half-reactions.

For this solution, the value of C_{EDmax} refers to a single contaminant (or electron donor). Alternatively, C_{EDmax} can be set as the sum of oxidisable organics on the assumption that they will degrade at the same rate. However, C_{EAmax} can be the sum of dissolved oxygen (O_2), nitrate (NO_3) and sulphate (SO_4.).

This solution is provided by Steve Thornton, University of Sheffield.

Description of analytical solution to represent biodegradation as an oxidant mixing-limited process

The analytical equations given in Tables D2–D5 assume that biodegradation can be represented as a first-order decay process (Domenico 1987). However, many field and laboratory studies have shown that biodegradation is better characterised if the kinetics of these processes are consider to be fast compared with transport processes (e.g. mixing by dispersion) (Borden and Bedient 1986, Huang *et al*. 2003, Thornton *et al.* 2001, Wilson *et al.* 2004). Wilson *et al.* (2004) give a useful review of existing approaches to evaluating natural attenuation.

The equations presented in Table D6 provide an alternative solution where degradation is assumed to be a instantaneous process and dependent on an oxidant mixing-limited process.

The analytical model presented predicts the transport and concentration of an oxidisable contaminant under steady state and transient conditions. Organic and inorganic contaminants (e.g. BTEX, phenols, NH_4) can be considered, provided the compound is oxidisable (i.e. it functions as an electron donor) and is oxidised by the corresponding reduction of a dissolved electron acceptor (e.g. O_2, NO_3, SO_4). The model does not consider oxidation by solid phase electron acceptors (e.g. MNO_2 and FeOOH) and does not account for sorption to aquifer solids. This means that predictions of plume length and time to steady-state will be conservative. The model is a modification of the analytical solution for three dimensional solute transport produced by Domenico (1987).

The solution of the equation requires concentrations of oxidisable contaminants and oxidants to be corrected to electron equivalents as follow:

$$\text{Concentration meq/l} = \frac{\text{Contaminant concentration (mg/l) x Number of electrons donated in half reactions}}{\text{Contaminant molecular weight (g/mol)}}$$

The additional assumptions to those for the equations given in Tables D2–D5 are:

- sorption cannot be included in this solution;
- biodegradation is represented as an instantaneous reaction between an electron donor (i.e. organic contaminant) and an electron acceptor.

More information on the underlying concepts and use of the analytical solutions can be found on the CORONA website (http://www.shef.ac.uk/corona).

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Appendix E Case example – soil

Soil contamination has been identified below a former chemical site, the principal contaminants being cadmium, phenol and benzo(a)pyrene. The contamination is present within fill materials (a mixture of slag, clinker and gravel). The total area of the site is about 20,000 m^2. The observed concentrations of contaminants are shown in Table E1.

Table E1 Contaminant concentrations

Contaminant	Concentration (mg/kg)	Description
Cadmium	5–10	Over most of site area, no clear-cut distribution
Phenol	1– 2	Over most of site
	10–20	Hot spots within site
Benzo(a)pyrene	5–30	Over most of site
	200–300	Hot spots within site

The site is underlain by Triassic Sherwood Sandstone, classified as a principal aquifer by the Environment Agency. A public water supply borehole, with a licensed abstraction of 2,000 m^3/d is located about 1,900 m from the site. The site falls within the catchment (Source Protection Zone III) of this abstraction borehole.

Preliminary findings

The potential receptors were identified as:

- the Triassic Sherwood Sandstone aquifer;
- the public water supply source.

The source of contamination is the soil zone. No information is available on the strata at depth, but it is assumed that any contaminants would migrate vertically down through the unsaturated zone to the saturated zone.

A risk assessment is necessary to determine whether this site represents a risk to water resources.

Derivation of target concentrations

Information on background quality and environmental standards related to the intended use of the receptor was collated for each contaminant and is summarised below. This information has been used to determine target concentrations.

Table E2 Derivation of target concentrations

Contaminant	Background concentration (mg/l)	Environmental Standard[1] (mg/l)	Target concentration[2] (mg/l)
Cadmium	<0.01	0.005	0.005
Phenol	<0.001	0.0005	0.0005
Benzo(a)pyrene	No data	0.00001	0.00001

[1] In this case the most sensitive receptor was taken as the public water supply borehole.
[2] Set as the Environmental Standard.

Level 1 assessment

Information on soil pore water quality available from leaching tests is summarised in Table E3.

All the leaching test results exceed the target concentrations, indicating the potential need for remediation. An initial analysis of costs indicates that the cost of remediation is an order of magnitude greater than undertaking a Level 2 assessment. The decision, therefore, is to proceed with the next level of analysis.

No immediate need for interim action is considered necessary while the Level 2 assessment is undertaken because:

- there is no evidence of any contamination at the public water supply source;
- the public water supply source is located 1.9 km from the source of contamination, and from discussion with the Environment Agency hydrogeologist, this source is not considered to be at immediate risk due to relatively slow rates of groundwater movement.

Table E3 Soil pore water chemistry*

Contaminant	Target concentrations at receptor (C_T) (mg/l)	Soil leaching test (mg/l)[1]
Cadmium	0.005	***0.01***
Phenol	0.0005	***0.2***
Benzo(a)pyrene	0.00001	***<0.001[(2)]***

*Values in bold italics exceed the target concentration.
[1] Based on maximum soil concentration.
[2] Below detection level.

Level 2 assessment

Borehole drilling and hydraulic testing were undertaken to determine aquifer thickness, hydraulic conductivity and hydraulic gradient. Information was also obtained from the Met Office about the effective rainfall for the site. This information is required to calculate the Level 2 dilution factor.

Table E4 sets out the parameter values for and the calculation of the dilution factor.

Table E4 Level 2 parameter values

Parameter		Unit	Range	Value used in Level 2 assessment[1]	Source
Hydraulic conductivity	K	m/d	5–12	5	Falling head tests
Hydraulic gradient	i		0.01	0.01	Water level measurement[2]
Depth of mixing	M_z	m	Base of aquifer not penetrated	10	Evidence of high permeability horizon from borehole logs
Length of site parallel to flow	L	m	100	100	
Width of site parallel to flow	W	m	70	70	
Infiltration	Inf	m/d	0.0005[3]	0.0005	Met Office

[1] For this assessment, conservative values were selected. Further assessment may warrant undertaking a sensitivity analysis.
[2] Hydraulic gradient determined from water level measurement in six boreholes across the site.
[3] Infiltration derived from MORECS (Met Office Rainfall and Evaporation Calculation System) data.

The background concentration is assumed to be zero when calculating the dilution factor:

$$DF = 1 + \left(\frac{K.i.M_z}{Inf.L} \right) = 1 + \left(\frac{5 \times 0.01 \times 10}{0.0005 \times 100} \right) = 11$$

The leaching test results are compared to the Level 2 remedial target concentrations in Table E5.

Table E5 Determination of Level 2 remedial targets*

Contaminant	Level 2 remedial target[1] (mg/l)	Leaching test concentration (mg/l)
Cadmium	0.055	0.01
Phenol	0.0055	***0.2***
Benzo(a)pyrene	0.00011	***0.001***

*Values in bold italics exceed the target concentration.
[1] Remedial target concentration = Dilution factor (DF) × Target concentration (Table E3).
Dilution factor = 11.

Groundwater

Sampling of the monitoring boreholes down-hydraulic gradient of the site identified elevated phenol concentrations (0.2–15 mg/l) compared with background concentrations (<0.001 mg/l) in a borehole located up-hydraulic gradient of the site. These concentrations are higher than would be expected from the observed soil concentrations. This is interpreted as indicating that phenol has by-passed the soil zone. Benzo(a)pyrene was not detected in any groundwater samples.

Discussion

The leaching tests results show that phenol and benzo(a)pyrene exceed the soil remedial targets. In addition, the observed phenol concentration in groundwater exceeds the remedial target concentration of 0.01 mg/l, though benzo(a)pyrene was not detected.

In view of these results, it was decided to proceed with Level 3 assessment. In the case of phenol, groundwater rather than the soil represents the main risk to the identified receptors as groundwater concentrations exceed those that would be expected from the observed soil concentration.

Level 3 assessment

Additional information was obtained to determine the degree of attenuation of contaminants moving beyond the site boundary and towards the public water supply source. This included drilling boreholes down-hydraulic gradient of the site to obtain additional information on water quality and the hydraulic gradient and hydraulic conductivity of the aquifer.

For the assessment, a compliance point was set at 100 m from the site boundary in order to provide protection to the Triassic Sandstone aquifer itself, rather than to just the public water supply borehole.

The additional site information was used to recalculate the dilution factor. The attenuation factor was calculated using the Domenico analytical equation (assuming steady-state conditions). This attenuation factor is relevant to the calculation of the Level 3 remedial target for both soil and groundwater.

Table E6 Parameter values and calculation of attenuation factor

Parameter		**Unit**	**Value used in Level 3 assessment**			**Source**
Source width	w/S_z	m	70			
Source thickness	S_y/M_z	m	10			
Hydraulic conductivity	K	m/d	8	(4–20) range		Falling head tests
Hydraulic gradient	i		0.01			Water level measurement
Porosity	n		0.15			Literature
Bulk density	ρ	g/cm^3	1.65			Laboratory measurement
Distance to compliance point	x	m	100			
Dispersivity (longitudinal)	a_x		10			
Dispersivity (transverse)	a_z		1			
Dispersivity (vertical)	a_y		0.1			
Dilution factor	**DF**		**17**			Calculated
			cadmium	***phenol***	***benzo(a)pyrene***	
Partition coefficient	K_d	l/kg	120	0.18	7 328	Laboratory tests
Input concentration	C_0	mg/l	1	1	1	Assumed unit concentration[1]
Half life		days	No	300	No degradation	Literature[0]

Parameter		**Unit**	**Value used in Level 3 assessment**			**Source**
			degradation			
Calculated concentration at compliance point	C_{ED}	mg/l	0.96	0.32	0.96	Calculated[3]
Attenuation factor	**(C_0/C_{ED})**		**1.04**	**3.1**	**1.04**	**Calculated**

[1] Since the Domenico equation is linear with respect to the input concentration, an assumed concentration can be used to calculate the attenuation factor.

[2] No evidence identified from literature for biodegradation of cadmium (metal) or benzo(a)pyrene (recalcitrant PAH) in similar hydrogeological environments.

[3] Calculated from equations given in Table D5, Appendix D

Soil

The soil leaching test results are compared with the Level 3 soil remedial target concentration in Table E7.

Table E7 Determination of Level 3 soil remedial target[1]

Contaminant	**Attenuation factor (Table E6)**	**Level 3 remedial target (mg/l)**	**Leaching test concentration (mg/l)**
Cadmium	1.04	0.09	0.01
Phenol	3.1	0.025	0.02
Benzo(a)pyrene	1.04	0.0002	0.001

[1] Remedial target = AF × DF × Target concentration (C_T).
Dilution factor (DF) = 17 (recalculated at Level 3)

Groundwater

The observed phenol and benzo(a)pyrene concentrations in groundwater are compared with the Level 3 groundwater remedial target in Table E8.

Table E8 Determination of Level 3 groundwater remedial target[1]

Contaminant	**Observed concentration (mg/l)**	**Level 3 remedial target (mg/l)**
Phenol[1]	0.2–15	0.0015
Benzo(a)pyrene	<0.00001	0.00001

[1] Remedial target = AF × Target concentration (C_T).
For phenol, AF = 3.1 and C_T = 0.0005.

Summary

The analysis has shown that the levels of soil concentration for phenol are close to the remedial target. A decision to implement remedial action on the basis of observed soil phenol concentrations is marginal, particularly when the results of the sensitivity analysis (see below) are taken into account.

However, the observed phenol concentrations in groundwater are significantly above the remedial target for groundwater. Remedial action therefore needs to be implemented in respect of contaminated groundwater.

The observed concentrations in groundwater are interpreted as indicating that phenol has by-passed the soil zone. However, it is also likely that the main source of contamination no

longer exists and that phenol concentrations in groundwater would be expected to decrease with time. Leaching of the contaminated soil may give some additional loading, but this is considered to be small compared with the original source.

For benzo(a)pyrene, soil leaching concentrations exceed the remedial target but no evidence for this contaminant has been identified in groundwater. Benzo(a)pyrene has a very low mobility (high partition coefficient) and sorption in the unsaturated zone may explain its absence in groundwater.

No action is required for cadmium.

Sensitivity analysis

A sensitivity analysis was also carried out as part of the assessment. This examined the influence of changing the values of the least certain parameters (hydraulic conductivity, partition coefficient and the degradation rate) on the calculated remedial target for phenol.

Each parameter value was varied by ±25 per cent; the results are given in Table E9.

The leaching test concentrations are below the calculated remedial targets, providing confirmation that the assessment for soils has been conservative. In addition, the remedial target was calculated using the range of values of hydraulic conductivity derived from field-testing.

Table E9 Sensitivity analysis (phenol)

Parameter	**Percentage change in value**	**Calculated remedial target for soil (mg/l)**
Remedial target (Table E7)		0.025
Hydraulic conductivity (m/d)	+25	0.027
Hydraulic conductivity (m/d)	-25	0.027
Degradation rate (m/d)	+25	0.032
Degradation rate (m/d)	-25	0.023
Partition coefficient (l/kg)	+25	0.031
Partition coefficient (l/kg)	-25	0.023
Hydraulic conductivity		
Minimum value = 4m/d		0.032
Maximum value = 20m/d		0.035
Leaching test concentration (mg/l)		**0.02**

NB An increase in the value of hydraulic conductivity will increase the dilution factor but decrease the attenuation factor.

Appendix F Case example – groundwater

Investigations revealed that groundwater below a former chemical site was contaminated. Benzene was the main contaminant identified at concentrations of 1–10 mg/l. The site is located on a sand and gravel aquifer, which provides baseflow to a river located about 200 m from the site. The target concentration for benzene entering the river as baseflow has been set as equivalent to the Environmental Quality Standard of 0.03 mg/l.

Level 2 assessment

Benzene concentrations observed in groundwater (0.5 to 20 mg/l) below the site exceed the Level 2 target concentration (0.03 mg/l), with the requirement to either remediate groundwater or to undertake a Level 3 assessment. The cost of Level 3 in this case is significantly lower than remediation and the decision has been made to proceed with this assessment.

Level 3 assessment

Information on the aquifer properties determined as part of an initial investigation is summarised in Table F1.

Table F1 Parameters values and calculation of attenuation factor and remedial target

Parameter		**Unit**	**Value**	**Assessment of compliance point position**	
Width of plume at source	S_z	m	60		
Thickness of plume at source	S_y/M_z	m	10		
Hydraulic conductivity	K	m/d	20		
Hydraulic gradient	i		0.005		
Porosity	n		0.25		
Bulk density	ρ	g/cm^3	1.8		
Distance to compliance point	x	m	200	100	50
Dispersivity (longitudinal)	a_x		20	10	5
Dispersivity (transverse)	a_z		2	1	0.5
Dispersivity (vertical)	a_y		0.0002	0.0002	0.0002
Partition coefficient	K_d	l/kg	0.83		
Input concentration	C_0	mg/l	20		
Half life	t0.5	days	300		
Calculated concentration*	C_{ED}	mg/l	0.02	0.04	2.2
Attenuation factor	**(C_0/C_{ED})**		**940**	**50**	**9**
Remedial target	RT	**mg/l**	**28**	**1.5**	**0.27**

* Using the steady state Domenico equation (see Table D3).

The observed groundwater concentrations below the site were compared with the target concentration multiplied by the attenuation factor. The summary provided in Table F2 also includes the remedial targets that would be applied if virtual boreholes located at 50 and 100 m from the site had been used as the compliance point.

Table F2 Comparison of observed benzene concentrations with remedial targets

Target concentration (mg/l)	Distance to compliance point (metres)	Attenuation factor	Level 3 remedial target (mg/l)	Observed concentration (mg/l)
0.03	200 (distance to receptor)	940	28	0.5–20
	100	50	1.5	
	50	9	0.27	
	200 (no degradation)	1.4	0.04	

* Calculated using the above parameters but for a non-degrading pollutant.

The observed benzene concentrations are below the remedial target calculated for a compliance point set at the receptor. No action is considered necessary to protect the river.

However, the calculations include the potential for groundwater downgradient of the site to be impacted, i.e. if the compliance point was set at 50 m from the site, there would be the potential need for remediation. The sand and gravel aquifer is not currently used for water supply, so it is proposed scheme to implement a monitoring programme, including routine sampling of boreholes drilled along the site boundary and at a distance of 50 m down-hydraulic gradient of the site to provide confirmation that attenuation is a significant process and that there is limited migration of benzene.