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3D Groundwater Vulnerability

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Foreword

This report is the product of a joint British Geological Survey (BGS) – Environment Agency (EA) study to assess the vulnerability of groundwater in relation to deep sub-surface hydrocarbon activity (3D Groundwater Vulnerability) in England.

Since the late 1980s, groundwater protection in England has benefited from a series of national groundwater vulnerability maps. These are now routinely used to inform decisions around allowing and/or managing activities on, or just below, the land surface that are potentially polluting. The recent increased interest in onshore exploration and exploitation of the deeper subsurface and concerns about the risk to groundwater has highlighted the fact that the existing groundwater vulnerability assessment methodology focuses solely on risks from hazards that are above the groundwater that requires protection.

Plans to exploit the deep sub-surface, in particular for shale gas using hydraulic fracturing, have attracted considerable public interest and concerns over the potential for these activities to cause pollution of groundwater. It is therefore essential that in considering any proposals for use of the deep sub-surface, tools and methods for assessing groundwater vulnerability and risk are fit for purpose.

Hence, the aim of this project was to develop a new vulnerability method that could address the potential risks to groundwater from activities below, or at similar depths to, groundwater systems (aquifers) that are currently used or have the potential to be used in the future. These systems are those requiring protection under current EU and UK legislation. To this end we present a methodology along with five different hydrocarbon activity case study examples from across England. The report describes how information can be compiled, interpreted and presented in order to assess the vulnerability of groundwater and an indication of the risks associated with a hydrocarbon development activity at a site. The outputs are designed for use primarily by those needing to understand better the hydrogeological context of subsurface developments, the vulnerability of groundwater and the potential risks. It is also hoped that the hydrogeological data and methodology will aid decision making and provide impartial information to inform public debate.

The report is not designed to set out in a formal way how information and modelling should be used to reach regulatory decisions. A wider set of site-specific information will be required for this and this is outside the scope of the research presented here.

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The 3DGW Vulnerability project is a co-funded project between the British Geological Survey and the Environment Agency. The authors would like to thank the Environment Agency for their financial support for the project as well as contributing to the project vision. The project has also benefitted significantly from the contribution and involvement of the project Steering Group: Lynn Foord, Jan Hookey, Rudi Liu, Paul Doherty, Sarah Scott, Jenny Thomas and Sara Matthews.

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Executive Summary

This report is the product of a joint British Geological Survey (BGS) – Environment Agency (EA) study to develop a methodology for attributing vulnerability of groundwater to pollution from sub-surface oil and gas activities. It follows the UK Government's guidelines for environmental risk assessment and management (Defra, 2011). The methodology considers:

- hazards associated with unconventional and conventional oil and gas exploration, coal bed methane (CBM) and underground coal gasification (UCG);
- near-surface and deeper aquifers as receptors, including;
    - groundwater that is currently used as a resource and/or supports surface water flows/wetlands (designated groundwater bodies);
    - other groundwater that could potentially be used in the future as a drinking water resource or for other beneficial purposes.

From a review of the location of hydrocarbon sources and groundwater in England, and potential contamination pathways, a prototype Tier 1 (qualitative) ("Guidelines for Environmental Risk Assessment and Management: Green Leaves III", Gormley et al., 2011) screening methodology has been developed to assess groundwater vulnerability and risk from sub-surface hydrocarbon activities in three dimensions, at a site-specific scale. The methodology identifies and reviews the potential risks to groundwater and provides a means of communication of the outcomes of the vulnerability assessment. Outputs are intended for use by regulators (e.g. the Environment Agency and local planning authorities) to support environmental consultants advising industry and the public.

The vulnerability and risk screening methodology is described in this report and implemented in a supporting spreadsheet tool. A digital data package is also associated with this report for use with the methodology. This comprises the National Geologic Model (UK3D v2015) for England, which can be viewed in LithoFrame Viewer software (downloadable free from the BGS website). Application of the methodology has been demonstrated using generic case studies from five areas across England.

The methodology is based on the DRASTIC model (a standardized system to evaluate groundwater pollution potential using hydrogeologic settings) that uses an overlay/index approach to assess risk where there is insufficient data for detailed numerical modelling. Each component of the assessment is described in different sections of this report:

- Importance and classification of potential receptors; (rock units containing groundwater);
- intrinsic vulnerability of potential receptors (due to the geological characteristics of the rock units between the hydrocarbon source rock and potential receptors);
- specific vulnerability of the potential receptors (due to the nature of the hydrocarbon exploitation activity, driving head and intrinsic vulnerability) and;
- risk group of the potential receptors (the specific vulnerability combined with the potential receptor classification).

The framework for the assessment is a conceptual model for an Area of Interest (AOI), i.e. the area at the ground surface below which hydrocarbon extraction activities in the sub-surface may impact groundwater. The spreadsheet tool can be used to guide development of the conceptual model, and the vulnerability and risk screening process. The LithoFrame Viewer 3D model comprises a series of geologic cross-sections across England. As part of this project, each cross-section has been attributed, where relevant, with: a) potential hydrocarbon source rocks, and b)

EA/BGS aquifer designations. This information provides a regional understanding of the 3D spatial relationship between hydrocarbon source rocks and aquifers.

Vulnerability and risk are assessed for all geological units (potential receptors) in an AOI. The potential receptors are assigned a class from ‘A’ to ‘D’, representing progressively decreasing importance or value of groundwater according to the Environment Agency’s aquifer designation schema and the UKTAG guidance on the maximum depth of groundwater bodies (UKTAG, 2011). Evidence is also presented for decreasing water quality with depth and this factor is also considered in the methodology with an option to re-assign the class of the potential receptor according to groundwater quality (total dissolved solids (TDS)) where evidence exists. However, information on water quality at depth is generally sparse.

To determine the qualitative risk group for each potential receptor (low, medium-low, medium-high or high) both intrinsic vulnerability and specific vulnerability have to be assessed. A confidence level is also provided. This reflects the lowest of all confidence levels assigned to each factor in the intrinsic and specific vulnerability assessments. The risk groups and confidence levels can be used to identify sites where further information is required.

The intrinsic vulnerability assessment considers the geological characteristics of the rock units between the hydrocarbon source rock and a potential receptor(s) and their influence on the contaminant pathways between source and receptor. The proximity of the source and receptor, total thickness of low permeability mudstone in the intervening units and predominant groundwater flow mechanism(s) are all considered as part of the intrinsic vulnerability assessment. Preferential flow paths such as faults, mine workings and existing boreholes acting as conduits can allow contaminant transport over large distances in the sub-surface and therefore the presence of these is considered. A rating and weighting is also attributed to each potential receptor for each intrinsic vulnerability factor.

The specific vulnerability assessment combines the intrinsic vulnerability with the hazard (contaminant pathway driving force introduced by the sub-surface hydrocarbon exploitation activity) and natural drivers for contamination (i.e. groundwater head-controlled flow). A hazard factor is calculated from the potential impacts resulting from the hydrocarbon release mechanism (i.e. permeability enhancement, pressure/temperature changes, depressurisation) and natural head gradients (assumed from source to receptor if there is no evidence to the contrary). Generally, little information exists about the latter at a regional scale and therefore a worst-case (precautionary) scenario in which groundwater flows from the source to the potential receptor is assumed in the absence of further information.

The methodology has been tested for scenarios where receptors would be considered to be in the high or low vulnerability/risk groups according to the specific hydrocarbon activities and geological situations considered. It has also been tested in five case studies from different parts of England with different hydrocarbon source rocks/exploitation methods: conventional oil and gas in southeast England, CBM in the East and West Midlands, shale gas in northwest England and shale gas and conventional oil and gas in northeast England.

While there are differences in the technologies used and in geological settings, the case studies demonstrate that contaminant pathways in the sub-surface from hydrocarbon activities can be assessed using a common risk screening approach and parameter sets presented in this report. The case studies also indicate that a methodology based on a Tier 1 assessment, is useful in assessing and communicating risk and highlighting areas where additional information or process understanding may be important to improve risk assessment, management and decision making.

1 Introduction

In principle, the EU's Water Framework Directive (WFD) and the Groundwater Directive (GD) require that all groundwater is protected, though in the UK, groundwater bodies, which require active management under legislation, are defined for aquifers down to a maximum depth of 400 m below ground level (bgl) (UKTAG, 2011). Nevertheless, it is being increasingly recognised that groundwater within rocks that are not traditionally considered not considered to be a usable resource, and at a range of depths, may also be beneficial to society and require protection. Moreover, because of their nature, the impacts from contamination on such groundwater systems may not be observed for a long time, are not easy to predict, and it may not be possible to remediate in such instances. Consequently, any deep potentially contaminating activities, such as the exploration for, and development of, unconventional hydrocarbons should be assessed using a risk-based approach. In this context, a Tier 1 methodology is described in this report to assess risk to groundwater regardless of location (depth) and aquifer status, from the exploration for, and development of, unconventional hydrocarbons. This is consistent with the UK Government guidelines for environmental risk assessment and management (Gormley et al., 2011 "Guidelines for Environmental Risk Assessment and Management: Green Leaves III).

Onshore conventional hydrocarbon exploitation is long established in the UK but in the last five years there has been a renewed interest. In particular, there has been increasing interest in unconventional hydrocarbon extraction e.g. shale gas, coal bed methane (CBM) and underground coal gasification (UCG), where the geological formations require some form of stimulation, such as hydraulic fracturing, to release the gas/oil. Until now, shale gas has received most attention in England, although exploration licences have also been granted for CBM and mine gas, in addition to more conventional hydrocarbon resources. At the time of writing, the UK Government has said that UCG is unlikely to go ahead in the near future. An up-to-date guide to the geological units and areas that are currently licensed or under consideration for hydrocarbon exploration and production can be found on the UK Government's Oil and Gas Authority website (https://www.ogauthority.co.uk/data-centre/data-downloads-and-publications /licence-data/).

Hydrocarbon extraction may impact the subsurface by introducing new chemicals (potential pollutants), disturbing/mobilizing existing natural contaminants within rocks, or by changing the permeability structure of the rock (introducing new pathways). These changes represent additional hazards which may impact groundwater quality. Hazards to groundwater from development of shale gas resources are summarised by Lefebvre (2017) and include contamination from spills or leaks of fluids at the surface (considered the most probable mechanism leading to groundwater contamination), through leaking wells (the most challenging issue that might lead to groundwater contamination) or via subsurface pathways from the source rock (about which there is ongoing scientific debate). The subsurface hazard is influenced by the exploitation technique, which differs between hydrocarbon activities.

Groundwater may be **vulnerable** to contamination from these subsurface hazards through subsurface 'pathways'. However, despite the abundant literature emerging, particularly from North America, there remain great uncertainties as to the vulnerability of groundwater associated with these pathways due to the influence of the geological and hydrogeological circumstances (Harkness et al., 2017)

Factors influencing vulnerability include the geological properties of the rock between the **source** of contamination (the hydrocarbon source, i.e. where the contaminants exist or are introduced) and the **receptor** of contamination (geological formations that contain groundwater and require protection), pre-existing fracture and fault networks, and the stress regime.

Another key factor impacting groundwater vulnerability is the proximity of the source and receptor. A joint BGS/EA project (iHydrogeology) mapped the vertical separation distances between key shale units and principal aquifers in England and Wales (maps available at http://www.bgs.ac.uk/research/groundwater/shaleGas/iHydrogeology.html) (Loveless et al., 2018) using the BGS GB3D model (Mathers et al., 2014). This showed large variations in vertical separation between aquifer-shale pairs across England and Wales and even within basins. For example, the separation distance between the Bowland Shale (the hydrocarbon source unit of interest in the north-west) and Triassic Sandstone aquifer ranges from < 200 m to > 1,500 m. The iHydrogeology project highlighted the need for site specific assessments of vulnerability and risk.

This report describes a prototype, Tier 1 (Gormley et al., 2011), site specific, qualitative 3D risk screening methodology for potential receptor units (i.e. rock units that may contain groundwater) to hydrocarbon exploitation practices. The methodology (3DGWV) has been designed to support decision making and the management of subsurface hydrocarbon activities to ensure groundwater protection.

As far as possible, the framework is consistent with the terminology and definitions used for current groundwater vulnerability mapping and assessment tools (EA, 2017b). The methodology considers:

Intrinsic vulnerability: Characteristics of the intervening units between the potential receptor and hydrocarbon source rock (such as separation distance, thickness of mudstones and clays and geological pathways) which may influence potential receptor vulnerability.

Specific vulnerability: Intrinsic vulnerability * (nature of the hydrocarbon exploitation activity (and associated processes impacting the subsurface) * (driving heads).

Risk Group: Specific vulnerability and receptor classification (i.e. perceived importance of the rock unit for groundwater).

An overview of the vulnerability methodology is provided first. Factors influencing the receptor classification, intrinsic vulnerability and specific vulnerability are then presented with details of the methodology's scoring system. The 3DGWV methodology is accompanied by a software package containing; the 3DGWV Screening Tool Spreadsheet and the 3DGWV LithoFrame Viewer 3D model and user guide. This report provides guidance on how to undertake the 3DGWV screening and is intended to be used in conjunction with the 3DGWV Screening Tool Spreadsheet and the 3DGWV LithoFrame Viewer (LFV) 3D model.

The methodology is only concerned with risks to groundwater from hydrocarbon activities in the subsurface and does not include any considerations of either the effects of surface spillages or the integrity of boreholes which are dealt with through surface/near-surface groundwater vulnerability assessment tools and drilling regulation. It is designed to be used as part of a dynamic assessment which should be upgraded when additional information becomes available at each site. The risk group classifications are preliminary and used for illustrative purposes, and will be reviewed in the light of comments received, as will the scoring of the parameters within the assessment. Case studies in Appendix 7 demonstrate the effectiveness of the method and the potential use of the risk assessment.

2 Vulnerability screening methodology

The 3D groundwater vulnerability screening methodology for England (3DGWV) is designed to assess the intrinsic and specific vulnerability and assign a risk group to potential receptors, related to hazards associated with conventional or unconventional hydrocarbon exploitation activities in the subsurface. It is a prototype, Tier 1, qualitative risk screening method which can be used to identify whether or not a more detailed assessment is needed to aid risk prioritisation (see https://www.gov.uk/guidance/groundwater-risk-assessment-for-your-environmental-permit#history).

A risk group is attributed to each potential sub-surface receptor (rock unit) in a geological sequence. The risk group takes into account the importance of the receptor, the intrinsic vulnerability of the receptor, and the nature of the hazard (specific vulnerability). As far as possible, the framework is consistent with the terminology and definitions used in current groundwater vulnerability assessment framework for England (EA, 2017a):

Intrinsic vulnerability (IV): considers geological factors related to the intervening units between the potential receptor and hydrocarbon source rock (such as separation distance, mudstone and clay thickness and geological pathways) which may influence potential receptor vulnerability;

Specific vulnerability (SV): is Intrinsic vulnerability * nature of the hydrocarbon exploitation activity (and associated processes impacting the subsurface) * driving heads.

Risk Group (RG): Specific vulnerability and receptor classification (i.e. perceived importance of the rock unit for groundwater).

Since this is a Tier 1 methodology (Gormley et al., 2011), likelihood and impact (standard risk factors) are not quantified but are accounted for implicitly in the nature of the hazard. The methodology accounts for potential contamination to groundwater from specified hydrocarbon source units in the sub-surface only. It does not pertain to potential contamination from above ground sources, specific drilling practices or infrastructure (e.g. borehole integrity) failure. However, if a borehole is known to be leaking from a specific depth, the method can be applied to assess the vulnerability of receptors to contaminant release from this point.

The methodology has been developed in the context of current environmental regulations for England, including (but not limited to):

- The EA position statement on UCG, CBM, shale gas extraction and for oil and conventional gas exploration and extraction that it will "normally object to UCG, CBM or shale gas extraction infrastructure or activity within a SPZ1. This includes subsurface SPZ1 areas which are confined by impermeable strata at the surface". Outside SPZ1s, the EA will also normally object when the activity would have an "unacceptable effect on groundwater" (Table 1 in EA, 2017b);
- the Infrastructure Act (2015) prohibits high volume hydraulic fracturing at depths of less than 1000 m below ground level (bgl). The Onshore Hydraulic Fracturing (Protected Areas) Regulations (2016) extends this to 1200 m bgl within protected groundwater source areas;
- drilling is controlled under the Environmental Protection Act (1990), through which protection is emphasised for groundwater that is currently used as a drinking water resource. Best Available Technology is expected to protect groundwater where drilling or operation of boreholes passes through a groundwater resource (EA, 2017b).

It is stressed that the risk group boundaries identified by this screening methodology are preliminary, based on professional judgment, and are expected to be revised with further review, testing and increasing scientific evidence. Therefore, it is not recommended that the initial risk screening be used on its own for site specific decision making by regulators, but that it be used to help guide further investigations. Where there is a lack of data for developing a conceptual model, either further research/investigation should be undertaken to address the knowledge gaps, or they should be identified as areas of high uncertainty where the precautionary principle should be applied in assessing the needs for protecting groundwater quality.

2.1 APPROACH

The methodology uses an overlay/index approach similar to the DRASTIC method, a standardized system model to evaluate ground water pollution potential using hydrogeological settings (Aller et al., 1987). Overlay/indexing approaches are used as an alternative to detailed numerical groundwater modelling, when there are insufficient quantitative data. In DRASTIC, parameters which are considered to be influential to the overall vulnerability of groundwater from surface activities are combined. Each parameter has a range of possible values, indicating the degree to which that parameter protects or makes groundwater vulnerable in a region. Overlay/indexing methods are relatively easy to implement, using readily available data over large areas, and typically produce categorical results (Focazio et al., 2002). DRASTIC and other related approaches have been very widely used (Gogu and Dassargues, 2000a; Kumar et al., 2015; Shirazi et al., 2012). Other approaches, which take into account preferential flow pathways, have been considered for karst environments e.g. EPIK, PI and COP (Andreo et al., 2009; Doerfliger et al., 1999; Gogu and Dassargues, 2000b; Goldscheider, 2005; Vías et al., 2006).

To date, the majority of published overlay/indexing models for hydrocarbon exploitation have been developed to assess the risks to groundwater from the surface aspects of the development These include gas exploration in the Karoo Basin (Karoo Groundwater Expert Group, 2013), tar sand extraction in Nigeria (Ojuri et al., 2010), open cast removal of oil shale in Jordan (Mohammad et al., 2016), coal mining in India (Tiwari et al., 2016), tight petroleum exploration in Quebec, Canada (Raynauld et al., 2016), tight shale exploration in Ohio (Thompson, 2012) and shale gas development in South Africa. WorleyParsons (2013) developed a methodology to assess the risk to groundwater and related receptors from the exploitation of coal seam gas (or CBM) using a hybrid approach within a source–pathway–receptor risk model combining an overlay/index method with a process-based model. A number of source hazards were identified and links between these and the pathways and receptors were then separately assessed to inform prioritisation. Each pathway and receptor factor was weighted, rated and scored. Water extraction and gas migration were considered to be the most significant hazards, together with five pathway factors and three groundwater receptors. Application of this risk mapping to each of the individual coal seams enabled identification of seams which presented the greatest risk to groundwater and its receptors.

The 3DGWV screening methodology comprises a series of steps, beginning first, and most importantly, with the conceptual model of the deep to shallow hydrogeological system for the full 3D footprint of the proposed hydrocarbon activity, below the Area of Interest (AOI). The AOI is the area at the surface below which sub-surface hydrocarbon extraction activities could potentially impact groundwater. The AOI includes all boreholes laterals and cavities created as part of the extraction process, in addition to a 2 km buffer zone.

The vulnerability screening should be carried out for every geological unit, or potential receptor, between the hydrocarbon source unit and the surface or, if the proposed activity is < 1200 m below ground surface, to a depth of 1200 m, including units below the proposed hydrocarbon activity**.** The exact resolution of units is dependent on the region, information available and purpose of the screening. '*Hydrocarbon source unit*' refers to the rock unit from which the hydrocarbon would be extracted, i.e. for conventional oil and gas, the reservoir storing the hydrocarbon, rather than the original source of the hydrocarbons. For shale gas and CBM/UCG the source rock will be the shale and coal units respectively.

The potential hydrocarbon source unit rocks and aquifers can be displayed in the 3DGWV LithoFrame Viewer 3D model. The LithoFrame Viewer 3D model comprises a series of geologic cross-sections across England. Each cross-section has been attributed, where relevant, with; a) potential hydrocarbon source rocks, and b) EA/BGS aquifer designations. This information provides a regional understanding of the 3D spatial relationship between hydrocarbon source rocks and aquifers. This can then be used to aid development of the conceptual model. Additional sources of information should also be utilised, where available, as outlined in this document. Confidence limits are explicitly recorded as part of the assessment process and should be taken into account when reviewing specific vulnerability scores and risk groupings. In AOIs where there is a high degree of geological variability and/or uncertainty regarding the conceptual model, a number of potential geological scenarios may be possible and so each should be assessed in order to understand the sensitivity to changing parameters. As the site is investigated further, the screening can be refined with the additional knowledge, and uncertainty reduced. The stages of the assessment process are outlined below in Figure 2.1 and described in full in Table 2.1 to Table 2.3. An example is presented in Appendix 1.

Classification of the importance of potential receptors (PR); undertaken for all units within the geological sequence, according to EA aquifer designations and evidence for groundwater quality. These are classified as A to D, representing progressively lower value groundwater.

Intrinsic vulnerability (IntV); assessment of the intrinsic vulnerability of each potential receptor to the proposed hydrocarbon activity. Parameters relating to key factors (and sub-factors) influencing intrinsic vulnerability (e.g. proximity between hydrocarbon source unit and potential receptor) are provided with a parameter rating (r_x). Each subfactor is weighted according to its perceived influence on vulnerability (w_x). An overall score for each subfactor is calculated ($r_x * w_x$). The confidence level is also recorded for each sub-factor.

The scores for each subfactor ($r_x * w_x$) are then added together to obtain an overall intrinsic vulnerability ($V = \Sigma (r_x * w_x)$) for each potential receptor in the geological sequence

Specific vulnerability (SpecV); hazard factors are ranked according to the nature of the hazard(s) resulting from the hydrocarbon activity and contaminant release mechanism (H_1) and local hydraulic gradient(s) or driving force(s) (H_2). The rankings are not weighted. H_1 and H_2 are both multiplied with the intrinsic vulnerability.

Risk group (RG); the receptor classification and specific vulnerability score are combined to assign potential receptors as low, medium-low, medium-high or high risk, according to Table 2.4.

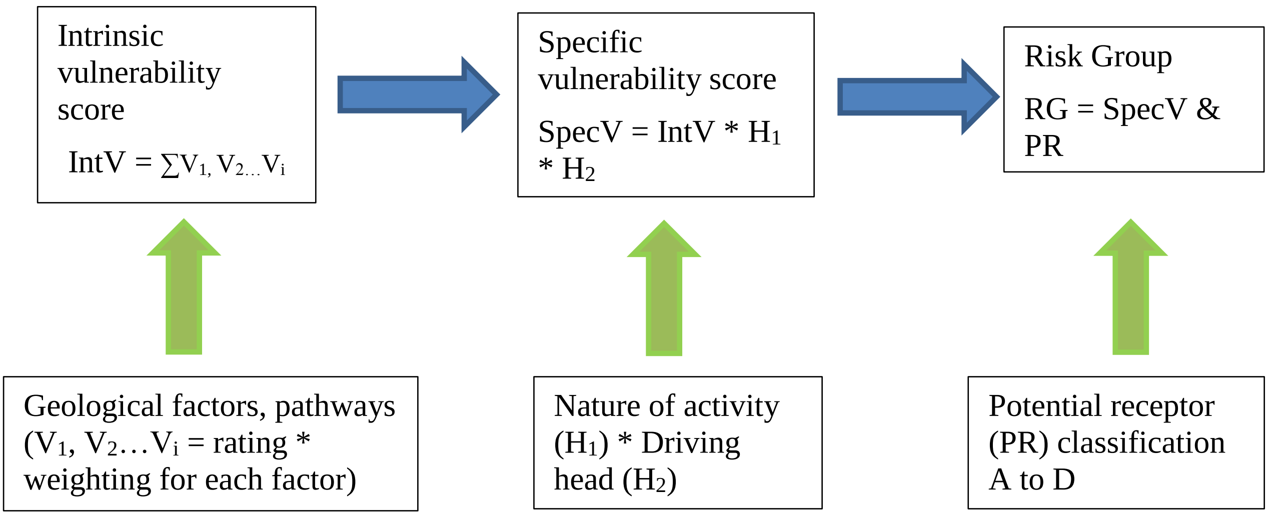


Figure 2.1 Flow chart showing the screening process (full process in Table 2.1 to Table 2.4)

Table 2.1 Receptor classification. (Classifications are currently preliminary).

RECEPTOR CLASSIFICATION		
Potential receptor classification	**EA aquifer designation and depth to top of unit below surface**	**Total dissolved solids (TDS)**
A	Principal aquifer < 400 m	< 1000 mg/l
B	Principal aquifer > 400 m, secondary aquifer < 400 m	1000-3000 mg/l
C	Secondary aquifer > 400 m	3000-10,000 mg/l
D	Unproductive	> 10,000 mg/l

Table 2.2 Hazard ranking. (Ranking is preliminary).

HAZARDS					
Hazard factor	**Hazard parameter**	**Ranking (r)**	**Weighting (w)**	**Confidence**	**Maximum score**
Release mechanism of hydrocarbon (H_1)	Permeability enhancement and increase in pressure and temperature (UCG)	5	N/A	H	5
	Permeability enhancement from high volume hydraulic fracturing (e.g. shale gas)	4			
	Permeability enhancement from low volume hydraulic fracturing (e.g. conventional oil and gas with hydraulic fracturing)	3			
	Water table lowering and depressurisation (CBM)	2			
	No permeability enhancement (passive) for conventional oil and gas.	1			
Head gradient driving flow (H_2)	Head gradient from hydrocarbon source to receptor (or unknown)	2		L, M or H	2
	No head gradient from hydrocarbon source to receptor	1			

Table 2.3 Intrinsic vulnerability. (Rating and weighting are preliminary only).

INTRINSIC VULNERABILITY						
Assessment for intervening zone between top of hydrocarbon source unit and base of the potential receptor unit						
Intrinsic vulnerability factor	**Intrinsic vulnerability subfactor**	**Intrinsic vulnerability parameter range**	**Rating (r)**	**Weighting (w)**	**Confidence**	**Maximum score**
Proximity of hydrocarbon source unit and potential receptor	Vertical separation of hydrocarbon source unit and potential receptor	>1200 m	1	1.5	M or H	12
		900-1199 m	2			
		600-899 m	3			
		400-599 m	4			
		300-399 m	5			
		200-299 m	6			
		100-199 m	7			
		<99 m	8			
	Lateral separation of hydrocarbon source unit and potential receptor	> 2000 m	0	3	M	12
		1000 to 1999 m	1			
		500 to 999 m	2			
		200 to 499 m	3			
		< 199 m	4			
Mudstones and clays in intervening zone between hydrocarbon source unit and potential receptor		>250 m mudstone or clay	1	3.5	M or H	17.5
		>100 m mudstone or clay	2			
		>50 m mudstone or clay	3			
		> 20 m mudstone or clay	4			
		No intervening strata or < 20 m mudstone or clay	5			

Assessment for intervening zone between top of hydrocarbon source unit and top of the potential receptor unit						
Factor	**Sub-factor**	**Range**	**Rating (r)**	**Weighting (w)**	**Confidence**	**Max score**
Groundwater flow mechanism		Only units designated 'Unproductive Strata' by EA	0	3	M or H	9
		> 50 % principal or secondary aquifers (EA designation) with intergranular flow (e.g. sands)	1			
		> 50 % principal or secondary aquifers (EA designation) fractured, poorly connected or mixed fracture and intergranular flow (e.g. well fractured sandstones, multi-layered Carboniferous rocks)	2			
		> 50% principal or secondary aquifers (EA designation) fractured, well connected (e.g. limestone)	3			
Prefer-ential flow path-ways	Faults	Faults not known in the area of interest	1	4.5	L, M or H	18
		Known faults within 2 km of the hydrocarbon activity	2			
		Known faults within 0.5 km, or transmissive fault within 2 km of the hydrocarbon activity	3			
		Faults known to be transmissive within 0.5 km of the hydrocarbon activity	4			
	Solution features	No potential solution features	0	2	L or M	6
		Potential for solution in evaporite minerals	1			
		Potential for karst or known solution features in evaporite minerals	2			
		Known karst features in area of interest	3			
	Anthrop-ogenic features-mines	No known mine (and assumed to be absent) within 2 km of maximum lateral extent of hydrocarbon activity, or 600 m vertically	0	8	H	16
		Known mine within 0.5-2 km of the maximum lateral extent of hydrocarbon activity, and/or 600 m vertically	1			
		Known mine within 0.5 km of the maximum lateral extent of hydrocarbon activity, and/or 200 m vertically	2			
	Anthrop-ogenic features-borehole s	No known boreholes (and assumed none present) within 600 m vertically or 2 km laterally of hydrocarbon activity	0	4	M or H	8
		Known boreholes extending to within 600 m vertically, and/or 0.5-2 km laterally of hydrocarbon activity	1			

		Known boreholes extending to within 200 m vertically, and/or 0.5 km laterally of hydrocarbon activity	2			
					TOTAL	**98.5**

Table 2.4 Risk groups based on potential receptor classifications and specific vulnerability scores. Note: classifications are preliminary.

	Specific vulnerability score			
Potential receptor classification	< 250	250-500	500-750	>750
A	Medium/Low	Medium/High	High	High
B	Low	Medium/Low	Medium/High	High
C	Low	Low	Medium/Low	Medium/high
D	Low	Low	Low	Low

2.2 DEVELOPMENT OF A GEOLOGICAL CONCEPTUAL MODEL

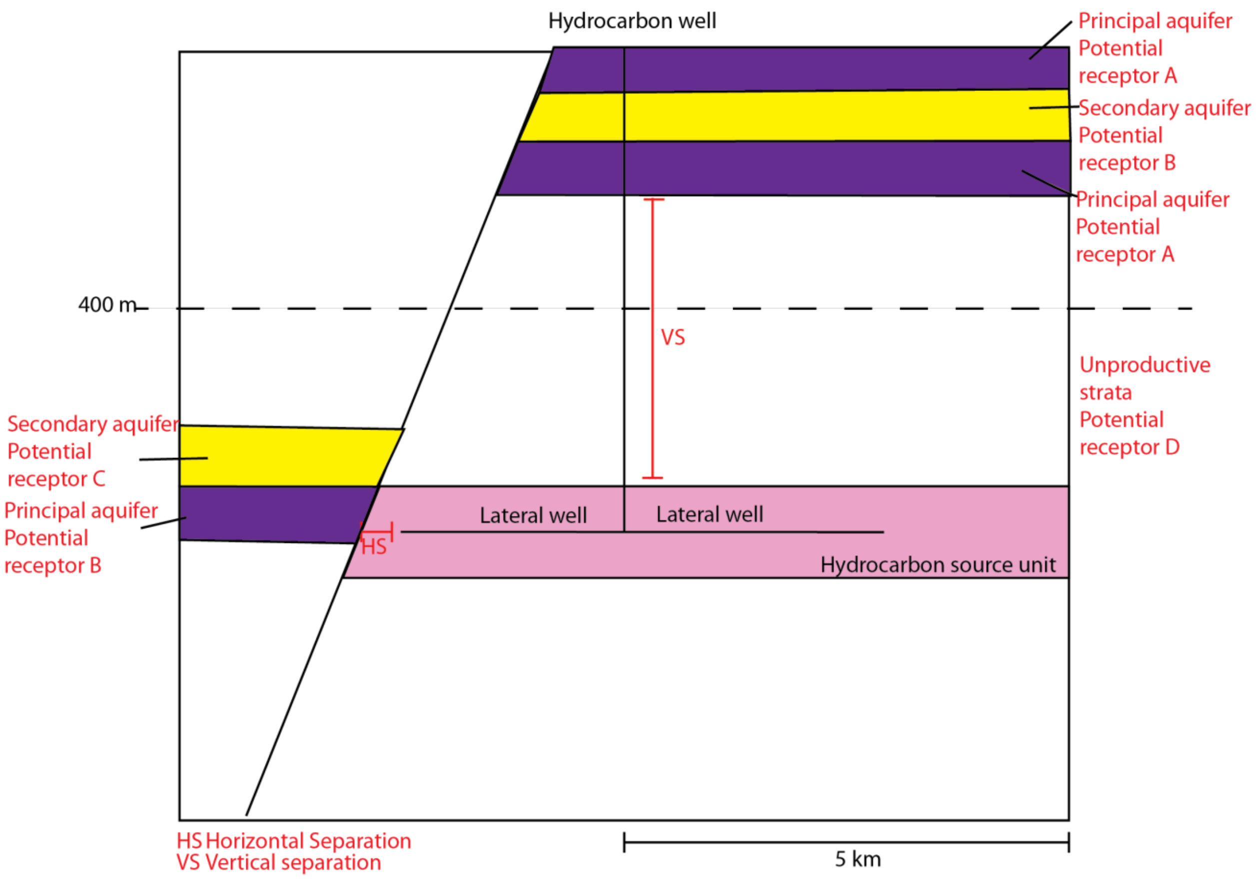
Key to the screening methodology is the development of a conceptual geological and hydrogeological model of the proposed hydrocarbon extraction site and surrounding area (Figure 2.2; Appendix 1). This is used to inform the classification of the importance of potential receptors (Section 3), intrinsic vulnerability (Section 4) and specific vulnerability (Section 5). In the model, all units across the footprint of the proposed hydrocarbon activity and within 2 km of the lateral extent of the hydrocarbon infrastructure (e.g. lateral and deviated boreholes or cavities), i.e. the 'Area of Interest' (AOI), should be identified.

The 3DGWV LithoFrame Viewer (LFV) 3D model, in conjunction with the 3DGWV screening tool (in associated digital media), can initially be used to guide this process and identify aquifer designations and hydrocarbon source units (in addition to other digital media). The LFV model comprises 195 intersecting cross-sections about 20 to 30 km apart, and therefore is not a full 3D volume. However, it gives a good general indication of the stratigraphic sequence at a specific location along, or close to, the lines of section. Where the closest cross-section is some distance away from the proposed site care must be taken as it may not be representative of the geological succession. In these cases other information should be examined. Additionally, due to the vertical exaggeration of the 3D sections provided as part of the accompanying LFV project sections are likely to be more accurate in the vertical direction than in the horizontal.

The model is based on 1:625 000 scale geological mapping and hence there has been some generalisation. Most geological units in the model are identified at the group level, whereas the original aquifer designation was carried out at 1:50,000 scale (formation or member scale), and only for units that occurred at the ground surface. Similarly, potential hydrocarbon source and reservoir units refer only to particular formations within a group, but the whole group will have been identified as such in the model (Appendix 2). Where available, more site-specific information should be obtained from regional geological guides, memoirs, borehole logs and geophysical logs, as detailed in the 'sources of information' below to improve the conceptual site model.

As part of this process geological faults and structure should be identified. It is important to understand the location and hydraulic properties of geological faults and the uncertainties associated with their precise position at the surface as well as at depth. However, there are significant uncertainties regarding the spacing and character of faulting at depth in the UK (Monaghan, 2017). Faults are not currently indicated explicitly on the 3DGWV cross-sections in the LFV, although larger ones can be identified by the obvious offset of beds. Faults are often portrayed as a single line on geological maps whereas, in reality, they consist of zones of several tens of metres, or greater, in width, containing several fractures and fault rock. Whether or not small faults are shown on geological maps depends on the map and fault scale, the presence of superficial deposits (since the presence of thick superficial deposits overlying bedrock strata make it more difficult to accurately map the surface expression of faults), the date of the mapping, the lithology and thickness of the formation affected and also the economic importance of any minerals associated with the rocks. For example, historically more faults have been mapped in the Coal Measures, due to the effect that even small throws can have on the underground mining of coal seams. Faults are also occasionally recorded in borehole logs.

If there is significant geological variability across an AOI, either the most sensitive location or a number of locations could be used for the vulnerability/risk screening.



Potential receptor	Thickness (m)	% Mudstone	Groundwater flow
A	67	25	Intergranular
B	67	75	Fracture
C	67	25	Intergranular flow
D	300	100	NA

Figure 2.2 Schematic conceptual model. VS is the vertical separation and HS is the horizontal (lateral) separation. The pink unit is the hydrocarbon source unit. Purple indicates units designated as principal aquifers by the EA and yellow secondary aquifers. Not to scale.

Sources of information

- Cross-sections in 3DGWV LFV 3D model, faults can be identified from offset lithologies (see above for caveats relating to this model).
- Shale/ aquifer separation maps http://www.bgs.ac.uk/research/groundwater/shaleGas/aquifersAndShales/maps/separationMaps/home.html (BGS, 2017a).
- Mapped faults and cross-sections on the scanned geological maps at a range of scales (1:50 000 and 1:10 000). 1:50 000 maps are accessible from the BGS maps portal http://www.bgs.ac.uk/data/maps/home.html (BGS, 2017b).
- Geological memoirs and regional guides (for thickness variations, depth and faults) http://www.bgs.ac.uk/data/publications/pubs.cfc?method=listResults&topic=RU&series=RG&pageSize=100& (BGS, 2017c).
- Nearby boreholes (for thickness variations, depth and occasionally faults). The locations of all known boreholes over 400 m depth are shown in the 3DGWV ArcGIS layer (including those held confidentially). The depth and logs of all open access boreholes can be viewed via the BGS Geology of Britain viewer: http://mapapps.bgs.ac.uk/geologyofbritain/home.html (BGS, 2018). Some logs are held as 'management protect' and although not freely available, the data can be obtained on request. Information for hydrocarbon (management protect) boreholes are available via the Oil and Gas Authority's (2018) website https://www.ogauthority.co.uk/data-centre/access-to-information-and-samples/. Information for water (management protect[1]) and other (management protect) boreholes are available on request from BGS or may be available to the EA from other sources. Other confidential boreholes included in the layer may also be available to the EA on request to BGS.
- Legacy coal mine plans from the Coal Authority are likely to have information on the location of faults where they are available.

[1] Water (management protect) boreholes are generally for public water supply and will be known about and licensed by the Environment Agency.

3 Receptors

Groundwater and designated groundwater bodies are potential contamination receptors and understanding their designation and current practices related to their protection is essential in developing an effective 3D vulnerability methodology. The EU's Water Framework Directive (WFD) and the associated Groundwater Directive (GD) are cornerstones of groundwater governance in England. As transposed by the Environmental Permitting Regulations, these Directives establish a series of environmental objectives for groundwater that include preventing or limiting the inputs of pollutants to groundwater and ensuring that groundwater bodies achieve (and maintain) good chemical and quantitative status In England, responsibility for regulation of groundwater and its management and protection from any potentially polluting activity is the remit of the EA. The Agency's approach to this is outlined in the document 'The Environment Agency's approach to groundwater protection' (EA, 2017b).

Groundwater bodies are groundwater management units. They exist within aquifers, and are defined within aquifers or contiguous aquifers within which the groundwater resides. Delineation of groundwater bodies takes into account geological boundaries, groundwater flow divides, pollution/abstraction pressures natural chemical variations. UK guidance is that groundwater bodies would not extend below depths greater than 400m, except where management and protection is required at greater depths, i.e. WFD status and trends objectives apply, (UKTAG, 2011). However, all groundwater, regardless of depth or quality, requires protection from inputs of pollutants, unless the groundwater can be shown to be permanently unsuitable. This is because, for example, groundwater at depth could be part of a pathway for pollutants to travel to designated groundwater bodies, for which particular protective measures might be required. In addition, groundwater at greater than 400m depth could be considered for protection because of its value as mineral waters, cultural value, or potential for future use.

Considerations of groundwater quality may also influence decisions regarding groundwater protection and the development of a 3D vulnerability methodology. Groundwater quality (total dissolved solids or TDS) data to a depth of nearly 2500 m for England show a lower TDS bound which decreases in quality (increases in TDS) with depth. However, at most depths, TDS concentrations ranging up to three orders of magnitude, and data show that potable water (TDS < 1000 mg/l) exists at > 400 m bgl in places (Section 3.3.1). This limit also does not take into account potential future uses for groundwater with a range of qualities and technological developments. It is also well known that deep groundwater flow systems connect to the surface and feed strategically important springs used for recreational purposes (e.g. Bath Spring) and bottled waters. Therefore, a practical framework for protection of deep (> 400 m bgl) and brackish waters has been found to be lacking.

This chapter reviews the policies for the protection of groundwater in England, including the associated practical and regulatory guidance, and assesses the suitability of current definitions for vertical and lateral extent of aquifers in England. These definitions are considered in the context of deep groundwater quality data for England and the need to protect deep groundwater systems now and in the future. International best practices are subsequently discussed and details presented in Appendix 3. The resulting classification of receptors based on their importance is then presented.

3.1 CURRENT EA PRACTICE RELATED TO THE PROTECTION OF GROUNDWATER IN ENGLAND

The following is a summary of aspects of two key (though not the only) EU Directives and guidance on their application to groundwater that have a bearing on the definition of the 3D extent of groundwater systems. Further information is included in Appendix 3.

3.1.1 Overview of EU Directives and guidance

3.1.1.1 THE WATER FRAMEWORK DIRECTIVE AND GROUNDWATER DIRECTIVE

Directive 2000/60/EC (EC, 2000), adopted in October 2000, and referred to as the EU Water Framework Directive or simply the WFD, established a framework for community action in the field of water policy, including policy related to groundwater. Directive 2006/118/EC (EC, 2006), known as the Groundwater Directive, was developed in response to requirements of Article 17 of the WFD and sets groundwater quality standards and introduces measures to prevent or limit pollutants entering groundwater.

For groundwater, the key environmental objectives of the WFD, as described in Articles 4.1.b.i. and 4.1.b.ii., are for Member States to:

> "implement the measures necessary to prevent or limit the input of pollutants into groundwater and to prevent the deterioration of the status of all bodies of groundwater" and to "protect, enhance and restore all bodies of groundwater, ensure balance between abstraction and recharge of groundwater, with the aim of achieving good groundwater status at the latest 15 years after the date of entry into force of this Directive [the WFD]".

The WFD sets out steps and a timeframe for achieving good quantitative and chemical status (outlined in Appendix 3) of European waters, including groundwater. As part of this process, the WFD requires Member States to define and identify groundwater bodies within River Basin Districts and to report to the European Commission (EC) on the status of these bodies. The following groundwater-related definitions are set out in the WFD.

Groundwater is defined in the WFD in Article 2.2 as

> "all water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil".

In Article 2.11 an **aquifer** is defined as

> "a subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater";

in Article 2.12 a body of groundwater or **groundwater body** is defined as a

> "distinct volume of groundwater within an aquifer or aquifers";

As a pre-cursor to establishing the status of a GWB, the WFD requires member states to undertake an initial characterisation (risk assessment) of all groundwater bodies

> "to assess their uses and the degree to which they are at risk of failing to meet the objectives for each groundwater body under Article 4".

It requires member states to identify the location and boundaries of groundwater bodies, the pressures to which they are liable, the general character of overlying strata from which the bodies receive recharge and groundwater bodies for which there are directly dependent surface water ecosystems. It also notes that Member States may group groundwater bodies together for the purposes of this initial characterisation.

Annex 2, section 2.2 of the WFD sets out the requirements of further characterisation of groundwater bodies, or groups of bodies, which have been identified as being at risk based on the initial characterisation (Appendix 3).

In addition, Annex 2, section 2.4 of the WFD requires member states to review the impact of changes in groundwater levels and to

> "identify those bodies of groundwater for which lower objectives are to be specified under Article 4 including as a result of consideration of the effects of the status of the body on: (i) surface water and associated terrestrial ecosystems; (ii) water regulation, flood protection and land drainage; and, (iii) human development".

Similarly, Annex 2, section 2.5 requires member states to review the impact of pollution on groundwater quality and to

> "identify those bodies of groundwater for which lower objectives are to be specified under Article 4(5) where, as a result of the impact of human activity, as determined in accordance with Article 5(1), the body of groundwater is so polluted that achieving good groundwater chemical status is infeasible or disproportionately expensive".

After the WFD was adopted, a Common Implementation Strategy (CIS) (EC, 2001) was developed and agreed in May 2001. This sets out a common understanding of approaches to, and implementation of, the WFD, and provided a series of examples of best practice. This is detailed in Appendix 3.

3.1.2 Implementation in England

Allen et al. (2002) describe the interpretation of the WFD and outline procedures used by the EA to undertake the initial delineation and characterisation of the groundwater bodies to meet the requirements of the WFD. The principles set out in Allen et al. (2002) included the following key observations, that:

> "the delineation and characterisation of groundwater bodies [should be] … iterative. Thus, for example, only simple conceptual models are required at first in order to delineate the groundwater bodies, becoming, where required, more sophisticated (and expensive) as the characterisation process proceeds. Iteration also allows for the refining of boundaries or the subdivision or aggregation of groundwater bodies"; that: "Groundwater systems in aquifers should be subdivided or aggregated to form groundwater bodies of a suitable size for management (generally at least tens of square kilometres in area), which will reflect the pressures and impacts on groundwater"; and that: "Groundwater body boundaries should generally be chosen initially on the basis of geology, using WFD aquifer boundaries. If necessary, subsequent subdivision is performed using groundwater divides and finally using flowlines. The groundwater body as delineated will remain constant during a River Basin Management Plan, but may be subdivided or amalgamated with adjacent bodies in subsequent RBMP cycles, dependent on management needs".

The report concluded with two final principles, that

> "given that the definition of an aquifer in WFD terms is essentially based on abstraction and flow criteria, and that the lower abstraction limit is small, most geological materials in the UK are likely to be classified as aquifers in WFD terms. The main guiding principle for the delineation of groundwater bodies is that flowlines in an aquifer should not cross from one groundwater body to another. This is to enable groundwater bodies to be treated as coherent hydraulic systems (to aid determination of quantitative status) and to be managed as such."

Allen et al. (2002) also noted that

> "there may be geological materials which have sufficient porosity and permeability to support either abstraction or flow (and therefore are potential aquifers in WFD terms) but which do neither when saturated. This could be, for example, because such potential aquifer material lies at depth and therefore is not exploited and does not support surface flow. This material is classified as a potential aquifer on the basis of its aquifer properties, but need not be formally identified as a WFD aquifer"

Note that no explicit guidance was given by Allen et al. (2002) on the delineation of base of aquifers or groundwater bodies.

3.1.3 UK Technical Advisory Group (UKTAG) guidance on implementation of the WFD

UKTAG, the advisory group on implementation of the WFD and Groundwater Directive in the UK, published a paper setting out guidance on the delineation and characterisation of groundwater bodies in the UK in response the requirements of the WFD (UKTAG, 2011). The report refines the definitions of groundwater, aquifer and groundwater bodies, sets out the principles of how groundwater bodies should be delineated, provides guidance on groundwater body depth and the definition of groundwater body horizons and reporting to the EC. The following is a summary of UKTAG definitions and guidance relevant to groundwater body delineation.

3.1.3.1 UKTAG - REFINED DEFINITIONS RELATED TO GROUNDWATER

In addition to the definitions in the WFD, UKTAG (2011) introduces two new concepts of **pore water**, as

> "pore waters in low permeability subsoils (e.g. clays) do not represent groundwater as a receptor, because they do not provide a useful water resource and pollutants going to surface water receptors travel at velocities that are measured on a millimetre-scale per year. Therefore, water in these deposits should not be subject to the same management objectives as, for example, aquifers or groundwater bodies",

and of **groundwater at extreme depth**, as

> "groundwater that exists at extreme depth and is permanently unsuitable for use as a resource, e.g. due to high salinity, should not be considered as a groundwater body".

These are then related to interpretations of the WFD definitions of groundwater based on their respective roles in environmental management (see Table 3.1 below).

Table 3.1 Roles of sub-surface water in Environmental Management

Zone	Terminology	Role
Water in unsaturated zone	Pore water	Pore water above the water table. Protect as a vertical pathway to groundwater
Water in saturation zone		Pore water in low permeability deposits. The concept of the zone of saturation is not relevant in these deposits as it is usually not feasible to define a water table where lateral percolation is impeded. The main role of these strata is as a protecting layer for groundwater
	Groundwater in strata overlying or underlying groundwater bodies	Groundwater has a value as a lateral or vertical pathway to other receptors. May be usable but only for local supplies $<10m^3$/day
	Groundwater in a groundwater body	Groundwater is part of an aquifer and is a receptor as a long term resource that can be exploited for human activities or support surface flows & ecosystems
	Groundwater that is permanently unsuitable for use	Groundwater which has neither pathway nor resources value. For example, where salinity is greater than seawater.

3.1.3.2 Groundwater body depth

UKTAG (2011) extends the CIS guidance (EC, 2003) related to groundwater lateral boundaries (Appendix 3) and groundwater body depth. UKTAG (2011) notes that

> "the main driver for delineating groundwater bodies in three dimensions is groundwater body management", that "the drivers for groundwater body management relate to its use as a water supply or its contribution to surface water systems. The latter focuses on the unconfined aquifers and, to a lesser extent, discharge from confined aquifers ... Therefore, management of groundwater at greater depths mainly relates to its use for water supply".

UKTAG (2011) states that

> "At some depth, depending on the nature of the aquifer, groundwater loses its value as a resource that can be either exploited for human activities or support surface flows and ecosystems"

and goes on to define default depth values for the base of groundwater bodies in the UK, noting that these values

> "should be amended using local information if available. This information should comprise hydrogeological and hydrochemical information to identify the resource boundaries, preferably through the use of water table information and structural or stratigraphic features that represent aquitards".

UKTAG (2011) states that the default maximum thickness of groundwater bodies in the UK should be 400 m, with the exception of porous superficial aquifers, such as sand and gravel aquifers, and low transmissivity bedrock, such as the Dalradian, which should have an assumed maximum thickness of 40 m and 100 m, respectively (UKTAG, 2011). Measurement of the thickness should be from the upper extent of the groundwater body downward, where

> 'the upper extent of the groundwater body is the water table. Where information on the level of the water table is not available across the groundwater body as a whole, the upper extent can be considered to lie at ground level'.

It is not explicit in the UKTAG report how this applies to confined groundwater bodies. However, if it is assumed that for most confined aquifers the upper extent of the water table (piezometric surface) is not available, then one possible interpretation of the guidance would be that for confined aquifers the upper extent of the aquifer should be considered to be ground level. It could also be taken as the top of the aquifer unit.

3.1.4 Groundwater protection in England

The EA published a revised approach to groundwater protection in November 2017 (EA, 2017b). The principles and definitions set out in that report and associated documentation are consistent with the previous, more detailed Groundwater protection: principles and practice (GP3) report (EA, 2013).

The EA currently defines principal aquifers, secondary aquifers (secondary A, B and undifferentiated), and unproductive strata (Table 3.2) based on their geological characteristics, the quantity and ease with which groundwater can be obtained from the aquifers, and the extent to which they support flow in rivers and habitats.

Table 3.2 Aquifer types in England

Aquifer type	Description
Principal aquifer	Rocks that provide significant quantities of water for people and may also sustain rivers, lakes and wetlands. Formerly referred to as 'major aquifers'.
Secondary aquifers	Rocks that provide modest amounts of water, but the nature of the rock or the aquifer's structure limits their use. They remain important for rivers, wetlands and lakes and private water supplies in rural areas. Formerly referred to as 'minor aquifers'.
Secondary A	Permeable rocks capable of supporting water supplies at a local rather than strategic scale, and in some cases forming an important source of base flow to rivers.
Secondary B	Predominantly lower permeability rocks that may store and yield limited amounts of groundwater due to localised features such as fissures, thin permeable horizons and weathering.
Secondary undifferentiated	Designation assigned in cases where it is not been possible to attribute either category Secondary A or B to a rock type. In most cases, this means that the layer in question has previously been designated as both 'minor' and 'non-aquifer' in different locations due to the variable characteristics of the rock type.
Unproductive strata	These are rocks that are generally unable to provide usable water supplies and are unlikely to have surface water and wetland ecosystems dependent upon them. Formerly referred to as 'non-aquifers'.

The EA approaches groundwater protection in the context of a risk-based framework, where the technical framework for groundwater risk assessment includes:

- a source–pathway–receptor (S-P-R) approach;
- a conceptual model;
- a tiered approach from qualitative risk screening to detailed quantitative risk assessment (Tier 1 -3);
- identification of sources or potential hazards, examining consequences and evaluating the significance of any risk;
- dealing with uncertainties and sensitivity analysis; and
- risk management.

and where this is employed in conjunction with the use of the 'precautionary principle'.

The EA (2017b) provides position statements that apply to developments and activities in SPZ1 for a range of activities, including: Underground coal gasification, coal bed methane and shale gas extraction (C6) and oil and conventional hydrocarbon exploration and extraction (C7). Position statement C6 states:

> "The Environment Agency will, where appropriate, work in partnerships on initiatives to facilitate development of sustainable sources of energy. However, it will normally object to UCG, CBM or shale gas extraction infrastructure or activity within a SPZ1. This includes subsurface SPZ1 areas which are confined by impermeable strata at the surface.
>
> Outside SPZ1, the Environment Agency will also normally object when the activity would have an unacceptable effect on groundwater. Where development does proceed and where any associated drilling or operation of the boreholes/shafts passes through a groundwater resource, the Environment Agency expects best available techniques (BAT) and pollution prevention measures to be applied to protect groundwater.
>
> The Environment Agency will expect a detailed hydrogeological risk assessment to be produced for any onshore oil or gas site activity. The assessment must include potential impacts to all groundwater which could be affected, such as any groundwater bearing strata even at depth. Mitigation measures to protect all groundwater will be expected to reflect the sensitivity of that groundwater and any associated receptors. The receptors may include drinking water sources, surface waters and wetlands; as well as the potential uses of deeper groundwater (for example, artificial storage and recovery or geothermal uses)."

and for oil and conventional gas exploration and extraction, C7 states:

> "The Environment Agency will normally object to such hydrocarbon exploration, extraction infrastructure or activity within SPZ1, which will also include any subsurface SPZ1 areas which are confined by impermeable strata at the surface.
>
> Outside SPZ1, the Environment Agency will also normally object when the activity would have an unacceptable effect on groundwater. Where development does proceed, the Environment Agency expects BAT and pollution prevention to protect groundwater to be applied where any associated drilling or operation of the boreholes passes through a groundwater resource.
>
> The Environment Agency will expect a detailed hydrogeological risk assessment to be produced for any onshore oil or gas activity. The assessment must include potential impacts to all groundwater which could be affected, such as any groundwater bearing strata even at depth. Mitigation measures to protect all groundwater will be expected to reflect the sensitivity of that groundwater and any associated receptors. The receptors may include drinking water sources, surface waters and wetlands as well as the potential uses of deeper groundwater (for example, artificial storage and recovery, or geothermal uses).
>
> Where oil and gas activities already exist, the Environment Agency will work with operators to assess and if necessary mitigate the risks. It will normally object to any redevelopment scheme involving retention of oil exploration, extraction infrastructure or activity within SPZ1 unless there are substantial mitigating factors."

GP3 (EA, 2013) provided more information on the concept of "groundwater that exists at extreme depth and is permanently unsuitable for use as a resource" that was used by UKTAG (2011). In GP3 it was noted that

> "[the WFD] require us to take all necessary measures to prevent the input of hazardous substances into groundwater and to limit the input of non-hazardous pollutants so as to avoid the pollution of groundwater. However, provided it does not compromise the objectives set

out in Article 4 of the Water Framework Directive, we may grant a permit for the injection of water containing hazardous substances from hydrocarbon or mining activities or the injection for storage of natural gas or liquefied petroleum gas – but only where the strata have been determined as permanently unsuitable. The geological formation must be examined before being deemed permanently unsuitable. EPR 2010 states that the geological formation must for natural reasons be permanently unsuitable for other purposes. Contamination of the formation as a result of human activity would not be cause for its determination as permanently unsuitable."

3.2 IDENTIFYING 3D AQUIFER EXTENT IN ENGLAND

The 2D extent of aquifers and unproductive strata was mapped for the EA's aquifer designation maps using geological maps of the ground surface or rockhead at a scale of 1:50,000 (see http://www.bgs.ac.uk/products/hydrogeology/aquiferDesignation.html; http://www.bgs.ac.uk/products/hydrogeology/aquiferDesignation.html; and http://apps.environment-agency.gov.uk/wiyby/117020.aspx). These maps show aquifer designations for superficial deposits (Quaternary age) (575 units), and bedrock formations (3700 units). These designations are used for groundwater vulnerability mapping (Carey and Thursten, 2014) to help manage potentially contaminating activities at or near the ground surface.

There is currently no equivalent designation at depth, in part due to a lack of knowledge of the vertical and lateral distribution of aquifers at depth. The first systematic study to characterise the 3D distribution of principal aquifers in England and Wales was undertaken as part of a recent BGS/EA co-funded project (iHydrogeology, http://www.bgs.ac.uk/research/groundwater/shaleGas/aquifersAndShales/maps/home.html; Loveless et al., 2018) to map the vertical separation between the top of selected shale formations and base of overlying principal aquifers across England and Wales. This entailed modelling, at a scale of 1:625,000, of the top surface of six major shale and clay units that are potentially oil/gas bearing (the Kimmeridge Clay Formation, Oxford Clay Formation, the Lias Group, Marros Group, the Bowland Shale Formation and the Upper Cambrian shales) and the depth to base of 11 geological formations corresponding to bedrock principal aquifers (Crag Group, Chalk Group, Lower Greensand Group, Spilsby Sandstone Formation, Corallian Group (limestone), Great and Inferior Oolite groups, Triassic sandstones, Zechstein Group, Permian sandstone, Carboniferous limestone, and Border Group (Fell Sandstone)). Surfaces were created using BGS's National Geological Model (UK3D) of the UK (Mathers et al., 2014). The 3DGWV LFV project extends this work and accounts for the vertical and lateral extent of both principal and secondary aquifers in England using UK3D2015 (Waters et al., 2016), which includes additional geological cross sections and named bedrock units since the iHydrogeology project, improving the spatial and stratigraphic resolution, respectively. Due to the very local and sometimes discontinuous nature of many of these units it is not justifiable to produce interpolated surfaces and thus full subcrop maps for all of the potential receptors across England. Instead, potential receptors on the geological sections in the 3DGWV LFV project have been attributed with EA aquifer designations. Designations, lateral and vertical extents can be viewed within the LFV software.

3.3 WATER QUALITY OF DEEP GROUNDWATER SYSTEMS IN ENGLAND

Water quality standards, including specific electrical conductance (SEC) or total dissolved solids (TDS), are used to regulate supply and use of groundwater in England and elsewhere. The Council of the European Union (1998) specified that the maximum SEC at 20°C should be 2500 µS/cm (about 1625 mg/l TDS), and the water should not be aggressive. This limit has been embodied in the water supply regulations for England that specify the maximum admissible concentrations and values for parameters in drinking water for both public supply (The Water Supply (Water Quality) Regulations (2016)) and private water supplies for human consumption (Private Water Supplies

(England) Regulations (2016)). The World Health Organisation (WHO) describes water with a TDS of < 600 mg/l as good quality and that with a TDS of >1000 mg/l as increasingly unpalatable (WHO, 2011). For comparison, the US EPA (2017), states a guideline maximum TDS value of 500 mg/l in the Secondary Drinking Water Standards but considers an underground drinking water source to have a TDS of < 10,000 mg/l.

Understanding of groundwater quality at depth is integral to 3D groundwater vulnerability and risk assessments and, arguably, the related policy development and management decisions. Water quality tends to deteriorate with increasing depth as lower hydraulic gradients and slower groundwater movement result in longer residence times during which the water can interact with the host rock and result in increased mineralisation. There are some exceptions to this, for example, in the East Midlands better quality Sherwood Sandstone groundwater occurs below more mineralised shallower waters associated with the overlying gypsiferous Mercia Mudstone and groundwater subjected to recent near surface pollution from agriculture or coal mining.

3.3.1 Deep groundwater quality in England

There are 13 public water supply sources with depths over 400 m in the BGS Wellmaster database (a comprehensive database of water borehole logs in the UK) in England, though none are over 500 m deep.
Table 3.3 indicates that these boreholes all terminate in sandstone aquifers (either the Lower Greensand or the Sherwood Sandstone). Water in silicate aquifers is generally less mineralised than that in carbonate ones. However, it is not clear whether the lack of boreholes > 400 m deep in carbonate aquifers is due to a decrease in dissolution and secondary fractures affecting yields or poor groundwater quality at depth within these aquifers.

Table 3.3 Public water supplies from > 400 m depth in BGS' Wellmaster database

Aquifer	Number of supplies	Depth (m)
Palaeogene, Chalk and Folkestone Formation (Lower Greensand Group)	1	422
Folkestone Formation (Lower Greensand Group)	6	400, 414, 442, 457, 468, 489
Folkestone Formation (Lower Greensand Group) and Hastings Beds (Purbeck Group)	1	433
Sherwood Sandstone Group	5	400, 414, 430, 431, 500

The Geothermal Data Catalogues provide the most complete data on groundwater quality at depth, including information on locations, depths, sample types and aquifers. The first comprehensive catalogue of underground temperature, heat flow and hydrogeochemical data was published in 1978 by the Department of Energy (Burley and Edmunds, 1978). This was updated by the British Geological Survey's 'Investigation of the geothermal potential of the UK' project in the 1980s and published in three revisions (Burley and Gale, 1982; Burley et al, 1984; Rollin, 1987). The majority of the data were derived from drill stem tests (Table 3.4).

Data from the Geothermal Data Catalogues have been digitised and anomalous values removed. Site locations given to the nearest 1 km (in some cases 10 km) were cross-referenced by location names and depth and identified to at least the nearest 100 m. Mine drainage data were also removed, since these analyses may not be representative of natural groundwater conditions and the depth from which the water drains is ambiguous. The remaining 500 analyses range from springs (surface) to a maximum borehole depth of 2385 m, although the number of observations decrease significantly with depth (Table 3.5). Where the source rock was not recorded but a depth provided, borehole logs were used to identify the formation from which the water sample was most likely derived. Where only a borehole depth (not sample depth) was available, the sample was assumed to be from the formation at the final borehole depth.

Analyses were from a range of formations, but primarily the Chalk, Sherwood Sandstone, Zechstein Group, Coal Measures, Millstone Grit and Carboniferous Limestone (Table 3.6). Where no TDS was recorded in the original data, it was assumed to be the sum of all the ions quoted (major ions plus silica), although in many cases some ionic concentrations (mainly potassium, bicarbonate, sulphate and silica) were not recorded and hence the calculated TDS content is a minimum estimate. The dataset is a collection of all data available at the time of compilation, rather than being a comprehensive review of water quality from different formations at specific depths. For example, many more data exist for aquifers at shallow depths which are not included, and these data indicate that the lowest TDS range for any unit in Table 3.6 relates to the London Clay at depths of > 150 m, not a formation generally considered to form a significant aquifer, is anomalous and an artefact of the way data was originally selected for inclusion in the catalogues.

Table 3.4 Sources of water quality samples, data from the Geothermal Data Catalogues (Burley et al., 1984; Rollin, 1987)

Data source	Number of sites
Spring (including thermal springs)	10
Depth sample	9
Interstitial	23
Pumped sample	71
Artesian discharge	10
Drill stem test	309
Unknown	68

Table 3.5 Depths of water quality samples, data from the Geothermal Data Catalogues (Burley et al., 1984; Rollin, 1987)

Depth (m)	Number of sites
0-500	176
500-1000	137
1000-1500	115
1500-2000	65
2000-2500	6

Table 3.6 Water quality analyses by formation, data from the Geothermal Data Catalogues (Burley et al., 1984; Rollin, 1987)

Period	Formation	Number of sites	Depth range (m)	TDS range (mg/l)
Palaeogene	London Clay	3	167-179	129-298
Cretaceous	Chalk	28	90-532	124-35287
	Upper Greensand	7	120-626	181-5350
	Lower Greensand	13	0-687	110-7999
	Wealden	2	665-759	2314-6965
Jurassic	Portland	3	804-865	14186-116890
	Corallian	3	580-1258	19993-93725
	Kellaways and Oxford Clay formations	4	105-833	10812-47625
	Great Oolite	5	224-1246	11259-67304
	Inferior Oolite	6	158-1369	375-131736
	Bridport Sand Formation	14	0-1180	321-143470
	Middle Lias	1	1085	69025
	Lias	4	317-1200	6289-93974
Triassic	Penarth Group	1	1247	109637
	Mercia Mudstone	2	321-683	1474-52418
	Dolomitic Conglomerate	1	102	2819
	Sherwood Sandstone	100	9-2297	52-299714
Permian	Collyhurst	1	136	210
	Zechstein	57	151-1918	296-331597
	Rotliegendes	4	1316-1814	103015-315711
Carboniferous	Coal Measures	83	90-2375	365-275911
	Millstone Grit	94	282-2266	950-317298
	Bowland Shale	2	0 (springs)	637-1195
	Carboniferous Limestone	56	0-1799	160-205957
	Lower Limestone Shale	2	1684-1834	87875-101610
Devonian	Old Red Sandstone	3	104-1919	225-136744
Silurian	Silurian	1	1397	22839

Figure 3.1 shows TDS as a function of depth for all of the Geothermal Data Catalogue data. Figures A3.2 to A3.7 in Appendix 3 show TDS as a function of depth highlighting data for the Chalk, Sherwood Sandstone, Zechstein Group, Coal Measures, Millstone Grit and Carboniferous Limestone. Figure 3.1 shows that there is significant variation in TDS at any given depth. For

example, at ~ 400 m bgl, measured TDS may vary by over three orders of magnitude from ~100 to >100,000 mg/l. The corollary of this is that a given TDS may be found over a wide range of depth intervals. For example, TDS values of 10,000 mg/l have been reported from the near surface down to depths of >1km.

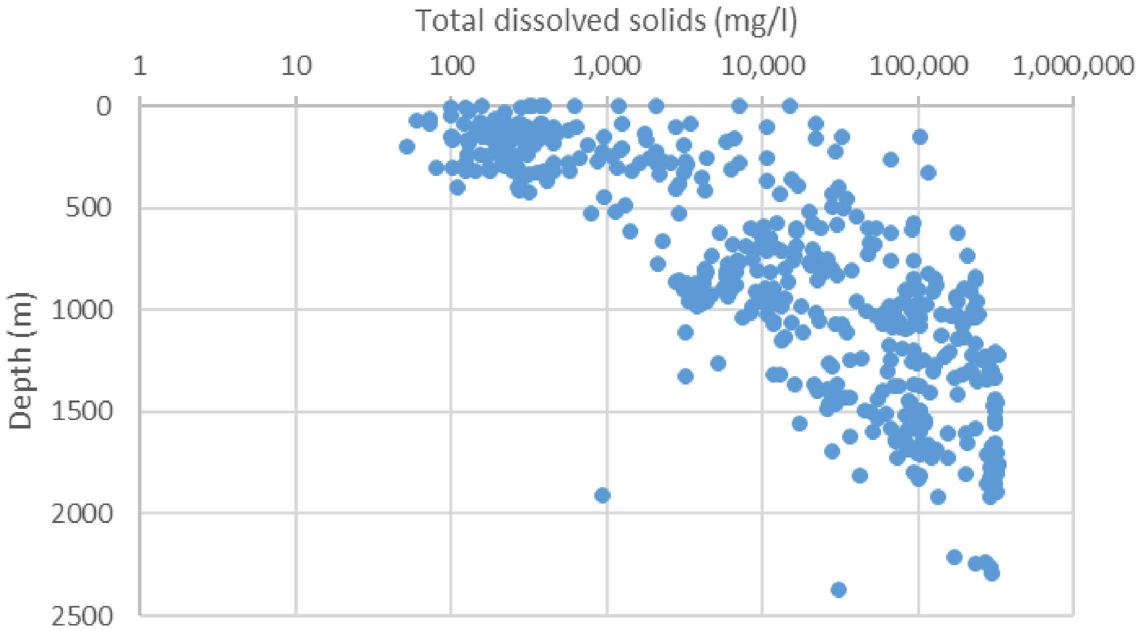


Figure 3.1 TDS as a function of depth for England based on data from the Geothermal Data Catalogues (Burley et al., 1984; Rollin, 1987).

However, groundwater at greater depths will generally be older, allowing more time for water-rock interaction and hence more mineralised. Hence there is a broadly linear lower bound to the distribution of TDS (Figure 3.1). This means that for a given depth interval an equivalent minimum TDS can be approximately identified. The lower TDS bound for a given depth indicates a maximum depth of ~ 900 m for potable groundwater in England (maximum TDS ~ 1625 mg/l based on the current statutory SEC limit for potable groundwater of 2500 µS/cm) (Figure 3.2). Groundwater below ~1,750m is likely to be more saline than seawater (35,000 mg/l TDS) (Figure 3.2). However, estimation of depth intervals associated with specific TDS thresholds will depend on the precise location and shape of the lower bound to the TDS-depth trend and these figures should only be taken as approximate values. A similar lower bound to groundwater quality-depth data has also been described for data from California (Kang and Jackson, 2016). In California, however, the lower bound is lower than for England, reflecting lower TDS at greater depths. This difference could result from a range of factors, including the length of time that groundwater has been in contact with the host rocks which in turn is a function of the hydrogeological setting, rock hydraulic conductivity, and rock solubility.

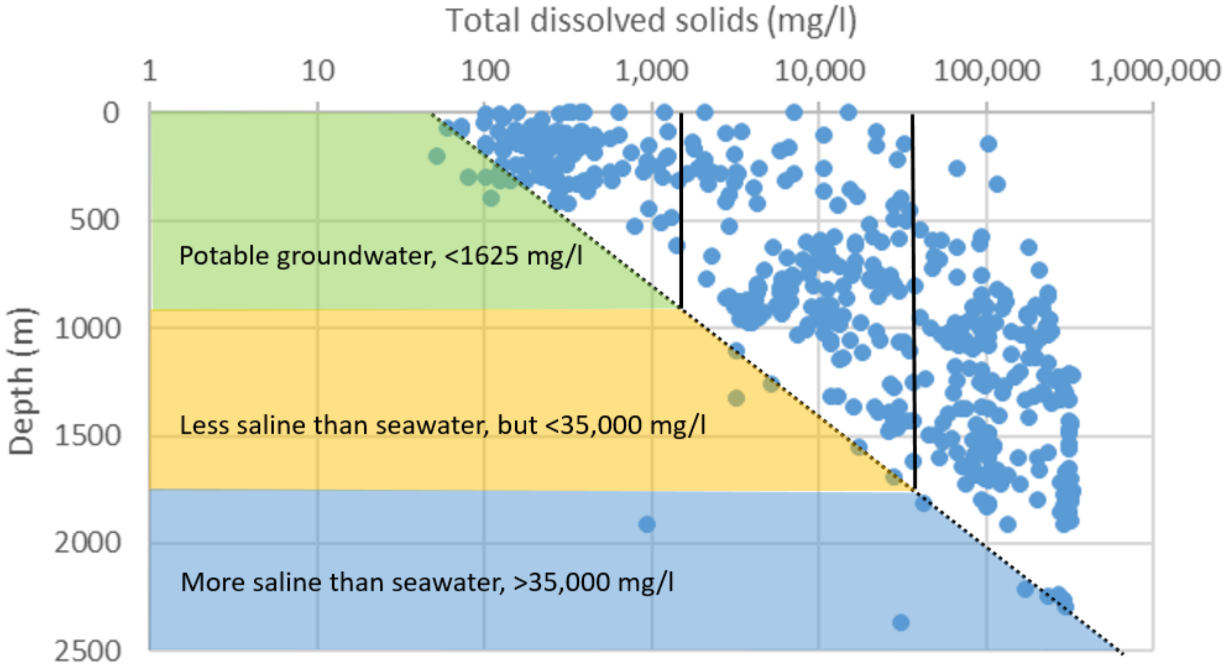


Figure 3.2 TDS as a function of depth for England with interpolated depths associated with limit of potable water (<1625 mg/l) and groundwater more saline than seawater (>35,000 mg/l).

3.4 GROUNDWATER PROTECTION SUMMARY

According to the groundwater governing frameworks in England (WFD and GD), all groundwater should be protected from the input of pollutants. There is a general characteristic of increasing mineralisation of groundwater with depth (Figure 3.2). Consequently, in practice, the use and hence protection of groundwater < 400 m bgl has been prioritised. However, with an increasing focus on the use of deeper geological environments for potential hydrocarbon development, there is a need to consider the application of protection for deeper, more highly mineralised groundwater. Although such groundwater is currently not considered as a groundwater body and so is not subject to the same management objectives as a groundwater body (UK TAG, 2011), recognition of the importance of deep groundwater as a pathway, as well as its potential for future uses, means that it should still be afforded certain defined protections.

3.5 POTENTIAL RECEPTOR CLASSIFICATION

Potential receptor classification

In the 3DGWV methodology, potential receptor units are used to assess groundwater within different strata, in accordance with possible differences in the groundwater condition at different depths, laterally, and within different geological units. Each geological unit identified in the geological sequence within the AOI should be classified as a potential receptor on the basis of their geological and hydrogeological properties (primarily identified through their EA aquifer designation) and their shallowest depth in the AOI.

The 400 m default maximum depth for Groundwater Bodies in the UK (UKTAG, 2011) is central to receptor classifications in the absence of groundwater quality data (Table 3.7). However, where there are data for the TDS content of the groundwater within the unit (Table 3.7), this should be the determining factor in receptor classification. The groundwater quality boundaries are defined according to WHO (2011) with potable water having TDS < 1000 mg/l, slightly brackish water, which can be used for potable mineral water supply and agriculture, parks and gardens, from 1000-3,500 mg/l (EPA Victoria, 1997) and brackish water up to 35,000 mg/l. UKTAG(2011) suggests that groundwater with no resource value may be ‘permanently unsuitable’ for use, *for example*, where its salinity is greater than that of seawater, i.e. the TDS exceeds 35,000 mg/l.

The 3DGWV LFV model can be used to identify the EA aquifer designation attributed to a particular geological formation. Where the aquifer designation is variable, local information should be used to identify the nature of the unit, for example from the EA website:

http://maps.environment-agency.gov.uk/wiyby/wiybyController?topic=groundwater&layerGroups=default&lang=_e&ep=map&scale=5&x=531500&y=181500#x=353733&y=437974&lg=3,&scale=5.

It should be noted that aquifer designations are only shown at outcrop. Where units are confined, aquifer designation should be obtained from nearby outcrops of the potential receptor with the same lithology.

The shallowest depth of the unit should be used for aquifer depth, so if the top of the second principal aquifer in Figure 2.2 was at 300 m bgl, and the base was at 500 m bgl, the unit should still be classified as potential receptor class A. Where there is evidence (for example chemical) that groundwater bodies in the same aquifer unit may be separated by a barrier such as a fault, the receptor classification of the groundwater bodies can be assessed separately. TDS may also be estimated by summing all of the cations and anions to provide a minimum value, or by conversion of an SEC value, if available.

Where new information as to the groundwater quality in a particular potential receptor becomes available, this should be used to update the potential receptor classification.

Table 3.7 Receptor classification based on EA aquifer designation and TDS. Where there is evidence of the TDS of the groundwater within the unit, this should be the determining factor in receptor classification.

Potential receptor classification	EA aquifer designation and depth to top of unit below surface	Total Dissolved Solids (TDS)
A	Principal aquifer < 400 m	< 1,000 mg/l
B	Principal aquifer > 400 m, secondary aquifer < 400 m	1,000-3,500 mg/l
C	Secondary aquifer > 400 m	3,500-35,000 mg/l
D	Unproductive	> 35, 000 mg/l

4 Intrinsic vulnerability

This section describes potential pathways for contamination from the source (hydrocarbon source unit) to receptors (groundwater body). The general intrinsic vulnerability factors and methodology relating to each of the pathways are presented after each pathway has been described. Pathways relating to specific sub-surface hydrocarbon activities are detailed in Section 5.

The intrinsic vulnerability of a receptor is a function of the geological setting (geometrical relationships and hydrogeological properties) within which the receptor and the proposed hydrocarbon source occur.

Intrinsic vulnerability is assessed for each potential receptor in the geological sequence identified in the conceptual model, below the surface within the AOI, according to key factors, sub-factors and parameters that will influence the vulnerability.

For each factor, the full range of possible measurements or values is divided into between three and eight increments depending on the parameter. Each is given a rating value, i.e. 1, 2, 3 etc, a weighting (numeric, pre-ascribed reflecting its contribution to intrinsic vulnerability) and a confidence level (high, medium, low).

The rating (r) and weighting (w) for each factor are multiplied, and the scores for all the factors are summed to produce the receptor's intrinsic vulnerability score. A higher rating indicates higher intrinsic vulnerability. A confidence level is ascribed to each of the intrinsic vulnerability scores based on the lowest confidence of all the assessed subfactors. The rating is determined from the conceptual model (Section 2.2).

4.1 SEPARATION OF THE HYDROCARBON SOURCE ROCK AND POTENTIAL RECEPTOR

Rocks in the intervening zone between the source and receptor can facilitate or hinder the transport of contaminants. The further apart the source and receptor are, and the increased time taken for contamination to travel from hydrocarbon source to receptor, the lower the likelihood of contamination reaching the receptor, (e.g. US EPA, 2016). Longer pathways may also allow longer exposure to microbial degradation and attenuation, and prevent contamination reaching the receptor. Certain properties of the rock mass (porosity, permeability, attenuation capacity) will make the transport of contaminants more or less likely. This pathway is identified as 'R' in Figure 5.4, Figure 5.6 and Figure 5.8.

The groundwater flow in sedimentary formations at depth is up to two orders of magnitude greater in the horizontal than in the vertical direction, and simulations have shown that the majority of flow following hydraulic fracturing is in the horizontal direction (Brownlow et al., 2016). This is due to the permeability anisotropy resulting from sedimentary layering. The movement of contaminants is controlled by the lowest permeability layer.

In the 3DGWV methodology, proximity is divided into two subfactors; vertical and lateral separation distances. It reflects the greater likelihood of contamination through the rock mass and preferential pathways when the hydrocarbon source unit and the potential receptor are closer. The spatial extent of permeability changes resulting from extraction processes, in particular, hydraulic fracturing are also considered (Section 4.1.1). Different separation distances have been used in other industries, such as mining (Section 4.6) and could be used to modify distances in different locations and for specific industries if this methodology is extended to other sub-surface activities.

There are more categories for the intrinsic vulnerability parameter range for the vertical than for the lateral separation because better estimates of vertical separation can be made using the 3DGWV LFV model, or borehole logs. Since groundwater flow at depth is generally greater in the horizontal direction than in the vertical direction the lateral separation has a greater weighting so that a given distance scores higher (or the same) for the lateral than vertical direction (

Table **4.1**). There are also fewer categories for the lateral than vertical scores because of the lower resolution.

Table 4.1 Example separation distances (m) and total vertical and lateral scores

Separation distance (m)	**Vertical score**	**Lateral score**
1200	1.5	3
1000	3	3
800	4.5	6
600	4.5	6
400	6	9
200	10.5	12
50	12	12

4.1.1 Effect of hydraulic fractures

Induced hydraulic fractures are fractures thought to be micrometres (µm) in width (Younger, 2016), which are created to release gas from shale or other tight rock formations. Due to the orientation of stresses in the sub-surface, hydraulic fractures at depths > 1200 m are predominantly vertical and at depths < 600 m are predominantly horizontal, with a mixture of vertical and horizontal fractures in the interval between (Fisher and Warpinski, 2012).

Hydraulic fractures could potentially provide preferential pathways for contaminants from source to receptors depending on the height and aperture of the fractures and the vertical separation distance between the hydrocarbon source unit and the receptor. Even if the fractures do not directly link the source and receptor, they can shorten the pathway that a contaminant would have to travel without a preferential flow path (modified separation).

Local rock failure, which occurs as the hydraulic fractures form, creates microseismic events which can provide information on in-situ rock deformation. While geophysical data can be used to image fracture height in the subsurface (Fisher and Warpinski, 2012), data remains relatively limited since only 3% of hydraulic fracturing operations in North America are currently monitored with seismic arrays (Gassiat et al., 2013). Nevertheless, studies assessing induced fracture height from micro-seismic and micro-deformation data for high volume hydraulic fracturing indicate that most hydraulic fractures are less than 100 m in height (Davies et al., 2012; Fisher and Warpinski, 2012). Statistically, less than 1% of hydraulic fracturing stages have fractures that are greater than 350 m in height (Davies et al., 2012). On average, there are seven hydraulic fracturing stages per borehole, thus about one in fourteen boreholes could have a maximum fracture height exceeding 350 m. Monaghan (2014) used a similar cut-off of 305 m (1000 ft) for vertical separation between shale gas activities and coal mines in the Midland Valley based on communications with an experienced US shale gas company. The maximum upward propagation of recorded fractures in the data from five shale gas plays in the US, analysed by Davies et al. (2012), is 588 m in height. This work also concluded that fracture height probabilities are likely to be over-estimated due to difficulties identifying smaller fractures. In addition, Fisher and Warpinski (2012) show that fracture height distributions differ between regions and shale formations and there is currently no information on possible hydraulic fracture heights for England. Hydraulic fractures from lower pressure/volume fluid injection are expected to be smaller in extent (e.g. Flewelling et al., 2013).

There is limited information on the lateral extent of hydraulic fractures. The US EPA (2016) report fractures extending to horizontal lengths of 300 m from borehole data in the Fisher and Warpinski

(2012) dataset. Modelling of hydraulic fracturing in sandstone (at a depth of 640 m) indicates a potential fracture length of 244 m (Adachi et al., 2007). Evidence from well communications between closely spaced boreholes might also help to elucidate the fracture half lengths; Jackson et al. (2013a) report a borehole blow-out adjacent to a hydraulic fracturing borehole separated by a distance of 200 m. Interwellbore Communication (IWB) was also found to occur in the Barnett Shale Play in Texas at distances of 340 m and 760 m (US EPA, 2016). Lefebvre (2017) found that the average horizontal distance for well communication at depth was 400 m, with a range from 30 to 2000 m. From 179 wells in Oklahoma, Ajani and Kelkar (2012) (in US EPA, 2016) found that the maximum distance between wells in which an impact was identified was 2590 m (individual fracture length of ~ 1295 m). The likelihood of communication was < 10% for wells 1000 m apart (fracture length of 500 m) and up to 50% for wells < 300 m apart (fracture length 150 m).

Hydraulic fractures can also interact with other pathways such as faults or boreholes and seismicity resulting from hydraulic fracturing can impact borehole integrity as seen at Preece Hall, Lancashire (Ward et al., 2015).

Vertical separation of hydrocarbon source unit and potential receptors

This is the shortest (perpendicular) distance between the top of the hydrocarbon source unit and the base of the overlying potential receptor or, where the potential receptor is below the hydrocarbon source unit, the perpendicular distance between the base of the hydrocarbon source rock unit and the top of the potential groundwater bodyreceptor.

There are eight possible vertical separation distance ratings (Table 4.2). The lowest rating is for > 1200 m, accounting for the maximum distance of natural hydraulic fracture height (Davies et al., 2012) and would be the minimum depth of hydraulic fracturing below groundwater in SPZ1. Other incorporated boundaries include 100 m (most likely height), 400 m (< 1 % of hydraulic fracturing stages have fractures > 350 m in height) and 600 m (maximum recorded height of induced hydraulic fracture). The weighting for this sub-factor is 1.5. If a receptor does not directly overlie the hydrocarbon activity footprint (but is within the area of interest) this should be given a rating of 1. The weighting for this subfactor is 1.5.

Table 4.2 Proximity of hydrocarbon source unit and potential receptor: Vertical separation. Scores are preliminary.

Intrinsic vulnerability parameter range	Rating (r)	Weighting (w)
>1200 m	1	1.5
900-1199 m	2	
600-899 m	3	
400-599 m	4	
300-399 m	5	
200-299 m	6	
100-199 m	7	
<99 m	8	

Sources of information

Conceptual model (Section 2.2). Vertical separation is calculated from unit depths entered into the 3DGWV methodology spreadsheet.

Confidence

- High to medium = conceptual model based on site specific information from nearby boreholes. This will be dependent on the quality of the borehole log, proximity to the AOI and geological variability in the area.
- Medium to low = conceptual model based on 3DGWV LithoFrame ViewerLFV 3D model, shale/ aquifer separation maps, cross-sections on geological maps and geological memoirs.

Lateral separation of hydrocarbon source unit and potential receptors

Lateral separation is calculated between the hydrocarbon source unit and potential receptor units when they occur at the same horizontal plane in the AOI. This may be due to geological structures such as faults and steeply dipping beds. In the case where an additional unit is introduced to the succession, for example in the hanging wall of a fault or on a deepening succession, this factor can be used to provide a distance between the hydrocarbon source unit and the additional potential receptors even though it is not included in the vertical succession.

Table 4.3 Proximity of hydrocarbon source unit and potential receptor: Lateral separation

Intrinsic vulnerability parameter range	Rating (r)	Weighting (w)
> 2000 m	0	3
1000 to 1999 m	1	
500 to 999 m	2	
200 to 499 m	3	
< 199 m	4	

Sources of information

Conceptual model (Section 2.2).

Confidence

- High to Medium = conceptual model based on site specific information from nearby boreholes. This will be dependent on the quality of the borehole log, proximity to the AOI and geological complexity in the area.
- Medium to Low = conceptual model based on 3DGWV LFV 3D model, shale/ aquifer separation maps, cross-sections on geological maps and geological memoirs.

4.2 MUDSTONES AND CLAYS IN INTERVENING ZONE

Clays, mudstones and shales limit transport of contaminants (Flewelling and Sharma, 2014; Birdsell et al., 2015) due to their low permeability (2.4×10^{-7} to 9.6×10^{-4} mD at depth) as evidenced by their ability to behave as cap rocks for conventional hydrocarbons (Younger, 2016). They also have the ability to adsorb charged particles. Their adsorption properties are largely governed by the nature and quantity of clay minerals present and the available surface area (between clay particles in unconsolidated material and on fracture surfaces in consolidated rocks). In the UK, Early Palaeozoic (Cambrian, Ordovician, Silurian, Devonian) shales and slates would typically contain illite and chlorite with rather low adsorption capacity, whereas Late Palaeozoic (Carboniferous and Permian) shales and mudstones often contain interlayered clays with a higher adsorption capacities. Mesozoic and younger mudstones and clays are typified by increasing amounts of smectite and therefore have the highest adsorption capacity. Clay particles in sandstones and siltstones may also have adsorption properties and will lower bulk permeability (S. Kemp *pers. comm)*.

Mudstones and clays in intervening zone between hydrocarbon source unit and potential receptor

This factor accounts for potential barriers (mudstones and clays) to contaminant migration between the top/base of the hydrocarbon source unit and the base/top of each potential receptor.

The rating is based on the cumulative thickness of mudstone/clays (Table 4.4). The potential receptor adjacent to the hydrocarbon source unit will always have a rating of 5 as there are no intervening units.

Table 4.4 Thickness of mudstone or clay in intervening units between the top/base of the hydrocarbon source rock and the base/top of the potential receptor.

Intrinsic vulnerability parameter range	Rating (r)	Weighting (w)
>250 m mudstone or clay	1	3.5
>100 m mudstone or clay	2	
>50 m mudstone or clay	3	
> 20 m mudstone or clay	4	
No intervening strata, or < 20 m mudstone or clay	5	

Sources of information

Cumulative mudstone/clay thickness is calculated from the thickness of the units and the proportion of mudstone/clay within the unit:

Conceptual model (Section 2.2). Thickness of units is calculated from unit depths entered into the 3DGWV methodology spreadsheet. The thickness of mudstone/clay associated with a particular unit can be estimated from the unit thickness (above) and the proportion of mudstone/clay associated in with the unit in the 3DGWV spreadsheet. The proportion of mudstone/clay can be obtained from:

- Borehole logs in/close to the AOI
- 3D GWV LithoFrame ViewerLFV project and BGS Lexicon codes

If a unit comprises only mudstone/clay the total unit thickness can be entered. If only a proportion of the unit is mudstone then the total unit thickness should be multiplied by the fraction of the unit that is mudstone/clay. For each potential receptor, the thickness between it and the hydrocarbon source unit is summed. For example, in Figure 2.2, , the cumulative mudstone/clay unit thickness between the upper principal aquifer and the source unit would be:

Unit overlying hydrocarbon source unit: 100% mudstone and 300 m thick
Lower principal aquifer: 25% mudstone and 67 m thick
Secondary aquifer: 75% mudstone and 67 m thick
Cumulative mudstone thickness = (1×300) + (0.25×67) + (0.75×67) = 367 m

Confidence

- High = conceptual model based on site specific information from nearby boreholes and local information on unit lithology. This will be dependent on the quality of the borehole log, proximity to the AOI and geological variability in the area.
- Medium = conceptual model based on 3DGWV LithoFrame Viewer 3D model, shale/ aquifer separation maps, cross-sections on geological maps and geological memoirs.

4.3 GROUNDWATER FLOW MECHANISM

The groundwater flow mechanism (fracture flow or intergranular flow) of the intervening rock can affect the ease with which groundwater flows. Rocks, such as limestone, with predominantly fracture flow are likely to allow faster travel times than rocks with predominantly intergranular flow or multi-layered aquifers such as the Millstone Grit or the Coal Measures. Solution enlarged fissures and conduits (known as karst in carbonate rocks) can potentially create rapid contaminant pathways though the subsurface (e.g. Ruggieri et al., 2017). Solution features may also affect the permeability of the immediately overlying geological unit due to subsidence.

Groundwater flow processes

This factor accounts for key flow processes in the intervening zone between the hydrocarbon source and the top of each potential receptor. Potential receptors designated 'unproductive strata' by the EA are not considered.

The rating is based on the cumulative groundwater flow mechanism in the intervening units between the hydrocarbon source unit and the potential receptor, including the potential receptor. There are four possible ratings (Table 4.5).

Table 4.5 Groundwater flow mechanism in intervening units between the top/base of the hydrocarbon source rock and the base/top of the potential receptor, including the potential receptor itself.

Intrinsic vulnerability parameter range	Rating (r)	Weighting (w)
Only units designated 'Unproductive Strata' by EA	0	3
> 50 % principal or secondary aquifers (EA designation) with intergranular flow (e.g. sands)	1	
> 50 % principal or secondary aquifers (EA designation) fractured, poorly connected fracture flow or mixed fracture and intergranular flow (e.g. well fractured sandstones, multi-layered Carboniferous rocks)	2	
> 50% principal or secondary aquifers (EA designation) fractured, well connected (e.g. limestone), predominantly fracture flow	3	

Sources of information

The cumulative groundwater flow mechanism score is calculated from the thickness of the units and the groundwater flow mechanism.

Thicknesses of units are calculated from unit depths entered into the 3DGWV methodology spreadsheet from the conceptual model (Section 2.2).

The groundwater flow mechanism of a particular unit can be estimated from:

- Borehole logs in/close to the AOI
- Lithological descriptions from geological maps and memoirs
- 3D GWV LithoFrame ViewerLFV project and BGS Lexicon codes

Using the example in Figure 2.2, the cumulative groundwater flow mechanism categories would be:

- > 50 % principal or secondary aquifers (EA designation) *with intergranular flow* for the lower potential receptor A
- > 50 % principal or secondary aquifers (EA designation) fractured, poorly connected or *mixed fracture and intergranular flow* for the potential receptor B
- > 50 % principal or secondary aquifers (EA designation) not fractured, but *with intergranular flow* for the upper potential receptor A.

Confidence

- High = conceptual model based on site specific information from nearby boreholes and local information on unit lithology. This will be dependent on the quality of the borehole log, proximity to the AOI and geological variability in the area.
- Medium = conceptual model based on 3DGWV LithoFrame ViewerLFV 3D model, shale/ aquifer separation maps, cross-sections on geological maps and geological

4.4 SOLUTION FEATURES

Dissolution features occur in both carbonate and evaporite rocks. The depth of karst development is highly variable and is related to differences in geology and landscape evolution. In England, karst is quite common at shallow depths in parts of the Chalk and in the Carboniferous Limestone. Cave systems are known to nearly 300 m bgl (e.g. Brants Gill, Yorkshire Dales) (Waltham et al., 1997). Karst drainage may have developed at times of lower base levels (sea levels). Some deep caves are formed by water rising up from depth or by geochemical mixing, sulphuric acid dissolution or rising artesian flow through soluble rocks, and are unrelated to modern drainage systems (Farrant, 2008). Palaeokarst systems can be inferred at depth in Carboniferous Limestones, for example at the Buxton Springs, where groundwater circulation is inferred to 1500 m bgl (Aitkenhead et al., 2002) and at the Bath Hot Springs, where it is inferred up to 4000 m bgl (Edmunds et al., 2014). Palaeokarst is more likely to have developed below an unconformity. The maximum depth of karstification in England is limited by the base of the limestone. Gypsum karst has also formed phreatic cave systems, but the rapid solubility rate of the gypsum means that the karst can evolve on a human time scale (Farrant, 2008).

Solution features

This factor accounts for solution features in the intervening units between the hydrocarbon source rock unit and the potential receptor, including the potential receptor within the AOI. It accounts for evidence of solution features in the AOI and the potential for the development of solution features according to the lithology. There are four possible ratings (Table 4.6).

Table 4.6 Solution features in the AOI

Intrinsic vulnerability parameter range	Rating (r)	Weighting (w)
No potential solution features	0	2
Potential for solution in evaporite/soluble rocks	1	
Potential for karst or known solution features in evaporite minerals	2	
Known karst features in area of interest	3	

Source of data

Borehole logs and reports for the AOI might present evidence of solution features. Examples of evidence might include unexpected changes in pressure due to loss of drilling fluid or tracer tests.

Propensity of geological units to have solution features. This includes places where there are unconformities and disconformities above a unit. A list of areas with important solution features have been identified by Farrant (2008) and included in Appendix 4.

Confidence

- High = borehole logs
- Medium or Low = identification of units with propensity for solution features

4.5 FAULTS

Large volumes of fluids, for example deep brines (Warner et al., 2012; Llewellyn, 2014) and gases (Molofsky et al., 2013; Moritz et al., 2015), have been shown to migrate vertically through rock masses for large distances (up to 2.4 km (Llewellyn, 2014)) over long timescales. However, contaminant migration over the large vertical separation distances between deep hydrocarbon source units and shallow receptors (for example shales with an average depth of 2 km in the US, (US EPA, 2016) is considered unlikely, or would take a very long time, without preferential flow pathways (Lefebvre, 2017). Numerical models by Reagan et al. (2015) have shown that characteristics such as the presence of preferential flow pathways (e.g. faults) and production characteristics might have a greater impact on transport than vertical separation distances.

Faults are planes of movement along which adjacent blocks of rock strata have moved relative to each other. Faults commonly comprise zones, of up to several tens of metres (or greater) in width, of fractures and fault rock. Faults can enhance or hinder fluid flow, or a combination of both (preventing fluids crossing the fault while at the same time allowing fluids to flow parallel to the fault) (Bense et al., 2013). Faults that enhance (are conduits for) fluid flow can allow contaminants to travel along the fault (as a pathway) to a groundwater receptor and can provide vertical pathways through otherwise low permeability bodies of rock. Faults have been found to be conduits for methane (and thermal fluids) even through large thicknesses of shale in British Columbia, Canada (Grasby et al., 2016). Faulting may also bring receptor formations into contact with hydrocarbon source unit formations across the fault zone (known as juxtaposition) and result in laterally variable hydrogeological and rheological properties.

The largest faults can cut all of the brittle rocks in a geological sequence hence pathways provided by faults could be kilometres in length. For example, the Bath thermal springs are believed to flow along a deep fault from between 2.6 and 4 km depth to the surface (Andrews, 1982; McCann et al., 2013). Although faults are often segmented along strike and dip, they tend not to occur in isolation and where large faults occur smaller faults are likely to be present nearby (e.g. Torabi and Berg, 2011). The interaction and connection of these faults can also lead to long pathways.

Faults can also interact with hydraulic fractures, and the longest induced fractures are thought to result from interactions with existing faults (Davies et al., 2012). Monitoring of shale exploitation in Greene County, Pennsylvania, found the maximum height of hydraulically induced fractures corresponds with the maximum height of faults in the region (Hammack et al., 2014).

Natural fractures (where there has been no offset either side of a fracture) can also interact with hydraulic fractures. These were found by Davies et al. (2012) to be predominantly between 200-300 m in height, with 33% of > 350 m in height and a maximum height of 1106 m. The greater vertical extents (than induced hydraulic fractures) possibly result from the greater fluid volumes involved in a natural system and occurrence in more extensively homogeneous lithology (Davies et al., 2012; Lacazette and Geiser, 2013). However, the fracture height probabilities are likely to be over-estimated due to difficulties identifying smaller fractures (Davies et al., 2012).

Faults and fractures have been thought to act as preferential pathways for methane in areas of shale gas exploitation (Warner et al., 2012; Molofsky et al., 2013; Llewellyn, 2014 and Moritz et al., 2015). Numerical modelling has suggested that permeability and overall volume of the connecting fault or fracture have a greater impact on methane transport than separation distance (Reagan et al. 2015). However, Younger (2016) states that in the UK there are no known minewater discharges from natural faults although minor seepages are known to occur along natural faults in close proximity to major mine seepages, even if the fault does not deliver the bulk of the flow.

It is thought that a large number of factors might interact to determine whether or not a fault will enhance or hinder fluid flow, including orientation with respect to the regional stress field, lithology, fault throw and deformation history (history of movement and subsequent diagenesis) (e.g. Bense et al., 2013). Pressure changes surrounding faults, perhaps due to stimulation techniques such as Enhanced Oil Recovery (EOR) or hydraulic fracturing, might also alter the hydraulic behaviour of the fault, for example by fault reactivation, and can also lead to leakage along a fault (e.g. Rinaldi et al., 2014). Westwood (2017) found that the horizontal 'respect distance' (minimum lateral distance that hydraulic fracturing should occur from a pre-existing fault in order not to reactivate it) ranged from 63 to 433 m depending on fracture intensity and failure threshold, based on numerical models of hydraulic fracturing at Preese Hall, Lancashire.

Faults

This factor accounts for the proximity of faults to the hydrocarbon activity and their hydraulic behaviour**Error! Reference source not found.**. Distances relate to the minimum lateral istance between the hydrocarbon activity and the fault in the AOI since contaminants are more likely to reach a fault if the separation distance is smaller. It is assumed that a fault could cut the entire geological sequence. The distances correspond to lateral separation distances, based on the horizontal extents of high volume hydraulic fractures. This is larger than the maximum horizontal respect distance (minimum lateral distance that hydraulic fracturing should occur from a pre-existing fault in order not to reactivate it) suggested by Westwood (2017) of 433 m.

Since not all faults are permeable, faults that are known to be transmissive are given a higher rating. Evidence for transmissive faults includes discharge of thermal waters and other fluids from depth. There are four possible ratings (Table 4.7):

Table 4.7 Proximity and hydraulic behaviour of faults in the AOI. Scores are preliminary. Scores are preliminary.

Intrinsic vulnerability parameter range	Rating (r)	Weighti (w)
Faults not known in the area of interest	1	4.5
Known faults within 2 km of the hydrocarbon activity	2	
Known faults within 0.5 km, or transmissive fault within 2 km of the hydrocarbon activity	3	
Fault known to be transmissive within 0.5 km of the hydrocarbon activity	4	

Sources of information

Conceptual model (Section 2.22.2).

Confidence

- High = faults proven in nearby borehole or at outcrop, on seismic sections, or evidence of fault behaviour
- Medium = faults inferred from geological maps or memoirs

4.6 MINES

Mines, for coal and other minerals, can create voids in the subsurface which can provide multiple pathways for contaminants over relatively large volumes (Ward et al., 2015; Monaghan, 2017). The footprint of voids from coal mines can be 50,000 to 200,000 m^2 in area (Younger, 2016). Younger (2016) states that minewater discharges overwhelmingly occur via anthropogenic mined features such as shafts, adits or boreholes.

Mining also impacts the characteristics of the surrounding rock, forming an anthropogenic aquifer (e.g. O' Dochartaigh et al., 2015). Longwall mining, in which a long wall of coal (3 to 4 km in length, and 400 m in width) is mined in a single slice, allows the mine to collapse within two to three years of coal extraction, forming voids filled with goaf (broken rock) (Younger, 2016). As a result of the collapse, bed-parallel fractures can form up to 20 m above the roof of the mined seam (or 1/3 of the distance between underground mine roadways which are typically 100 to 200 m). This fractured zone is overlain by a zone of net compression (and reduced permeability) of up to 1/9 of the distance between the roadways which isolates an upper extensional zone of the same thickness (Younger, 2016). Jones et al. (2004) estimate that the permeability of seams and surrounding strata is increased up to 160-200 m above and 40-70 m below worked seams as a result of previous longwall mining. Nevertheless, Younger (2016) presents the case at Selby Coalfield, Yorkshire, where mines were developed at depth with no connections to shallower workings and 'complete' hydraulic isolation from the near-surface hydrogeological environment. Stoop and room mining, in which pillars are left in place and coal mined from around these, can be stable for many years before collapsing (Younger, 2016).

The statutory stand-off interval between longwall workings and the seabed or aquifer is 105 m, reducing to 45 m for supported methods of mining and have been extensively tested including in flooded old workings with head gradients of up to 200 m (Younger, 2016). The current UK criterion for safe longwall mining induced net tensile strain at the base of any overlying aquifer is 100 mm per m, thus a minimum of 60 m of interburden is required regardless of the distance between roads (Younger, 2016).

Hydraulic fracturing of the Marcellus shale is undertaken beneath active coal mines in Kentucky, Pennsylvania and West Virginia in the USA with a vertical separation distance of ~ 2200 m (Monaghan, 2017). Regulations ensure the special casing and plugging of boreholes through coal-bearing intervals and well plans must be made available to coal operators when the mine is within 90 m of a well, but there are no regulations regarding separation distances (Monaghan, 2017).

Mines

This factor accounts for the vertical and lateral proximity of the hydrocarbon activity to mines. The distances correspond to lateral separation distances based on the horizontal extents of high volume hydraulic fractures. Mine shafts can be deeper than the worked coal seams (Monaghan, 2014). There are three possible ratings (Table 4.8).

Table 4.8 Lateral and vertical distances to mines in the AOI. Scores are preliminary.

Intrinsic vulnerability parameter range	Rating (r)	Weighting (w)
No known mine (and assumed to be absent) within 2 km of maximum lateral extent of hydrocarbon activity, or 600 m vertically	0	8
Known mine within 0.5-2 km of the maximum lateral extent of hydrocarbon activity, and/or 600 m vertically	1	
Known mine within 0.5 km of the maximum lateral extent of hydrocarbon activity, and/or 200 m vertically	2	

Sources of information

ArcGIS layers have been provided in the digital dataset showing the locations where there is a likelihood of either coal or non-coal mines. More information may also be available from mine plans from The Coal Authority, the uncertainty in the location of mines from the mine plans is expected to be < 1 m for depth on mid-20th Century plans, with a slightly larger uncertainty on spatial extent (Monaghan, 2017).

Confidence

High = mine plans have been recorded in England since 1873 and by the 20th Century the standard of these was high. Uncertainties exist for shallower (typically < 150 m depth, rarely ~ 300 m bgl) mine workings prior to the 1870s (Younger, 2016).
Medium= ArcGIS layers provided in the digital dataset.

4.7 PRE-EXISTING BOREHOLES

Boreholes drilled into the subsurface create potential pathways for contaminants to a receptor. While deep hydrocarbon and mineral boreholes are generally completed to prevent leakage, with both steel casing and cement bonding, borehole integrity failures (defects in steel casing, holes in casing joints, mechanical seals and cement e.g. Jackson et al., 2014) can occur. 3% of all hydraulic fracturing operations in the USA involved a downhole mechanical integrity failure (US EPA, 2016). Davies et al. (2014) present data from around the world for the percentage of boreholes (including production, injection, idle and abandoned boreholes) that have some form of borehole barrier or integrity failure. Percentages range from 1.9 % (onshore, nationwide CCS/natural gas storage facilities, dates unknown, including well integrity failure only, described as significant gas loss, for 470 boreholes) to 75% (onshore, operational wells in the Santa Fe Springs Oilfield, discovered 1921, including well integrity failures, leakage based on the observation of gas bubbles seeping to the surface along well casing for more than 50 wells). The probability of borehole integrity failure depends on the quality of completion (which will vary over time), the age of the well (degradation) and the exploitation processes but the high variability in recorded barrier or integrity in Davies et al. (2014) also reflects differences in classification of failure (e.g. well, single barrier, significant or bubbles), geological setting and importantly regulation (e.g. Thorogood and Younger, 2015; Davies et al. 2015). Of 143 active wells producing in the UK at the end of 2000, one has evidence of borehole integrity failure (Davies et al., 2014).

In many areas of hydrocarbon interest, there may be existing boreholes which can provide pathways for contamination if they are not properly sealed (for example the casing or cement) or have had a loss of integrity over time (Jackson et al., 2013a; Ward et al., 2015). Borehole leakage rates range from 2% to 50 % in the UK (Davies et al., 2014). If abandoned, boreholes might not be monitored and the integrity of their casing will be unknown. In the UK there were 2152 hydrocarbon wells drilled onshore between 1902 and 2013. The ownership of up to 53% of these wells is unclear today and between 50 and 100 are orphaned (Davies et al., 2014).

Hydraulic fracturing has been shown to impact on adjacent wells (US EPA, 2016). In Alberta and British Columbia, 5349 horizontal wells were drilled between 2009 and 2012 and there were 39 reported cases of wellbore connection with existing oil and gas wells, 95 % of which were producing in the same geologic unit. Alberta requires that locations of existing oil and gas wells be identified and their capability to sustain increased pressures be verified prior to hydraulic fracturing (Lefebvre, 2017).

Pre-existing boreholes

This factor accounts for the vertical and lateral proximity of the hydrocarbon activity to boreholes. The distances correspond to lateral separation distances based on the horizontal extents of high volume hydraulic fractures. Deep boreholes can be deviated and hence should be corrected to true vertical depth and also the geographic location of the base. There are three possible ratings (Table 4.9).

Table 4.9 Lateral and vertical distances to boreholes in the AOI. Scores are preliminary.

Intrinsic vulnerability parameter range	Rating (r)	Weighting (w)
No known boreholes (and assumed none present) within 600 m vertically or 2 km laterally of hydrocarbon activity	0	4
Known boreholes extending to within 600 m vertically, and/or 0.5-2 km laterally of hydrocarbon activity	1	
Known boreholes extending to within 200 m vertically, and/or 0.5 km laterally of hydrocarbon activity	2	

Sources of information

ArcGIS layers have been provided in the digital dataset showing the position of mines and all boreholes (including those held confidentially) over 400 m in depth. The depth and logs of all open access boreholes can be viewed via the BGS Geology of Britain viewer http://mapapps.bgs.ac.uk/geologyofbritain/home.html. Some logs are held as 'management protect' and although not freely available, the data can be obtained on request. Information for hydrocarbon (management protect) boreholes are available via the Oil and Gas Authority's website https://www.ogauthority.co.uk/data-centre/access-to-information-and-samples/. Information for water (management protect) and other (management protect) boreholes are available on request from BGS or may be available to the EA from other sources. Other confidential boreholes, included in the layer may also be available to the EA on request to BGS.

Confidence

High = borehole records are kept across England and although it is known that not all borehole records are sent to BGS (e.g. closed loop ground source heat pump holes), this is unlikely to be the case for deeper boreholes, therefore the confidence is high.

Medium or Low = unlikely due to the available records

5 Specific vulnerability

Specific vulnerability accounts for both intrinsic vulnerability and factors that do not pertain to the intrinsic vulnerability of the receptor, but which would influence the risk to a potential receptor from a hydrocarbon activity – i.e. the hazards. Hazard factors include the extraction mechanism of the hydrocarbon (H_1) and the local groundwater head gradient that might drive flow (H_2). Rankings (numeric, representing a number of possible categories) and confidence levels (high, medium, low) are applied to each factor. A higher ranking implies a higher hazard. Both hazard factors are multiplied by the intrinsic vulnerability score to produce a specific vulnerability score.

The following section briefly describes the specific contamination pathways associated with conventional and unconventional hydrocarbon extraction techniques, providing the background to the H_1 scores. More information on the history and characteristics of the techniques can be found in Appendix 5. Potential driving forces (H_2) are then discussed and the methodologies for each hazard factor presented at the end of the respective sections.

5.1 CONVENTIONAL OIL AND GAS

In conventional oil and gas extraction, boreholes are drilled into a reservoir and oil and/or gas flows to the surface under natural pressure (BGS, 2011) (Figure 5.1). Conventional reservoir rocks are commonly sandstone or limestone with a relatively high porosity and permeability (from 1 mD to several D), allowing the oil and gas to flow. Hydrocarbons have a lower density than other crustal fluids and therefore migrate upwards through permeable rock and along discrete pathways. The hydrocarbons are prevented from further migration by low permeability traps such as a geological fault or low permeability rock unit behaving as a ‘cap rock’. This allows for the accumulation of hydrocarbons within the pore spaces of the reservoir. Where both oil and gas are present, gas overlies oil due to its lower density (Figure 5.1).

The main potential pathways for contamination arising from conventional oil and gas reservoirs is the borehole infrastructure and other existing/abandoned boreholes in the area (Figure 5.2). This is because conventional hydrocarbons can be exploited in areas with a large number of existing boreholes. Well integrity failure is also possible if reservoir stimulation techniques are used, such as hydraulic fracturing or enhanced oil recovery (EOR) (Ward et al., 2015). Additionally, pressure or permeability changes within the reservoir, perhaps due to stimulation techniques might also alter the behaviour of the fault or cap rock behaviour with respect to fluid movement and potentially allow leakage (Figure 5.2).

Since hydrocarbon reservoirs have relatively high porosity and permeability, the same rock unit could be an aquifer at shallower depths, and therefore, mass transfer is possible within the unit towards the aquifer where in continuity.

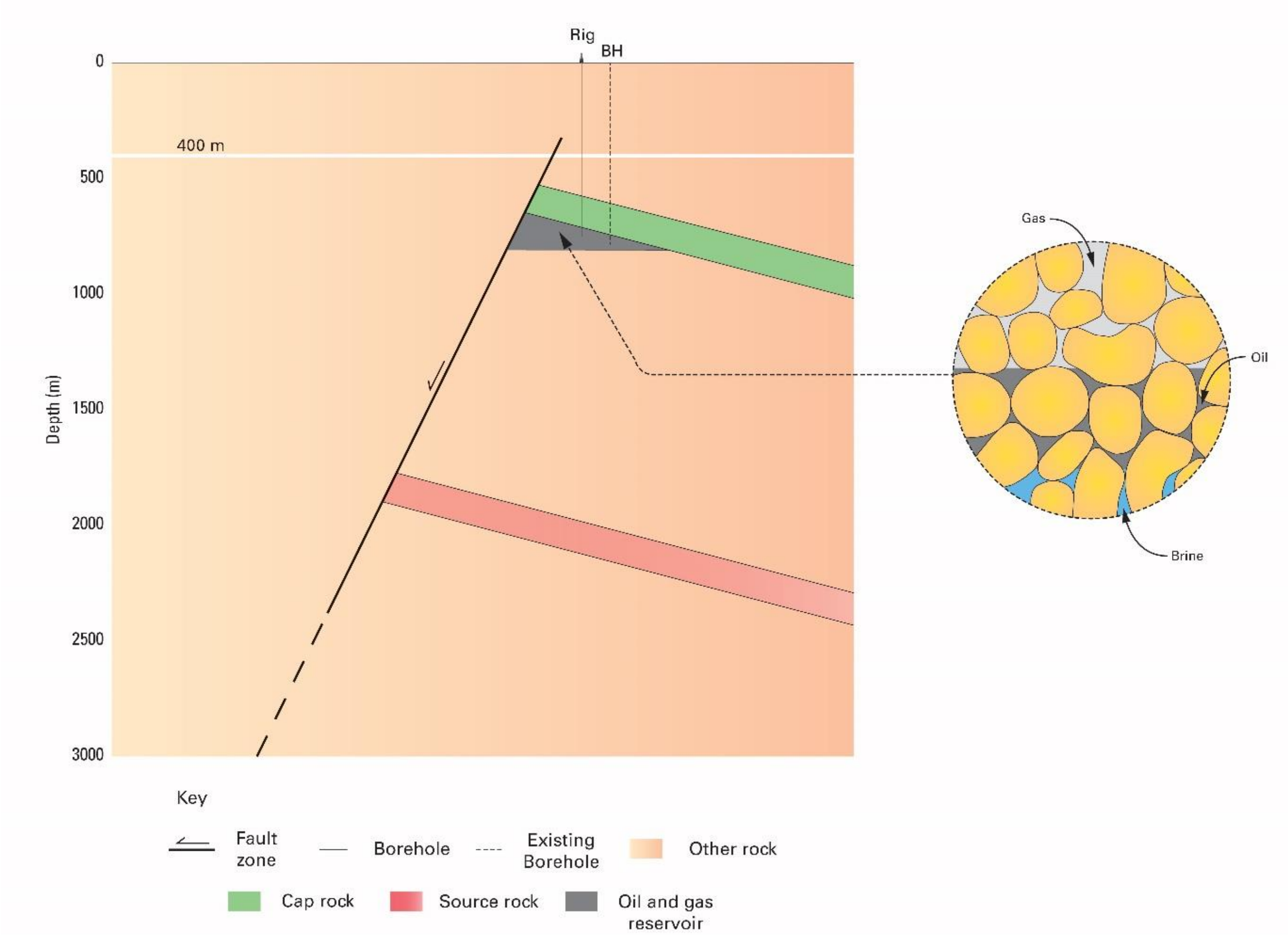


Figure 5.1 Simplified diagram of conventional hydrocarbon extraction. Aspects of the diagram are not to scale due to drawing limitations, such as the borehole width. 400 m indicates the maximum depth of groundwater bodies designated in the UK for management under the WFD (UKTAG, 2011). Reservoirs may be present at a range of depths and there may be multiple reservoirs in a section.

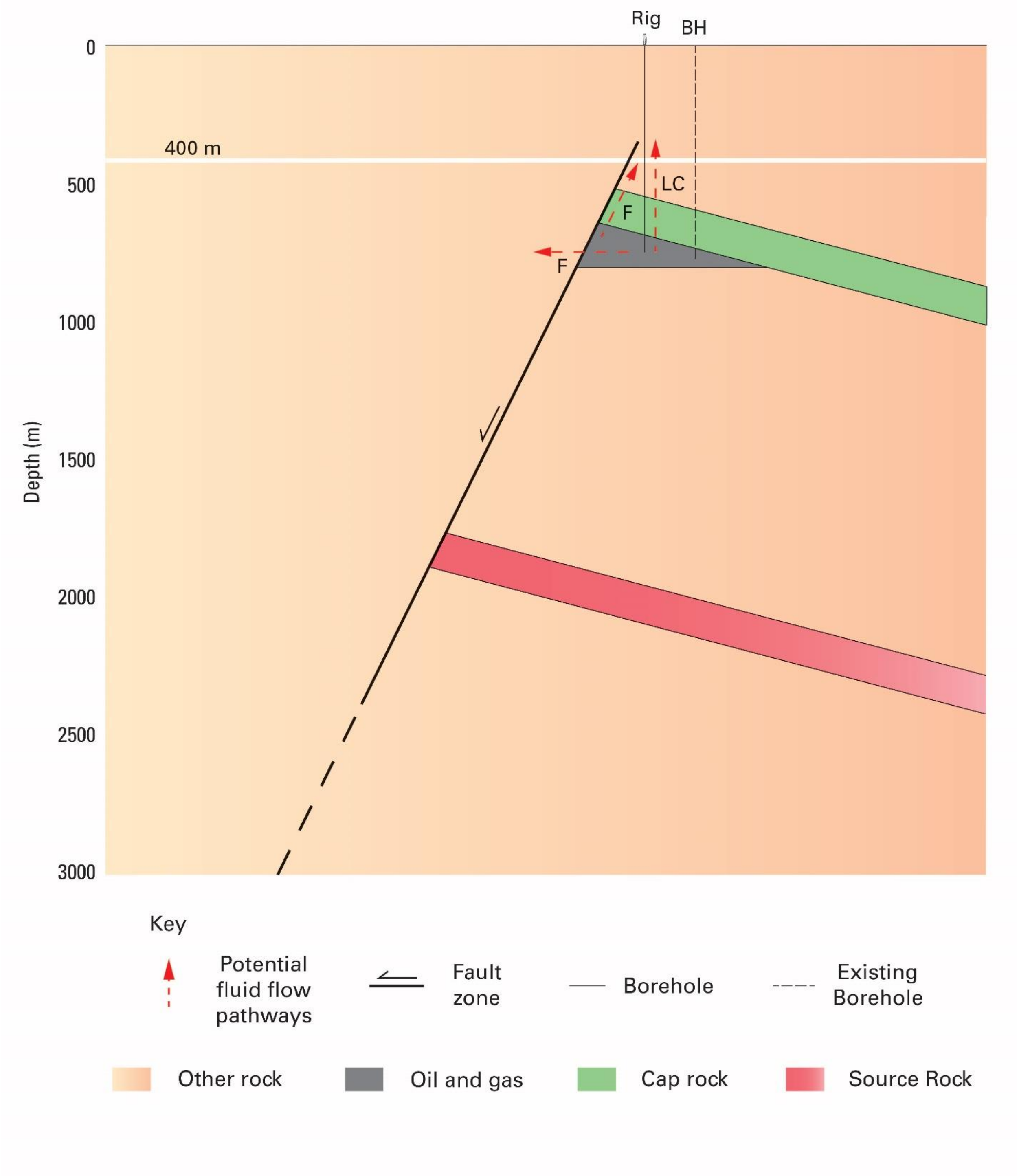


Figure 5.2 Simplified diagram of conventional oil and gas extraction from a reservoir with associated potential contamination pathways. Aspects of the diagram are not to scale due to drawing limitations, such as the borehole and length of pathways. 400 m indicates the maximum depth of groundwater bodies designated in the UK for management under the WFD (UKTAG, 2011). Pathways are labelled as follows; F is fault, LC is leaky casing, BH is existing boreholes.

5.2 SHALE GAS

Shale gas and shale oil are extracted directly from organic rich shales (Figure 5.3). The low permeability of shales (<0.001 to 0.0001 mD) (CSUR, 2016) means that a proportion of gas or oil produced from the organic material in shales is trapped within the pore spaces. Gas can also be bound to the matrix by adsorption. Other tight (low permeability) reservoirs (such as limestones or siltstones) are also often called shale gas reservoirs even through the rocks do not contain a high enough proportion of clay minerals to generally be called shales (Lefebvre, 2017). The permeability of tight formations ranges from 0.001 to 0.1 mD (Naik, 2003). Similarly to shales, tight formations have small pore throat apertures (0.5-10 µm) and low delivery rates (Aguilera & Harding, 2008) and porosity of less than 10% (DECC, 2013a).

Shale gas is extracted via a borehole, which may be deviated from vertical and/or have horizontal sections within the shale (Gallegos and Varela, 2015). High volume hydraulic fracturing (fracking) is used to increase the permeability of the shale, allowing gas to flow from the shale to the borehole. The process involves injecting a high volume of ‘frack fluid’ (water containing a proppant and chemical additives) into the borehole under a very high pressure in order to fracture the rock surrounding the well. These induced fractures increase the shale porosity from 1-10% to 35% (Brownlow et al., 2016). The fractures are kept open by the proppant (sand or ceramic beads) after the borehole is depressurised to allow the gas to the surface. The chemical additives are used to optimise the efficiency of the hydraulic fracturing process (The Royal Society, 2012). Hydraulic fracturing is not always required for oil production from tight formations (US EPA, 2016).

There are a number of potential pathways for contamination from shale gas exploitation. There is no requirement for a cap rock because the gas is trapped in the rock unit. Therefore, once gas is released, transport of gas and fluid through the rock mass is possible (Figure 5.4). There are no characteristic proximities between shales (or tight formations) and aquifers. In the US, 90% of disclosed wells had vertical separation distances between 880 m and nearly 4 km (US. EPA, 2016) although the US Well File Review found that 20% of wells had < 600 m vertical separation between the shallowest point of fractures and the base of aquifers (protected groundwater resources based on well authorisation documents and aquifer maps) (US EPA, 2015). In New Albany the vertical separation ranges from 30 to 490 m between source and aquifer, and from ~ 3 km to 4 km between aquifers and the Haynesville-Bossier shales (US EPA, 2016). In the UK a minimum depth of high volume hydraulic fracturing was set at 1 km in the UK Infrastructure Act (2015), which means that there is a minimum 600 m vertical separation between the ‘default’ maximum depth of designated groundwater bodies as indicated by UKTAG (2011) and shale gas hydrocarbon source unit formations.

Shales and tight formations are not commonly aquifers due to their low permeability (Aguilera & Harding, 2008). However, water-bearing zones can be present within shales or tight formations where depositional settings led to localised or transitional silt/sandstone or limestone deposition. For example, in Pavillion, Wyoming, the Wind River Formation is the principal source of groundwater and also one of the main gas hydrocarbon source units. Contamination of the groundwater here is thought to have occurred because stimulation fluids were directly injected into water-bearing units, but there was also casing failure at five production wells which probably allowed migration into water-bearing units (DiGiulio and Jackson, 2016).

Because of the high density of boreholes in areas where shale gas is being exploited in comparison to conventional hydrocarbons, there are more likely to be existing boreholes in the vicinity of new boreholes. The presence of horizontal boreholes increases the likelihood of the path of the new borehole being close to existing boreholes.

Ingraffea et al. (2014) found a six-fold higher incidence of cement and/or casing issues for shale gas wells relative to conventional wells from analysis of 75,505 compliance reports from

Pennsylvania, 2000-2012. Borehole integrity failures may be more common when boreholes are used for high volume hydraulic fracturing due to the different geometries (longer and sometimes curved) and high volumes and pressures involved in the hydraulic fracturing process (e.g. Jackson et al., 2014). It is also difficult to maintain casings centred in the horizontal section of boreholes, which makes it difficult to ensure a good cementation of the casing (Lefebvre et al., 2017). Integrity failure may also occur due to ground movement and seismic events that could be triggered by hydraulic fracturing (Ward et al., 2015).

In a study of 68 drinking water wells above the Marcellus and Utica shales in Pennsylvania and upstate New York, Osborn et al. (2011) found an increase in the concentration of methane with proximity to shale gas boreholes when the boreholes were located within 1 km. Jackson et al., (2013b) also found a significant increase in methane and ethane concentrations in groundwater < 1 km from shale gas boreholes in Pennsylvania, from 141 samples (including 60 from Osborn et al. (2011). They found no elevated methane in wells located more than 4 km from a borehole and propane and ethane were generally absent in wells located at distances of more than 1 km. Llewellyn et al. (2015) document a case in Pennsylvania where contamination in a number of wells is likely to have been caused by high volume frack fluids escaping from a shale borehole into an aquifer due to high pressures. Heilweil et al. (2015) found fugitive gas in a groundwater fed stream close to a Marcellus shale well under investigation for stray-gas.

Fontenot et al. (2013) found that a number of chemicals exceeded the EPA's Maximum Contaminant Limit in some wells within 3 km of active natural gas wells, from 100 tested drinking water wells overlying the Barnett Shale, Texas. Lower levels were detected outside of the Barnett Shale region and > 3 km from active natural gas wells. The random distribution could, however, point to a number of causes, including the mobilisation of naturally occurring constituents, lowering of the water table or faulty drilling equipment and well casings.

Darrah et al. (2014) identified seven discrete clusters of fugitive gas contamination from shale gas wells, from 113 groundwater samples from the Marcellus Shale and one cluster from 20 samples from the Barnett Shale. They identified the cause of four of the clusters was due to failure of annulus cement, three faulty production casing and one to an underground gas well failure.

It should be noted that there are also numerous studies where high concentrations of methane in drinking water have been attributed to natural processes rather than wells (e.g. Molofsky et al., 2013; Christian et al., 2016; Wen et al., 2016; Harkness et al., 2017; Nicot et al., 2017a; Nicot et al., 2017b; Nicot et al., 2017c; Ward et al., 2017) and may be expected in areas where gas exists in the subsurface, or no significant increases of thermogenic methane were identified (e.g. Warner et al., 2013; McMahon, et al. 2015). This may reflect the time taken for contaminant migration, or different geological conditions or well completion characteristics. In addition to the size and nature of datasets analysed (Li et al., 2016). In parts of northern England legacy deep coal mines occur above shale gas resources. These may, in some places, be an additional contamination source and pathway (Monaghan, 2017).

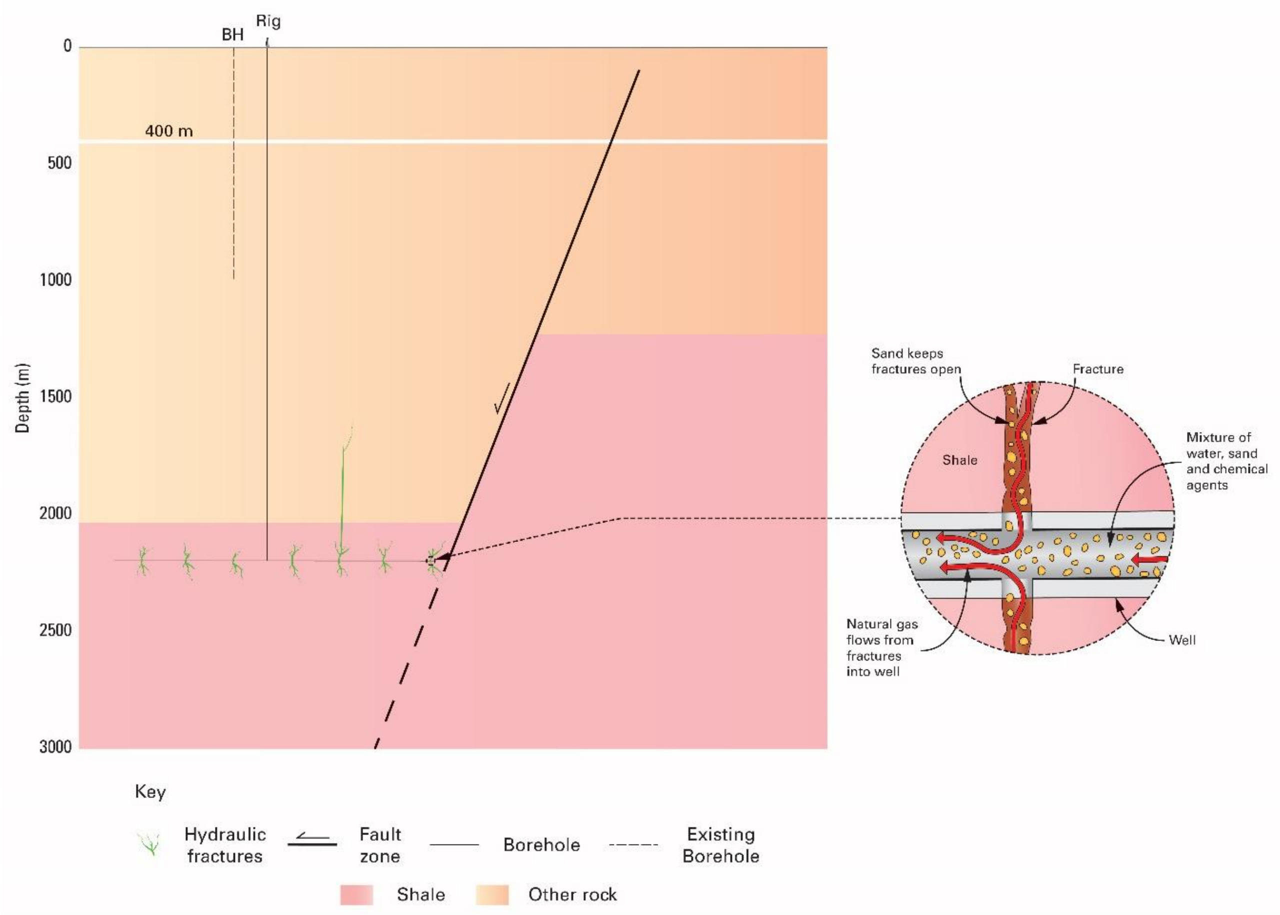


Figure 5.3 Simplified diagram of shale gas extraction. Aspects of the diagram are not to scale due to drawing limitations, such as the borehole width. 400 m indicates the maximum depth of groundwater bodies designated in the UK for management under the WFD (UKTAG, 2011). Hydrocarbon source rocks may be present at a range of depths. Hydraulic fractures are schematic, with heights based on investigations of hydraulic fracture heights by Davies et al. (2012) mostly from North American data. They show a standard vertical height of 100 m and a maximum of 600 m (Section 5.2).

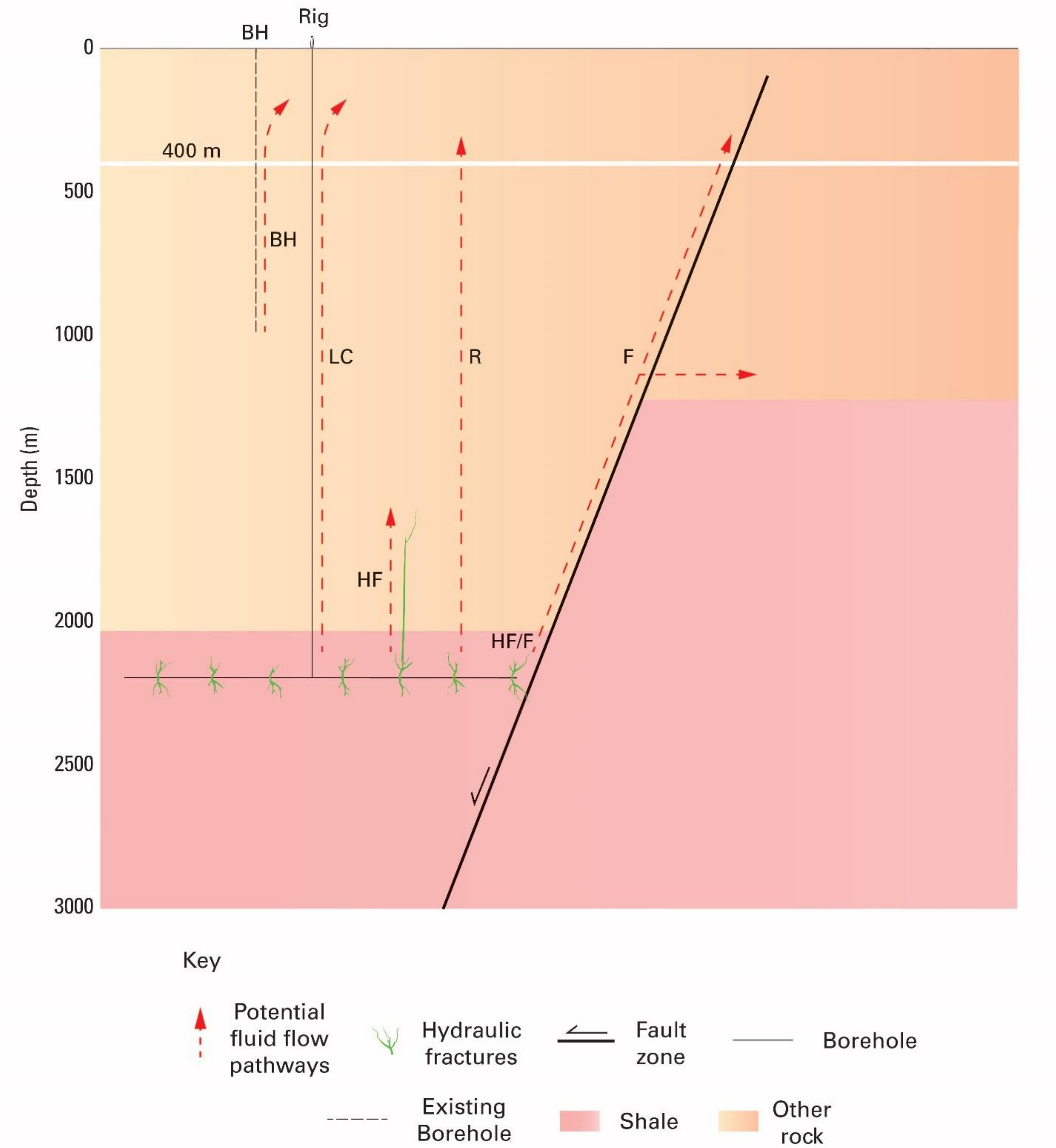


Figure 5.4 Simplified diagram of shale gas extraction from a reservoir with associated potential contamination pathways. Aspects of the diagram are not to scale due to drawing limitations, such as the borehole and length of pathways. 400 m indicates the maximum depth of groundwater bodies designated in the UK for management under the WFD (UKTAG, 2011). Pathways are labelled as follows; R is transport through the intervening rock mass, LC is leaky casing, BH is existing boreholes, F is fault, HF is Hydraulic Fractures and HF/F shows Hydraulic Fractures intersecting a fault. Hydraulic fracture heights are drawn to scale, most are less than 100 m in height and can be up to 588 m in height.

5.3 CBM

Natural gas can be bound within coal seams by adsorption in which gas molecules adhere to the surfaces within the coal. This gas can be extracted in situ, i.e. directly from coal seams (Figure 5.5).

For the extraction of CBM a borehole is drilled into the coal seam and water is pumped out in order to lower the pressure in the seam (Jones et al., 2004). In some cases, particularly where there has previously been mining, coal-bearing strata may already be dewatered (Al-Jubori et al., 2009). The lowering of pressure allows methane to desorb from the internal surfaces of the coal and diffuse into cleats (fractures within the coal) where it is able to flow, either as free gas or dissolved in water, towards the production well (DECC, 2013b). A good permeability is necessary to allow flow of gas to the production well during CBM production. Bituminous coals can have permeabilities of 1 mD, sometimes up to 30 mD although this is often anisotropic (Jones et al., 2004). Permeability can be imparted by cleats, and in some cases this may be as high as 100 mD, for example in the San Juan basin in the U.S., where natural production rates are similar to conventional reservoirs (Al-Jubori, 2009). While the permeability of coal seams in the UK is likely to be low (Jones et al., 2004) and decrease with depth (Moore, 2012), cleats are common (due to their age) and can increase coal seam permeability (EA, 2014). In areas of pre-existing mines, the permeability of coal seams and surrounding strata is increased due to rock collapses associated with longwall mining; this can be up to 160-200 m above and 40-70 m below the worked seam (Jones et al., 2004).

Coal mine methane (CMM) and abandoned mine methane (AMM) can be considered as subdivisions of CBM. CMM involves the removal of methane from a working mine to enable safe mining, by capturing it at high concentrations. In the UK, ‘post drainage’ is favoured in which methane is captured from strata above and below worked seams via suction pumps (EA, 2014). For deep, gassy longwall mines, boreholes are drilled at an angle above and sometimes below worked seams (EA, 2014). Boreholes may also enter the seams from inside the mines (Karacan et al., 2011). AMM recovers gas that accumulates in abandoned mines which would otherwise find its way to the surface. Boreholes are drilled into underground roadways or former workings. Drilling may be used to link adjoining mines and improve connectivity and to aid minewater drainage away from production zones (EA, 2014). In AMM, gas is also released via suction pumps (EA, 2014).

Coal seams in the UK are often interspersed with secondary aquifers. In the US, formation fluids in coal measures are often within the salinity threshold for some definitions of drinking water (US EPA, 2016). Coal Measures are also located in proximity to freshwater aquifers (Al-Jubori et al., 2009) in England, as they are often directly overlain by Permo-Triassic principal aquifers (Jones et al., 2004). Therefore, contaminants do not have to travel far from coal activities to reach a receptor. In addition, because CBM can take place at only 200 m bgl, this could be shallower than a receptor.

Many hydrocarbon source units for CBM in the UK are close to coal seams that have previously been worked and may have a high density of mines and abandoned boreholes (Figure 5.6). They are also generally highly fractured and faulted.

Hydraulic fractures are not necessary for CBM, although in England, despite coal beds being relatively well fractured due to a long history of tectonic deformation, permeability is relatively low. Hydraulic fractures for CBM are generally not created through high volume hydraulic fracturing and therefore are expected to be smaller in extent. In addition, because the hydrocarbon source unit is often shallower than 600 m bgl, they are more likely to be horizontal fractures than vertical.

De-gassing of coal seams could result in matrix shrinkage and formation of cleats (Moore, 2012) and associated depressurisation within the sub-surface has resulted in instability/subsidence outside England in relation to CBM (EA, 2014).

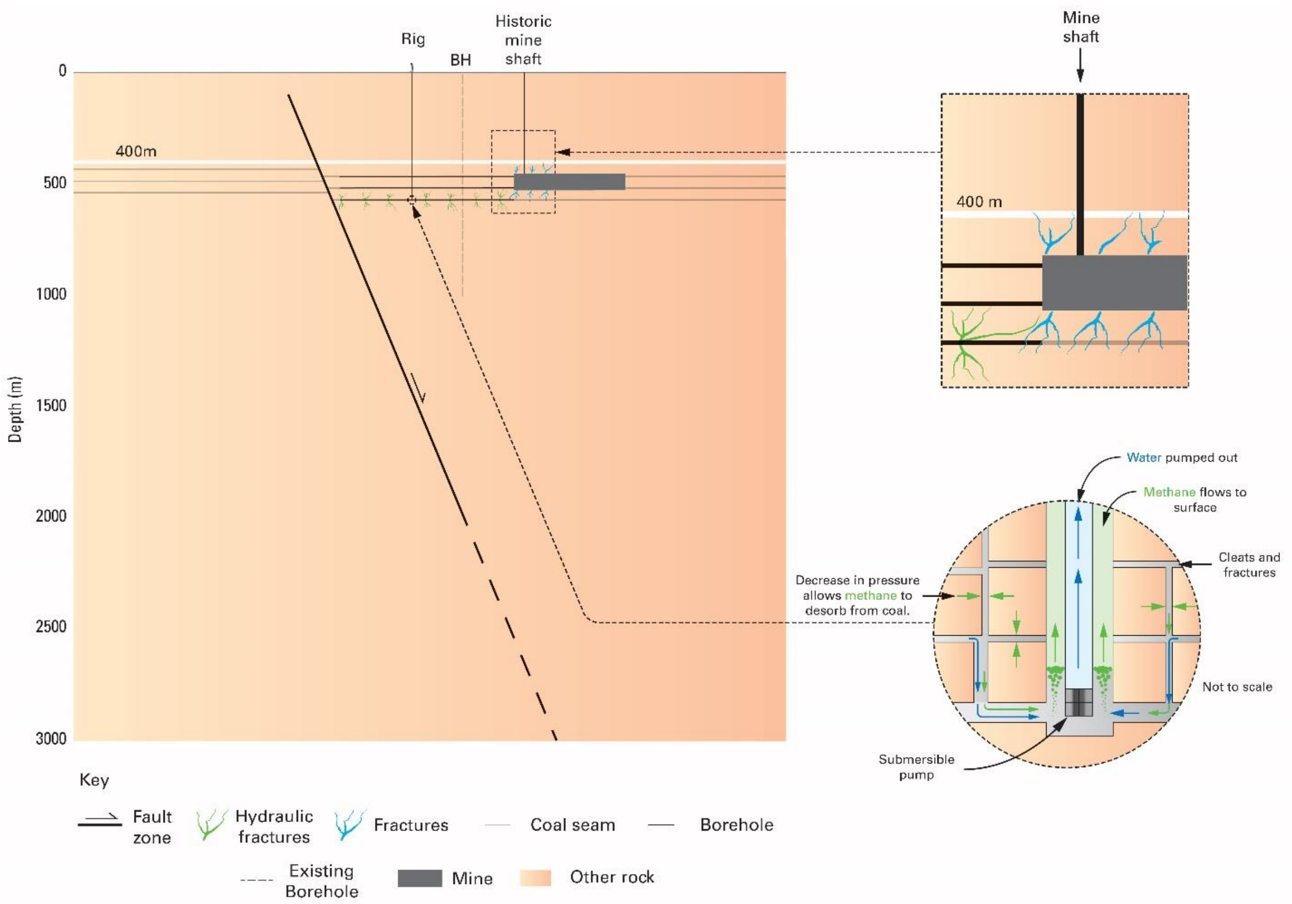


Figure 5.5 Simplified diagram of CBM. Aspects of the diagram are not to scale due to drawing limitations, such as the borehole width. 400 m indicates the maximum depth of groundwater bodies designated in the UK for management under the WFD (UKTAG, 2011).

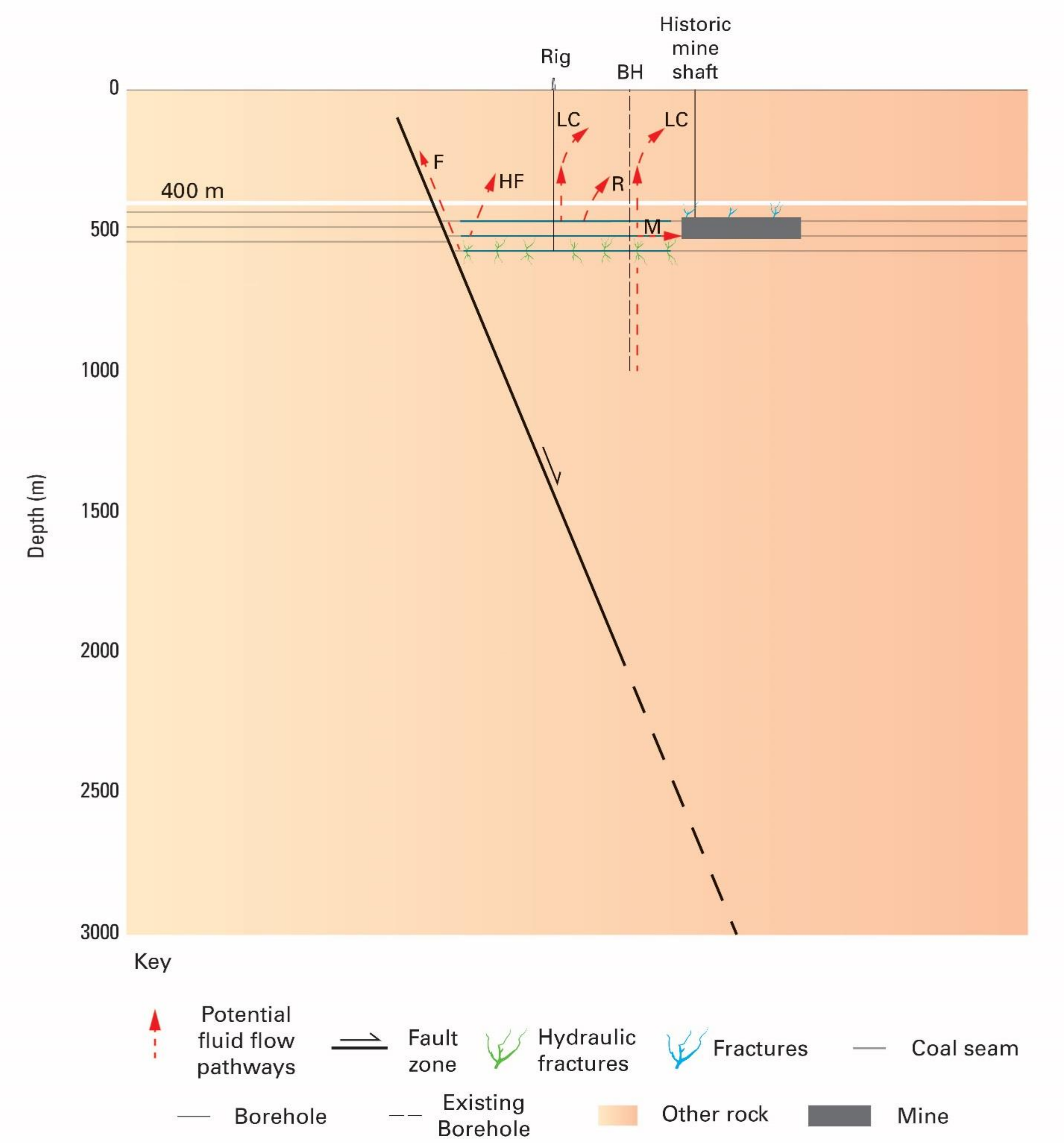


Figure 5.6 Simplified diagram of CBM with associated potential contamination pathways. Aspects of the diagram are not to scale due to drawing limitations, such as the borehole and length of pathways. See key for contamination pathways. 400 m indicates the maximum depth of groundwater bodies designated in the UK for management under the WFD (UKTAG, 2011). Pathways are labelled as follows; R is transport through the intervening rock mass, LC is leaky casing, BH is existing boreholes, F is fault, HF is Hydraulic Fractures.

5.4 UCG

UCG is the process in which oxygen and steam or water are injected into a coal seam via a borehole resulting in the partial *in-situ* combustion of coal to produce a combustible gas mixture consisting of carbon dioxide, methane, hydrogen and carbon monoxide. The product gas is then extracted via a producing well (Jones et al., 2004). UCG relies on high permeability within the coal in order to allow links between the boreholes but coals in England are typically low permeability (Jones et al. 2004) (Figure 5.7).

As noted above for CBM, Coal Measures in England are often interspersed with secondary aquifers. In the US, formation fluids are often within the salinity threshold for some definitions of drinking water (US EPA, 2016). Coal Measures are also located in proximity to freshwater aquifers (Al-Jubori et al., 2009) in England and are often directly overlain by Permo-Triassic principal aquifers (Jones et al., 2004). Therefore, contaminants would be closer to a potential receptor. In addition, because UCG can take place at only 200 m bgl this might be shallower than a receptor.

Many possible hydrocarbon source units for UCG in England are close to coal seams that have previously been worked and may have a high density of mines and abandoned boreholes (Figure 5.8). Because of the age of the Coal Measures in the UK, they are also generally highly fractured and faulted due to their deformational history. It has been suggested that UCG should take place > 45 m from faults (Shafirovich and Varma, 2009) since faults might provide pathways for contamination.

Because a cavity is generally created with UCG, ground instabilities and subsidence are common (Burton et al., 2006). This causes increased fracturing around the cavity and could cause borehole deformation (Figure 5.8) (Burton et al., 2006; Bhutto et al., 2013; Shafirovich and Varma, 2009).

Contaminant transport may be enhanced due to convection from increased temperatures and pressures (Burton et al., 2006). However, groundwater monitoring took place at Chinchilla, Australia, and did not reveal any contamination (Jones et al., 2004).

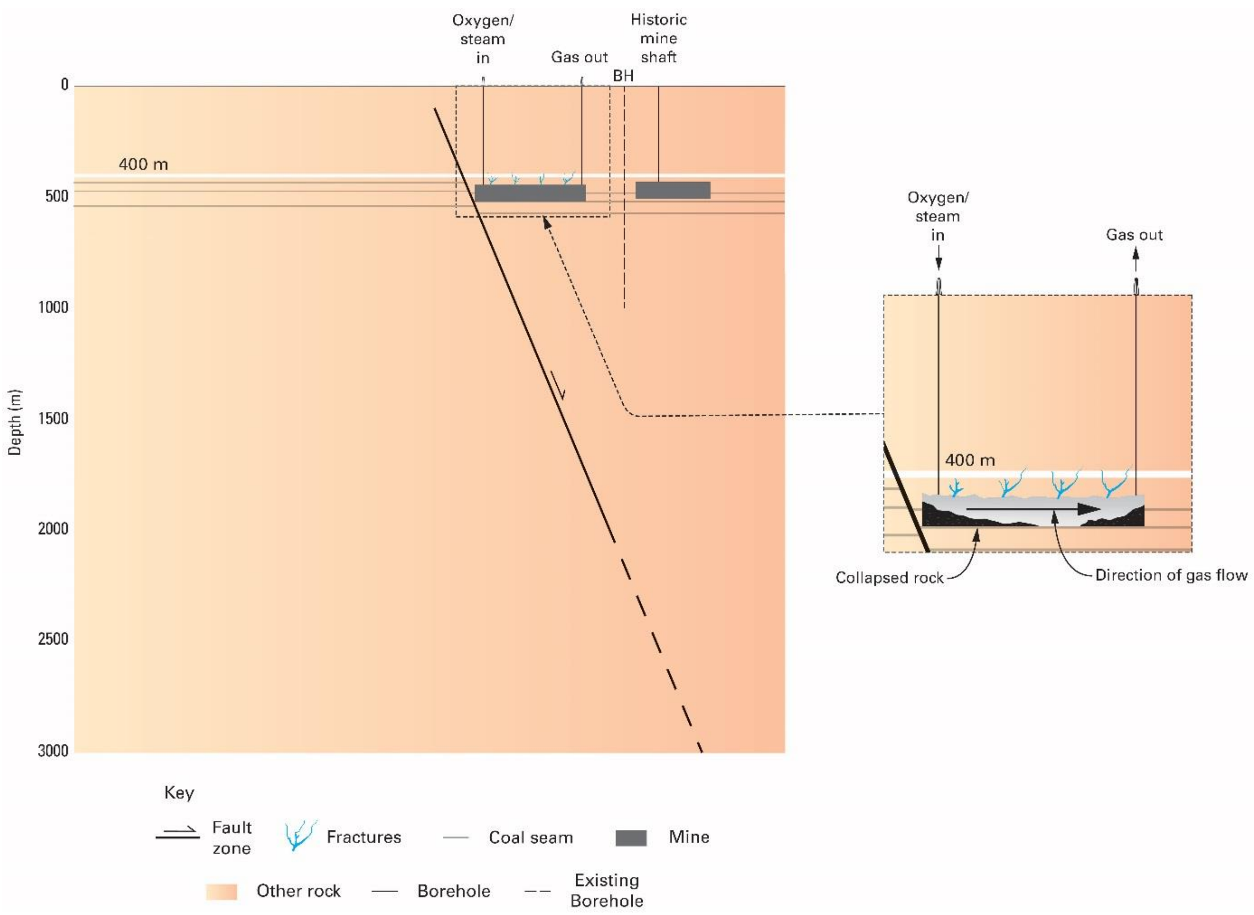


Figure 5.7 Simplified diagram of UCG. Aspects of the diagram are not to scale due to drawing limitations, such as the borehole width. 400 m indicates the maximum depth of groundwater bodies designated in the UK for management under the WFD (UKTAG, 2011).

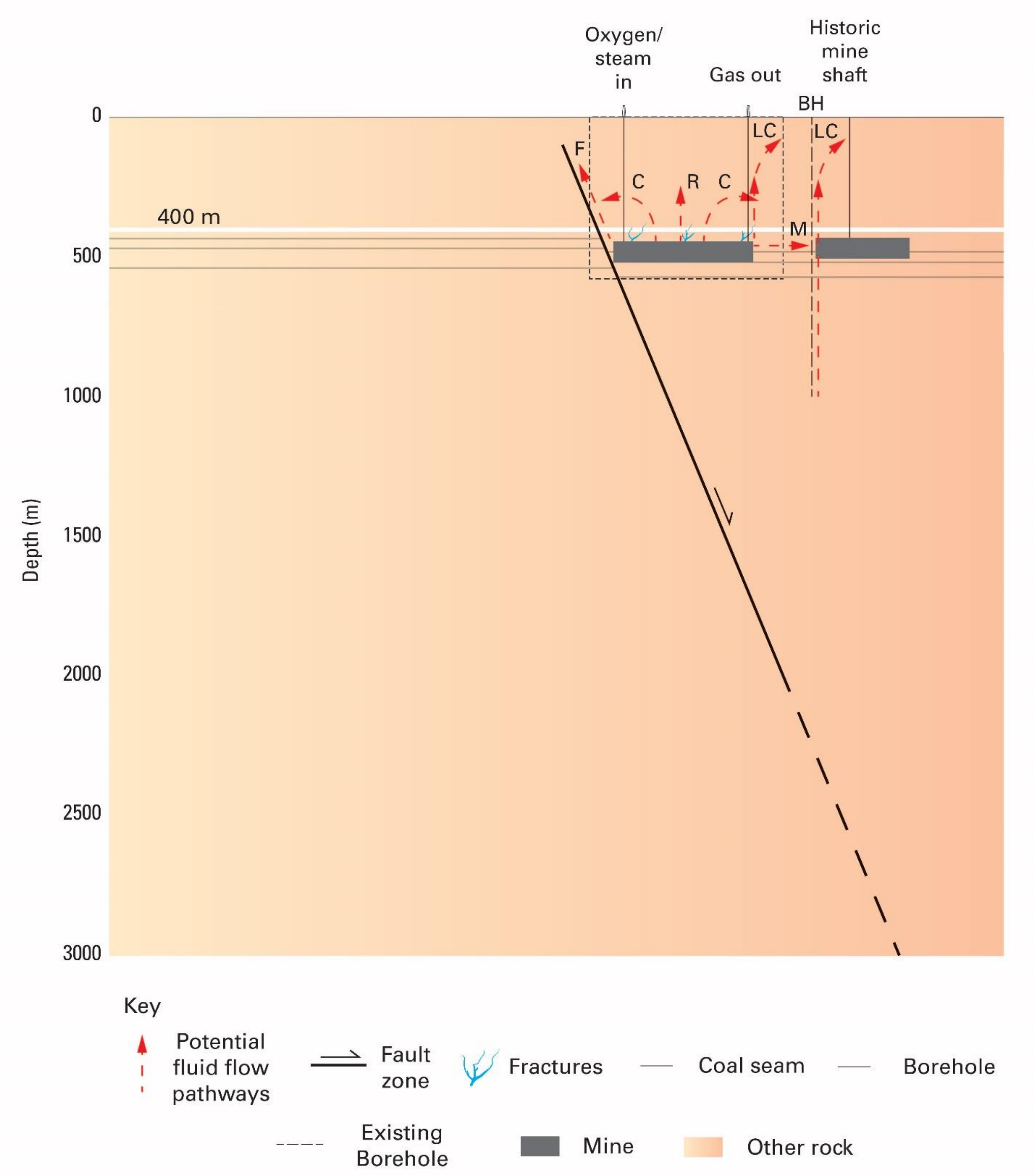


Figure 5.8 Simplified diagram of UCG with associated potential contamination pathways. Aspects of the diagram are not to scale due to drawing limitations, such as the borehole and length of pathways. See key for contamination pathways. 400 m indicates the maximum depth of groundwater bodies designated in the UK for management under the WFD (UKTAG, 2011). Pathways are labelled as follows; R is transport through the intervening rock mass, LC is leaky casing, BH is existing boreholes, F is fault, HF is Hydraulic Fractures, HF/F shows Hydraulic Fractures intersecting a fault, C is Convection.

5.5 DRIVING FORCES

Extraction mechanism of hydrocarbon (H_1)

This hazard factor results directly from the proposed hydrocarbon source and activity; conventional oil and gas, shale gas, UCG and CBM; and the specific techniques that will be employed. It identifies the possible release mechanism of contaminants associated with particular hydrocarbon activities resulting from the expected changes to the subsurface, e.g. increasing the permeability due to the creation of new flow paths or convection of contaminants due to increased pressure and temperature. There are five possible hazard rankings (Table 5.1). However, this are indicative, and a variety of other stimulation mechanisms (e.g. radial jetting or maintenance of reservoir pressure by injection of fluid into the oil or gas-bearing formation) can also occur.

Table 5.1 Hazard factor H_1, stimulation mechanism from proposed hydrocarbon activities. Scores are preliminary.

Hazard parameter	Parameter ranking
Permeability enhancement and increase in pressure and temperature (UCG)	5
Permeability enhancement from high volume hydraulic fracturing (e.g. shale gas)	4
Permeability enhancement from low volume hydraulic fracturing (e.g. conventional oil and gas with hydraulic fracturing)	3
Water table lowering and depressurisation (CBM)	2
No permeability enhancement (passive) for conventional oil and gas. This includes injection of fluid to maintain reservoir pressure (without hydraulic fracturing)	1

Sources of information

The proposed release mechanism should be readily available from the licence application.

Confidence

Because the release mechanism will be available from the licence application a high confidence score can be assigned to this parameter.

Whilst the presence of potential pathways and the characteristics of rocks between the source and receptor may contribute to the vulnerability of a receptor, a mechanism of transport is required for contamination to actually occur, i.e. to present a risk. Contaminant transport mechanisms include diffusion and advection. Diffusion is likely to be slow and not very significant with the distances and concentrations of chemicals involved in these processes compared to advection, which can transmit a greater volume of contaminants. Advection requires a driving force to make groundwater flow (e.g. Flewelling and Sharma, 2014).

In the majority of cases, the receptor will overlie the source and an upwards driving force will be required for contamination. Flewelling and Sharma (2014) and Birdsell et al. (2015) suggest that, generally, vertical hydraulic gradients are small and densities of deep fluids are high, preventing upwards migration. Contamination from methane and other light gases is more likely than from heavier ones due to their buoyancy. In England, groundwater flow paths tend to be controlled by topographic flow; from recharge areas in uplands (with high hydraulic head) to discharge areas in lowlands (with low hydraulic heads) (Downing et al., 1987). On a regional scale, this means that there is likely to be a downwards gradient at the margins or sides of a basin, and below OD (Ordnance Datum) there is likely to be an upwards head gradient in the centre of a basin. Other factors to consider include fluid buoyancy, palaeoflow systems and compacting sediments as discussed in Bethke (1989). There is little evidence of natural overpressurisation reported in England (e.g. DECC, 2013a). However, over-pressurised gas was encountered in the Hatfield Moors Gas Field in 1981 (Thorogood and Younger, 2015). Fluids are also known to flow from depth to the surface in some places, such as the hot springs at Bath and Buxton. High hydraulic heads seen at about 1,100 m bgl in the Sellafield area have recently been explained by relict heads from a wet-based ice sheet over the area (Black and Barker, 2016). Often the rate of upwards groundwater movement may be very low, taking in the order of thousands of years in deep basins to reach the surface, making it difficult to identify such flows (e.g. Llewellyn, 2014; Vengosh et al., 2014).

Some of the hydrocarbon activities listed above change subsurface pressures and provide an external driving force. During hydraulic fracturing, reservoir pressures are typically increased to about 15 MPa above virgin reservoir pressure, increasing hydraulic head by 1500 m (Brownlow et al., 2016). This pressure increase can drive fluids away from the stimulated zone into the surrounding rock and possibly through preferential flow pathways. However, during production, flow-back occurs and hydraulic heads are relaxed slightly (Brownlow et al., 2016). The time over which high heads are sustained is not well known. Lefebvre et al. (2017) and others suggest that it is unlikely that overpressures will be maintained after the production of a shale gas reservoir has finished. Brownlow et al. (2016) suggest that the increased heads of 1500 m during hydraulic fracturing decreased to nominal head values after 1 year, and decreased by a further 200 m after 15 years, inducing flow towards the well, consistent with other simulations and observations in the Eagle Ford shale, Texas. It should be noted that head propagation occurs over shorter timescales and greater distances than fluid migration (Brownlow et al., 2016).

The dewatering process associated with CBM lowers the water table and can create a zone of depressurisation around the borehole. This can mobilise gas and other contaminants from the source rock; however, generally the pathways will be towards, rather than away from, the borehole.

With UCG, convection of fluids surrounding the coal seam can be induced due to the high temperatures and pressures. This can force contaminants away from the source and towards a receptor.

Head gradient driving flow (H_2)

This hazard factor identifies natural groundwater head gradients which would act as a driving force for fluid flow and/or contamination from the hydrocarbon source towards the receptors.

The key factors are the direction and rate of groundwater flow (velocity). A natural groundwater flow direction from the hydrocarbon source towards the receptor increases the specific vulnerability of the potential receptor. Where groundwater flow is from the receptor formation towards the hydrocarbon source this decreases the vulnerability of the potential receptor. There are two possible parameter ratings (Table 5.2).

For most AOIs, there is likely to be very limited data from which a head gradient, or even direction, can be inferred at depth. There is more information available for head gradients at shallower (< 200 m) depths which can indicate groundwater flow directions in shallower units. If there is sufficient information it might be possible to infer the depth to which this applies.

At some sites, local hydraulic gradients have been measured, for example at Harwell, Oxfordshire, to 350 m depth (Alexander et al., 1987) and Sellafield, Cumbria, to 2000 m depth (Black and Barker, 2016). Downing et al. (1987) present conceptual models of large-scale, regional groundwater flow, with some identification or supposition of upwards/downwards flow for; the Eastern Province, Hampshire Province, Severn Province, Northwest Province.

Regional head gradients in the centre of basins at depth, where hydrocarbon sources are commonly found, are often in the upwards direction. Therefore, in accordance with the precautionary principle (e.g. EA, 2013) and unless there is contrary evidence, the head gradient is assumed to be from the hydrocarbon source to the receptor (i.e. the worst case scenario).

Table 5.2 Hazard factor H_2, head gradient driving flow from hydrocarbon source. Scores are preliminary.

Hazard parameter	Parameter rating
Head gradient from hydrocarbon source to receptor or unknown	2
No head gradient from hydrocarbon source to receptor	1

Sources of information

There is generally limited site specific information for hydraulic gradients at depth for site locations in England; however, some does exist in the literature, including:

- Harwell, Oxfordshire; groundwater flows into the Corallian Group upwards through the Oxford Clay Formation from the Great and Inferior Oolite Groups and downwards through the Gault Formation, Lower Greensand Formation and Kimmeridge Clay Formation from the Chalk Group and Upper Greensand Formation (Alexander et al., 1987).
- Sellafield, Cumbria; groundwater flows between the Borrowdale Volcanic Group and the Sherwood Sandstone Group (Black and Brightman, 1996; Heathcote et al., 1996; McKeown et al., 1999; Black and Barker, 2016).
- Selby coal mine, Yorkshire; highest measured head was hydrostatic in relation to the overlying ground surface (Younger, 2016).

Drilling logs might contain useful information on hydraulic head including unexpected changes in pressure such as over-pressure or loss of fluid. Where such information exists, they can be used for locations within their immediate vicinity.

Head gradients can be inferred from hydrogeological evidence such as the presence of thermal springs, for example from the Carboniferous Limestone Supergroup at Bath and Hotwells (Bristol), Buxton and Matlock.

Conceptual models of groundwater head gradients and groundwater for England are presented by Downing et al. (1987) with some supporting data.

Hydrogeological maps can provide information on shallow groundwater heads which may be useful in some locations (see http://www.bgs.ac.uk/research/groundwater/datainfo/hydromaps/hydro_maps_scanviewer.html).

Environment Agency groundwater models.

Confidence

- High = site specific information such as Harwell, Sellafield, thermal springs, drilling data
- Medium or low = inferred head gradients or regional groundwater flow e.g. Downing et al. (1987)

6 Risk Group

The risk group (RG) takes into account the receptor importance and the specific vulnerability to produce a classification of either low, medium-low, medium-high or high (Table 6.1). The risk group classifications are preliminary, and will require adjustment, as will the scoring of the parameters within the assessment.

A confidence level is also assigned – the lowest of all confidence levels assigned to each factor in the intrinsic and specific vulnerability assessments. The combination of risk groups and confidence levels can be used to identify sites where further information is required for assessment.

For a receptor classified as 'D' the risk group is always low because the unit is classified as unproductive and/or has a TDS of > 35,000 mg/l. It is therefore a low priority for protection. However, receptors that are classified as 'A' and 'B' may be principal/secondary aquifers and the impacts of contamination would be greater. Receptors classified as 'A' are so important that even low specific vulnerability scores would result in these receptors being in a medium/low risk group.

Table 6.1 Risk groupings based on specific vulnerability and potential receptor classification. Classifications are preliminary only.

	Specific vulnerability score			
Potential receptor classification	< 250	250-500	500-750	>750
A	Medium/Low	Medium/High	High	High
B	Low	Medium/Low	Medium/High	High
C	Low	Low	Medium/Low	Medium/high
D	Low	Low	Low	Low

6.1 BASELINE METHANE

Methane (natural gas) is commonly found at trace levels as a dissolved component in groundwater. Methane is produced by both natural processes and anthropogenic activities. Thermogenic natural gas is produced through thermal decomposition of organic matter at significant depth. Methane can also be produced by biogenic processes (bacterially) at much shallower depths. Because natural gas is buoyant in geological environments, if a pathway exists, it can move upwards and accumulate at shallower depths. Natural gas found in small, uneconomic quantities in shallow zones may have originated in place or may have migrated upwards, and is often referred to as stray gas. Anthropogenic activities that can produce or release methane include coal mining or landfill operations.

There are certain environments in which methane might be naturally high, such as peat bogs, wetlands, lake sediments and landfills or even confined groundwater bodies (Bell et al., 2016; Ward et al., 2017). Geochemical analysis can indicate whether the methane is from a shallow, biogenic source or a deeper, thermogenic source. In the latter case, it is possible that there exists a pathway for contamination from depth to the surface or groundwater body of interest and this should be noted as part of the vulnerability assessment. Where this is not clear, it should also be considered as a possible release from depth since this may be evidence for a higher vulnerability area with a potential driving force and pathway. This should be considered in conjunction with the risk assessment.

Bell et al. (2016) consider the concentration of methane in water of 1600 μg/l as high. This concentration represents the Lower Explosive Limit (LEL) (5% by volume) in a confined space.

Source of information

Information is available from the National Methane Baseline report (Bell et al. 2016) and http://www.bgs.ac.uk/research/groundwater/shaleGas/methaneBaseline/home.html. Because of the scale of the National Methane Baseline survey there are many AOI's where there will not be data. It is therefore recommended to consider regional datasets, for e.g. on the basin/sub-basin scale (e.g. Weald/Wessex basins).

7 Scenarios

In all case studies, a simple configuration of a vertical borehole drilled to the depth of the hydrocarbon source unit was used, with the option for laterals in the case of shale gas and Coal Bed Methane (CBM). It is recognised that, in reality, hydrocarbon activities are much more complex and the activities and geometries of the sub-surface infrastructure should be assessed according to the best information available.

Examples of the use of the methodology for conceptual scenarios with expected high and low risk are presented. Case studies demonstrate how the 3DGWV methodology could be used as part of site-specific risk screenings and to show the range of results which might be expected in areas of England where hydrocarbon source units exist and are included in Appendix 6. They are based on real data for each of these areas, but the case studies are generic and as such a precise site location has not been specified.

7.1 HIGH AND LOW RISK EXAMPLES

The highest risk scenario is likely to involve UCG exploitation as this has been identified as the activity with the highest hazard (Section 5). This scenario is shown below. However, since UCG is unlikely to be undertaken onshore in the UK in the near future, the hypothetical highest risk scenarios for shale gas (next highest hazard rating, but constrained to > 1000 m bgl) and CBM (lower hazard rating than shale gas but no depth constraints) were also tested.

7.1.1 High risk example, UCG

The high risk scenario for UCG is described in Table 7.1, which is based on the conceptual model in Figure 7.1. The scoring for the intrinsic vulnerability and hazard is shown in Table 7.2 and Table 7.3. The intrinsic and specific vulnerability scores and risk group are summarised at the bottom of Table 7.1. Both the limestone aquifer and coal measures are in the high risk group, and the specific vulnerability score is the highest possible (985).

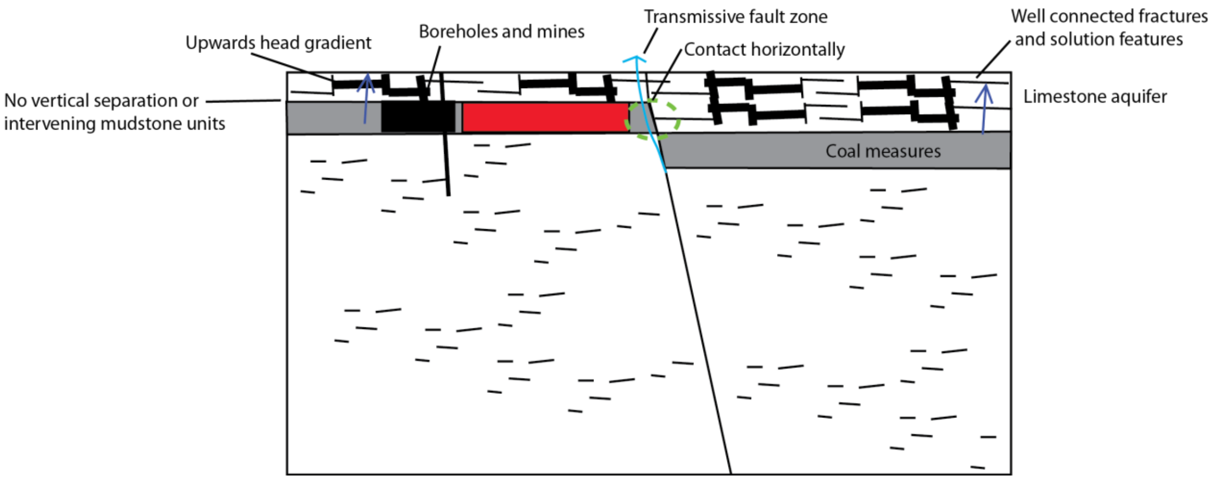


Figure 7.1 High risk scenario for UCG. Red rectangle indicates UCG activities. Underlying rocks are not assessed in this scenario. Not to scale.

Table 7.1 Scenario and intrinsic and specific vulnerability scores and risk group for UCG high risk example

Hydrocarbon source and extraction method				
Coal measures, UCG				
AOI				
2 km around vertical borehole				
Geological setting				
A limestone (fractured) aquifer directly overlies coal measures (Figure 7.1)				
Potential receptors	**Classification**			
Limestone aquifer	A (principal aquifer < 400 m bgl)			
Coal measures	B (secondary aquifer < 400 m bgl)			
Hazard	**Score**			
Release mechanism of hydrocarbon	UCG, permeability enhancement and increase in pressure and temperature (UCG)			
Head gradient driving flow	Upward from coal measures to limestone aquifer			
Vulnerability				
Vertical separation between source and base of receptor	Calculated from the conceptual model, no lateral change			
Lateral separation between source and receptor	Calculated from the conceptual model, no change			
Mudstones and clays in intervening units between source and receptor	No intervening units			
Groundwater flow mechanism in intervening units between source and receptor, including the receptor	Well connected fractures in both the limestone and coal measures			
Faults cutting intervening units and receptor	A fault cuts all units and is known to be transmissive to fluids. This fault also results in the horizontal connectivity of the hydrocarbon source unit and the aquifer.			
Solution features in intervening units and receptor	Known to be present in the AOI			
Anthropogenic features- mines close to site of interest	Known to be present in AOI			
Anthropogenic features- boreholes close to site of interest	Known to be present in AOI			
Potential receptor	Intrinsic vulnerability score	Specific vulnerability score	Risk group	Confidence
Limestone aquifer	98.5	985	High	Medium
Coal Measures	98.5	985	High	Medium

Table 7.2 Hazard factors for UCG high risk example. Hydrocarbon source is shown in red.

FACTOR	Release mechanism of hydrocarbon (H1)		Head gradient driving flow (H2)			
GEOLOGICAL UNIT	RANKING	CONFIDENCE	RATING	CONFIDENCE	HAZARD SCORE	CONFIDENCE
Limestone aquifer	5	high	2	high	10	High

Coal Measures			2	high	10	High

Table 7.3 Intrinsic vulnerability factors for UCG high risk example. Hydrocarbon source is shown in red.

FACTOR	Vertical separation between source and base of receptor		Lateral separation between source and receptor		Mudstones and clays in intervening units between source and receptor	
WEIGHTING (w)	1.5		3		3.5	
CONFIDENCE	high		medium		high	
GEOLOGICAL UNIT						
Limestone aquifer	8	12	4	12	5	17.5
Coal Measures	8	12	4	12	5	17.5

FACTOR	Groundwater flow mechanism in intervening units between source and receptor, including the receptor		Faults cutting intervening units and receptor		Solution features in intervening units and receptor		Anthropogenic features-mines close to site of interest		Anthropogenic features-boreholes close to site of interest		Intrinsic vulnerability score
WEIGHTING (w)	3		4.5		2		8		4		
CONFIDENCE	high		high		medium		high		High		
GEOLOGICAL UNIT											
Limestone aquifer	3	9	4	18	3	6	2	16	2	8	98.5
Coal Measures	3	9	4	18	3	6	2	16	2	8	98.5

7.1.2 High risk example, CBM

The high risk scenario for CBM is described in Table 7.4**,** which is based on the conceptual model in Figure 7.2. The geological setting is the same as for the UCG scenario. The scoring for the hazard is shown in Table 7.5 and intrinsic vulnerability in Table 7.7. The intrinsic and specific vulnerability scores are summarised at the bottom of Table 7.1 . The lower hazard score, due to the release mechanism, results in a lower specific vulnerability score and risk group for both geological units. The limestone aquifer is in the medium/high risk group, and the Coal Measures are in the medium/low risk group. The specific vulnerability scores are 394 for both geological units.

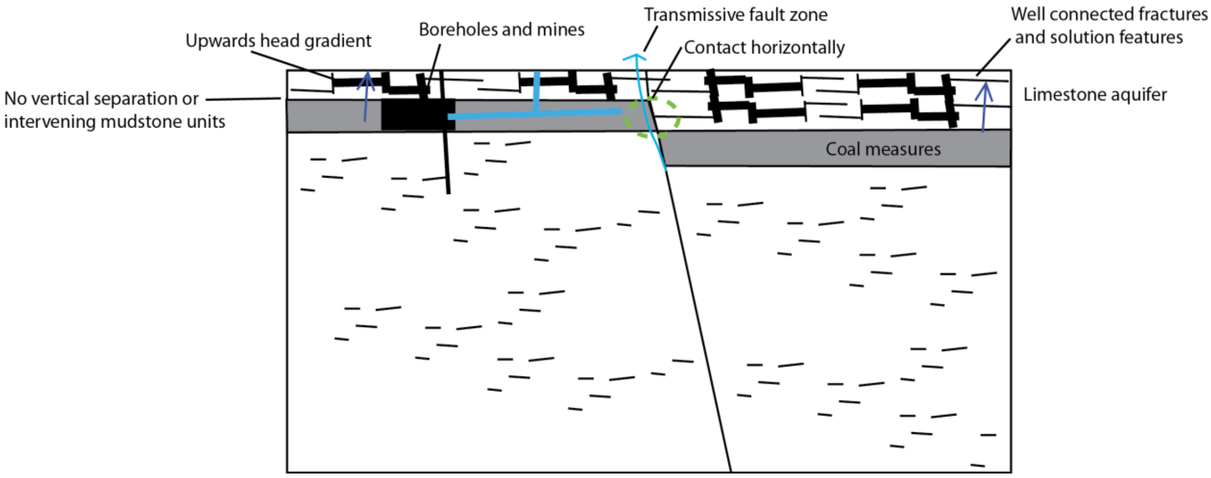


Figure 7.2 High risk scenario for CBM. Thick blue lines indicate CBM wells. Underlying rocks are not significant. Not to scale.

Table 7.4 Scenario and intrinsic and specific vulnerability scores and risk group for CBM high risk example

Hydrocarbon source and extraction method	
Coal Measures, CBM	
AOI	
2 km around vertical borehole	
Geological setting	
A limestone (fractured) aquifer directly overlies Coal Measures (Figure 7.2)	
Potential receptors	**Classification**
Limestone aquifer	A (principal aquifer < 400 m bgl)
Coal Measures	B (secondary aquifer < 400 m bgl)
Hazard	**Score**
Release mechanism of hydrocarbon	Water table lowering and depressurisation (CBM)
Head gradient driving flow	Upward from Coal Measures shale towards limestone aquifer
Vulnerability	
Vertical separation between source and base of receptor	Calculated from the conceptual model, no lateral change
Lateral separation between source and receptor	Calculated from the conceptual model, no change
Mudstones and clays in intervening units between source and receptor	No intervening units
Groundwater flow mechanism in intervening units between source and receptor, including the receptor	Well connected fractures in both the limestone and Coal Measures
Faults cutting intervening units and receptor	A nearby fault is transmissive, which results in the horizontal connectivity of the hydrocarbon source unit and the aquifer.
Solution features in intervening units and receptor	Known to be present in the AOI
Anthropogenic features- mines close to site of interest	Known to be present in AOI

Anthropogenic features-boreholes close to site of interest	Known to be present in AOI			
Potential receptor	Intrinsic vulnerability score	Specific vulnerability score	Risk group	Confidence
Limestone aquifer	98.5	394	Medium/high	Medium
Coal Measures	98.5	394	Medium/low	Medium

Table 7.5 Hazard factor for CBM high risk example. Hydrocarbon source is shown in red.

FACTOR	Release mechanism of hydrocarbon (H1)		Head gradient driving flow (H2)			
GEOLOGICAL UNIT	RANKING	CONFIDENCE	RATING	CONFIDENCE	HAZARD SCORE	CONFIDENCE
Limestone aquifer	2	high	2	high	4	high
Coal Measures			2	high	4	high

Table 7.6 Intrinsic vulnerability factors for CBM high risk example. Hydrocarbon source is shown in red.

FACTOR	Vertical separation between source and base of receptor		Lateral separation between source and receptor		Mudstones and clays in intervening units between source and receptor	
WEIGHTING (w)	1.5		3		3.5	
CONFIDENCE	high		medium		high	
GEOLOGICAL UNIT						
Limestone aquifer	8	12	4	12	5	17.5
Coal Measures	8	12	4	12	5	17.5

FACTOR	Groundwater flow mechanism in intervening units between source and receptor, including the receptor		Faults cutting intervening units and receptor		Solution features in intervening units and receptor		Anthropogenic features-mines close to site of interest		Anthropogenic features-boreholes close to site of interest		Intrinsic vulnerability score
WEIGHTING (w)	3		4.5		2		8		4		
CONFIDENCE	high		high		medium		high		high		high
GEOLOGICAL UNIT											
Limestone aquifer	3	9	4	18	3	6	2	16	2	8	98.5
Coal Measures	3	9	4	18	3	6	2	16	2	8	98.5

7.1.3 High risk example, shale gas

The high risk scenario for shale gas is described in Table 7.7, which is based on the conceptual model in Figure 7.3. The scoring for the hazard is shown in Table 7.8 and intrinsic vulnerability in Table 7.9. The intrinsic and specific vulnerability scores are summarised at the bottom of Table 7.7. The intrinsic vulnerability of the limestone aquifer and shale is 98.5 and the specific vulnerability score is 788. Both units are in the high risk group.

Table 7.7 Scenario and intrinsic and specific vulnerability scores and risk group for shale gas high risk example.

Hydrocarbon source and extraction method				
Shale, shale gas with high volume hydraulic fracturing				
AOI				
4 km, 2 km around 2 km lateral boreholes				
Geological setting				
The minimum depth that high volume hydraulic fracturing is permitted onshore in the UK (1000 m bgl) was used for the depth of the hydrocarbon source unit (shale). Similar to the UCG, a limestone aquifer is the main receptor and directly overlies the shale (the source) (Figure 7.3).				
Potential receptors	**Classification**			
Limestone aquifer	A (principal aquifer < 400 m bgl)			
Shale	B (secondary aquifer < 400 m bgl)			
Hazard	**Score**			
Release mechanism of hydrocarbon (H1)	High volume hydraulic fracturing			
Head gradient driving flow (H2)	Upward from shale to limestone aquifer			
Vulnerability				
Vertical separation between source and base of receptor	Calculated from the conceptual model, no lateral change			
Lateral separation between source and receptor	Calculated from the conceptual model, no change			
Mudstones and clays in intervening units between source and receptor	No intervening units			
Groundwater flow mechanism in intervening units between source and receptor, including the receptor	Well connected fractures in both the limestone and shale			
Faults cutting intervening units and receptor	A fault cuts all units and is known to be transmissive to fluids. This fault also results in the horizontal connectivity of the hydrocarbon source unit and the aquifer.			
Solution features in intervening units and receptor	Known to be present in the AOI			
Anthropogenic features- mines close to site of interest	Known to be present in AOI			
Anthropogenic features- boreholes close to site of interest	Known to be present in AOI			
Potential receptor	Intrinsic vulnerability score	Specific vulnerability score	Risk group	Confidence
Limestone aquifer	98.5	788	High	Medium
Shale	98.5	788	High	Medium

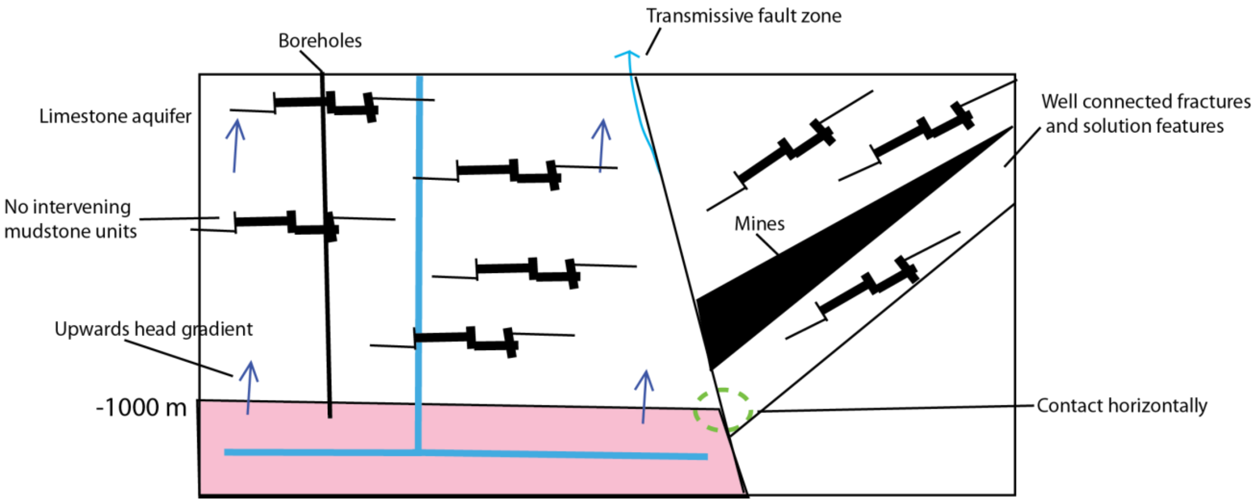


Figure 7.3 High risk scenario for shale gas. Shale unit is pink, thick blue lines indicate planned boreholes. Not to scale.

Table 7.8 Hazard factor for shale gas high risk example. Hydrocarbon source is shown in red.

FACTOR	Release mechanism of hydrocarbon (H1)		Head gradient driving flow (H2)			
GEOLOGICAL UNIT	RANKING	CONFIDENCE	RATING	CONFIDENCE	HAZARD SCORE	CONFIDENCE
Limestone aquifer	4	high	2	high	8	high
Shale			2	high	8	high

Table 7.9 Intrinsic vulnerability factors for shale gas high risk example. Hydrocarbon source is shown in red.

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FACTOR	Vertical separation between source and base of receptor		Lateral separation between source and receptor		Mudstones and clays in intervening units between source and receptor	
WEIGHTING (w)	1.5		3		3.5	
CONFIDENCE	high		medium		high	
GEOLOGICAL UNIT						
Limestone aquifer	8	12	4	12	5	17.5
Shale	8	12	4	12	5	17.5

FACTOR	Groundwater flow mechanism in intervening units between source and receptor, including the receptor		Faults cutting intervening units and receptor		Solution features in intervening units and receptor		Anthropogenic features-mines close to site of interest		Anthropogenic features-boreholes close to site of interest		INTRINSIC VULNERABILITY SCORE (V)
WEIGHTING (w)	3		4.5		2		8		4		
CONFIDENCE	high		high		medium		high		high		high
GEOLOGICAL UNIT											
Limestone aquifer	3	9	4	18	3	6	2	16	2	8	98.5
Shale	3	9	4	18	3	6	2	16	2	8	98.5

7.1.4 Low risk example, conventional oil and gas

The low risk scenario is constructed for conventional oil and gas exploitation since this has been identified as the activity with the lowest hazard. The low risk scenario for conventional oil and gas is described in Table 7.10, which is based on the conceptual model in Figure 7.4. The scoring for the hazard is shown in Table 7.11 and intrinsic vulnerability in Table 7.12. The intrinsic and specific vulnerability scores are summarised at the bottom of Table 7.10 . The vulnerability of the sandstone aquifer is 8 and the specific vulnerability score is also 8. A vulnerability of 0 is not possible because the maximum separation distance (>1200 m) and the maximum intervening mudstone thickness (>250 m) have minimum scores of 1.5 and 3.5 respectively.

The risk group is medium/low for this and low for both the mudstone and reservoir. The medium/low risk group, despite a very low specific vulnerability score, reflects the fact that there is a degree of risk to potential receptors with hydrocarbon activities in the subsurface. If the potential receptor was classified as B or C in this case, the risk group would be low.

Table 7.10 Scenario and intrinsic and specific vulnerability scores and risk group for conventional oil and gas, low risk example.

<table>
<tr><th colspan="5">Hydrocarbon source and extraction method</th></tr>
<tr><td colspan="5">Conventional oil and gas reservoir, no changes to permeability or pressure</td></tr>
<tr><th colspan="5">AOI</th></tr>
<tr><td colspan="5">2 km around vertical borehole</td></tr>
<tr><th colspan="5">Geological setting</th></tr>
<tr><td colspan="5">In the low risk scenario a sandstone aquifer overlies 1200 m of mudstones below which overlies a conventional oil and gas reservoir (the hydrocarbon source unit). The aquifer outcrops at the surface (Figure 7.4).</td></tr>
<tr><th>Potential receptors</th><th colspan="4">Classification</th></tr>
<tr><td>Sandstone aquifer</td><td colspan="4">A – principal aquifer < 400 m bgl</td></tr>
<tr><td>Mudstone</td><td colspan="4">D – unproductive</td></tr>
<tr><td>Reservoir</td><td colspan="4">C – secondary aquifer > 400 m bgl</td></tr>
<tr><th>Hazard</th><th colspan="4">Score</th></tr>
<tr><td>Release mechanism of hydrocarbon (H1)</td><td colspan="4">No permeability enhancement (passive) for conventional oil and gas.</td></tr>
<tr><td>Head gradient driving flow (H2)</td><td colspan="4">No head gradient from source to receptor</td></tr>
<tr><th colspan="5">Vulnerability</th></tr>
<tr><td>Vertical separation between source and base of receptor</td><td colspan="4">Calculated from the conceptual model, no lateral change</td></tr>
<tr><td>Lateral separation between source and receptor</td><td colspan="4">Calculated from the conceptual model, no change</td></tr>
<tr><td>Mudstones and clays in intervening units between source and receptor</td><td colspan="4">1200 m mudstone in intervening unit</td></tr>
<tr><td>Groundwater flow mechanism in intervening units between source and receptor, including the receptor</td><td colspan="4">Sandstone aquifer and reservoir intergranular flow. No receptors class A to C in intervening units. Therefore, > 50 % principal or secondary aquifers (EA designation) with intergranular flow.</td></tr>
<tr><td>Faults cutting intervening units and receptor</td><td colspan="4">A fault cuts all units and is known to be transmissive to fluids. This fault also results in the horizontal connectivity of the hydrocarbon source unit and the aquifer.</td></tr>
<tr><td>Solution features in intervening units and receptor</td><td colspan="4">No known solution and no potential for solution features</td></tr>
<tr><td>Anthropogenic features-mines close to site of interest</td><td colspan="4">No mines in AOI</td></tr>
<tr><td>Anthropogenic features-boreholes close to site of interest</td><td colspan="4">No boreholes in AOI</td></tr>
<tr><th>Potential receptor</th><th>Intrinsic vulnerability score</th><th>Specific vulnerability</th><th>Risk group</th><th>Confidence</th></tr>
<tr><td>Sandstone aquifer</td><td>8</td><td>8</td><td>Medium/low</td><td>Medium</td></tr>
<tr><td>Mudstone</td><td>17</td><td>17</td><td>Low</td><td>Medium</td></tr>
<tr><td>Reservoir</td><td>30.5</td><td>30.5</td><td>Low</td><td>Medium</td></tr>
</table>

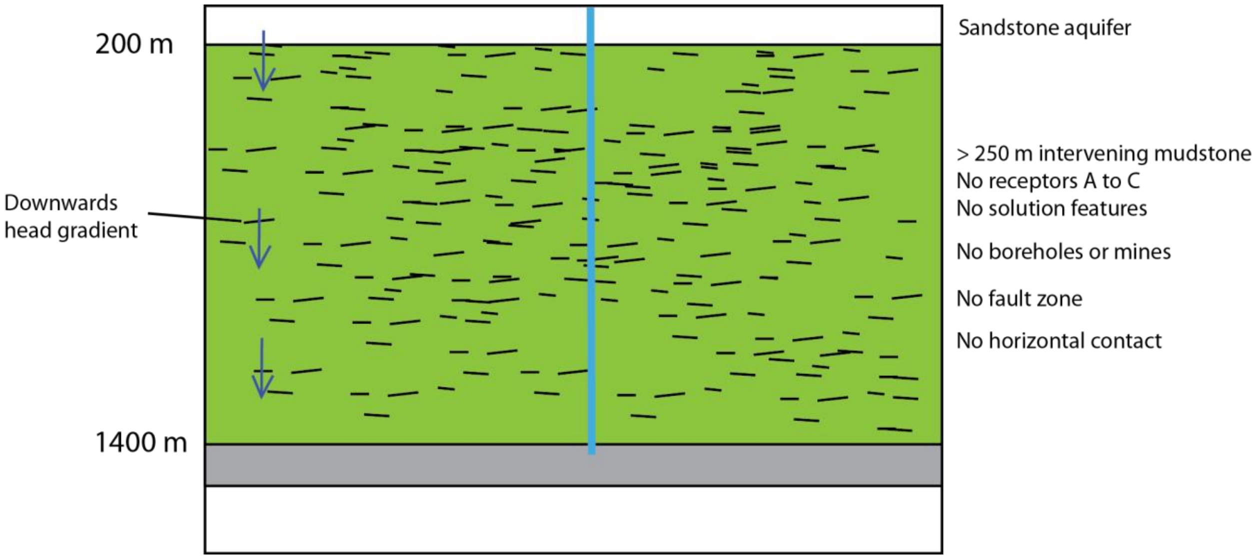

Figure 7.4 Low risk scenario for conventional hydrocarbon activities. Grey is the hydrocarbon reservoir and green is the overlying cap-rock (mudstone). Thick blue lines indicate boreholes. Not to scale.

Table 7.11 Hazard factors for conventional oil and gas low risk example. Hydrocarbon source is shown in red.

FACTOR	Release mechanism of hydrocarbon (H1)		Head gradient driving flow (H2)			
GEOLOGICAL UNIT	RANKING	CONFIDENCE	RATING	CONFIDENCE	HAZARD SCORE	CONFIDENCE
Sandstone aquifer			1	high	1	high
Mudstone			1	high	1	high
Reservoir	1	high	1	high	1	high

Table 7.12 Intrinsic vulnerability factors for conventional oil and gas low risk example. Hydrocarbon source is shown in red.

FACTOR	Vertical separation between source and base of receptor		Lateral separation between source and receptor		Mudstones and clays in intervening units between source and receptor	
WEIGHTING (w)	1.5		3		3.5	
CONFIDENCE	high		medium		high	
GEOLOGICAL UNIT						
Sandstone aquifer	1	1.5	0	0	1	3.5
Mudstone	1	1.5	4	12	1	3.5
Reservoir	8	12	4	12	1	3.5

FACTOR	Groundwater flow mechanism in intervening units between source and receptor, including the receptor		Faults cutting intervening units and receptor		Solution features in intervening units and receptor		Anthropogenic features-mines close to site of interest		Anthropogenic features-boreholes close to site of interest		INTRINSIC VULNERABILITY SCORE (V)
WEIGHTING (w)	3		4.5		2		8		4		
CONFIDENCE	high		high		medium		high		high		high
GEOLOGICAL UNIT											
Sandstone aquifer	1	3	0	0	0	0	0	0	0	0	8
Mudstone	0	0	0	0	0	0	0	0	0	0	17
Reservoir	1	3	0	0	0	0	0	0	0	0	30.5

7.2 DISCUSSION OF METHODOLOGY

The following discussion is based on the scenarios in Section 7, and case studies in Appendix 6.

The 3D Groundwater Vulnerability project has developed a prototype Tier 1 (Gormley et al., 2011) methodology for screening vulnerability and risk of groundwater to sub-surface hydrocarbon activities. Screening is site-specific rather than applied across larger areas such as previous EA vulnerability mapping (EA 2017a), due to the large number of inputs and considerations at each site and the variable availability of input data. It provides an indication of the relative risks of hydrocarbon activities in the subsurface to groundwater. The vulnerability and risk parameters and risk group boundaries are, at this stage, preliminary and used for illustrative purposes and it is anticipated that the methodology would be reviewed through experience.

The methodology can be applied as a quick, initial look at possible vulnerability and risk scenarios for a particular development (e.g. assessment of receptors at geological group scale) or as a much more detailed assessment (e.g. assessment of receptors at the geological formation scale). The time taken to undertake a screening using the methodology therefore varies according to the detail required and the purpose of the screening, but also the amount of information available, from one day up to a week or more. Confidence in the classification and groupings improves as more information is brought into the assessment.

The case studies (Appendix 6) demonstrate how the methodology could be applied in a site-specific setting, including the information that is required and how potential issues may be highlighted. It is not recommended that such initial site-specific risk assessments are decision making tools for regulators, but they could be used to help guide further investigations.

The high and low vulnerability and risk scenarios demonstrate that different geological situations could produce very different intrinsic and specific vulnerability scores. The intrinsic vulnerability is very dependent upon the geometry of the source-pathway-potential receptor system. The specific vulnerability is dependent on the intrinsic vulnerability and the hazard – i.e. the nature of the hydrocarbon activity that is taking place, and the possibility for groundwater flow from the source to the potential receptor. The risk group varies from low to high depending on the specific vulnerability score and the potential receptor value classification. For potential receptors of high value (classified ‘A’), the risk group will always be at least medium/low, recognising that risk can be mitigated but not eliminated when conducting sub-surface hydrocarbon activities. However, this is primarily related to drilling through the formations and not necessarily related to the actual sub-surface activity or the 3D geometry of the system.

The methodology was developed in order to compare the risks posed by conventional, CBM, shale gas and UCG hydrocarbon activities. As such, the vulnerability scores and risk groups are relative. In the current scoring system it is only possible to obtain the maximum specific vulnerability score when conducting UCG activities. However, such activities are unlikely to occur onshore in England in the near future. The high and low risk scenarios show that the maximum score for CBM and shale gas activities is 788 – in the ‘high’ risk group. The highest possible specific vulnerability score for conventional hydrocarbon activities is 197. In this case the highest risk group classification would be ‘medium/low’.

The case studies have shown that accurate potential receptor classification is very important in order to identify a realistic risk group. While classifications based on EA aquifer designations (at outcrop) are reasonable, there can be variations at site specific scales. For example, the case study for CBM in the West Midlands shows that local information on groundwater quality can be used to downgrade potential receptors (in this case the Sherwood Sandstone and Appleby Group), resulting in a low rather than a medium/low risk grouping for these potential receptors. Similar potential receptor intrinsic and specific vulnerability for CBM exist in the East Midlands. However, the potential receptors remain classified as ‘A’ and therefore the risk group is higher. The case study from Northeast England (Vale of Pickering) indicates that, in some cases, the potential receptors should be upgraded. For example, the Kimmeridge Clay is designated unproductive by the EA, but because it can provide reasonable quantities of potable water it is upgraded to ‘B’. These case studies demonstrate that it is important to compile as much data as possible on both the quantity and the quality of groundwater otherwise misrepresentation may result in overlooked groundwater resources or an overly-conservative view of the risk.

The risk group is the most informative category since it takes into account the sensitivity of the potential receptor. However, intrinsic and specific vulnerability scores must also be consulted to understand the risk group. In all of the case studies, there are a combination of risk groups for the potential receptors in any particular area. Most potential receptors were in the low risk group with the occasional potential receptor in the medium/low risk group. Units in the medium/high risk groups occur rarely, but include principal aquifers overlying shale gas and CBM activities. There are no potential receptors in the high risk group in the case studies under the current classifications (which may be subject to change). Many cases indicated that more information was required to reduce the high levels of uncertainty associated with the risk assessments. In some areas, additional data and information may exist to improve the site specific risk assessments. This should always be taken into account. For example, the information in the Vale of Pickering Methane Baseline Survey (Smedley et al., 2017) could point to natural hydrocarbon migration pathways which would need to be accounted for in the risk assessment methodology.

8 Conclusions

This report has described a Tier 1 (qualitative) methodology (3DGWV) for attributing vulnerability of groundwater to pollution from sub-surface oil and gas activities. The method considers a range of geological, hydrogeological and industry specific factors which influence vulnerability and risk to groundwater at a particular site. It is accompanied by a digital package, including the attributed UK3D2015, GIS data and a spreadsheet tool to guide development of a conceptual model and the assessments.

The methodology has been tested for scenarios where receptors would be considered to be of high or low vulnerability/risk according to the specific hydrocarbon activities and geological situations. It has also been tested in five case studies from different parts of England with different hydrocarbon source rocks/exploitation methods; conventional oil and gas in southeast England, CBM in the East and West Midlands, shale gas in northwest England and shale gas and conventional oil and gas in northeast England.

The case studies have demonstrated that contaminant pathways in the sub-surface from hydrocarbon activities can be assessed using the common vulnerability and risk screening approach and parameter sets presented in this report. By this means the relative vulnerability between sites and/or hydrocarbon development scenarios can be compared and used to assist in decision-making processes and risk communication.

The advantage of this approach is that it can be applied as a rapid, initial screening of possible vulnerability and risk scenarios for a particular development (with assessment of receptors at geological group scale, for example). It can also be used for more detailed assessment (for example, assessment of receptors at the geological formation scale) if required as well as identifying where information is lacking. One such area, highlighted by all the case studies is a need to improve the 3D understanding of the geological systems.

Confidence in the vulnerability and risk assessment improves as more information is considered. Consequently it is recommended that it is used in a dynamic manner.

The risk group (qualitative indicator of risk) is the most informative category since it takes into account the sensitivity of the potential receptor along with intrinsic and specific vulnerability. The examples considered in this report produced a range of vulnerability and risk outcomes that were consistent with the scenarios tested.

Refinements to the methodology are required in terms of the factor parameters and weightings, in addition to risk groupings. The methodology is only concerned with risks to groundwater from hydrocarbon activities in the subsurface and does not include any considerations of either the effects of surface spillages or the integrity of boreholes which are dealt with through surface/near-surface groundwater vulnerability assessment tools and drilling regulation.

Development of the methodology has also pointed to a number of topics that need further research in order to reduce uncertainty in such assessments. These include;

- a better understanding of the location and processes within deep aquifer flow systems and their behaviour, including volumes of water recharging to deep basins and regional and local head flow directions,
- attenuation capacities of mudstones/clays at depth and in relation to particular contaminants and the critical thicknesses,
- the impact of particular contaminants in potential receptor units,
- an improved understanding of time scales of contamination breakthrough and 'safe' separation distances,
- improved understanding of the pathway behaviour of faults and

- a more in-depth understanding of the occurrence of groundwater that should be protected.

Further development might also explicitly include more detail about the nature of the hazard including chemical characteristics and concentrations.

Appendix 1 – 3DGWV screening methodology, spreadsheet tool and example for low vulnerability scenario

GEOLOGICAL UNIT	LITHOLOGY	DEPTH TOP (M OD)	DEPTH BASE (M OD)	THICKNESS OF UNIT (M)	VERTICAL SEPARATION BETWEEN SOURCE AND BASE OF RECEPTOR (M)	UNIT MUDSTONE THICKNESS (M)	CUMULATIVE MUDSTONE THICKNESS (M) IN INTERVENING UNITS	EA AQUIFER DESIGNATION	POTENTIAL RECEPTOR CLASSIFICATION	UNIT FLOW TYPE (FOR RECEPTOR CLASSES A TO C)	CUMULATIVE FLOW TYPE (FOR RECEPTOR CLASSES A TO C) INCLUDING RECEPTOR	NOTES
Chalk Group	Chalk with subsidiary mudstone, flint and limestone.	81	-10	91	325	45.5	178	Principal	A	Fractured, well connected	> 50 % intergranular flow	
Gault Formation	Clay, mudstone and sandstone with subsidiary calcareous mudstone, chalk, conglomerate, limestone, sand, silt and siltstone.	-10	-90	80	245	80	98	Unproductive in this region	D	Not A to C	> 50 % intergranular flow	
Lower Greensand Formation	Sand and sandstone with subsidiary clay and silt.	-75	-139	64	196	0	98	Principal	A	Intergranular flow	> 50 % intergranular flow	
Weald Group	Mudstone, sandstone and siltstone.	-139	-279	140	56	70	28	Secondary in this area	B	Intergranular flow	> 50 % intergranular flow	Closest outcrop in Weald where both secondary and unproductive aquifer, take most sensitive - secondary
Purbeck Group	Limestone and mudstone with subsidiary gypsum-stone and non-carbonate salt rock	-279	-335	56	0	28	0	Secondary	B	Fractured, well connected	> 50% fractured, well connected	
Portland Group	Limestone, sand and sandstone with subsidiary calcareous sandstone, chert and mudstone.	-335	-352	17	0	0	0	Principal and secondary	A	Fractured, well connected	> 50% fractured, well connected	Isle of Purbeck where limestone is Principal
Kimmeridge Clay	Mudstone with subsidiary argillaceous,	-352	-555	203	0	203	0	Unproductive	D	Not A to C	> 50% fractured,	

	muddy limestone/cementstone/ calcilutite, limestone, sand, sandstone, sapropelite, silt and siltstone.										well connected	
Corallian Group	Mudstones, siltstones and argillaceous limestones	-555	-607	52	203	26	203	Principal and secondary	C	Fractured, well connected	> 50% fractured, well connected	Closest outcrop near Weymouth, where it is Secondary
Kellaways and Oxford Clay Formations	Silicate-mudstone, silicate-sandstone and silicate siltstone.	-607	-828	221	255	221	229	Unproductive	D	Not A to C	> 50% fractured, well connected	
Great Oolite Group	Calcareous mudstone, limestone, mudstone and ooidal limestone	-828	-902	74	476	0.5	450	Principal	B	Fractured, well connected	> 50% fractured, well connected	
Inferior Oolite Group	Limestone, ooidal limestone	-902	-963	61	550	0	450.5	Principal	B	Fractured, well connected	> 50% fractured, well connected	
Lias Group	Calcareous mudstone, mudstone and silty mudstone	-963	-1200	237	611	237	450.5	Principal, secondary and unproductive, closest outcrop is east of Lyme Regis, both secondary and unproductive	C	Fractured, not well connected	> 50% fractured, well connected	Secondary as most sensitive classification and no principal in this area

Conceptual geological model for the southeast England, conventional oil and gas, in the spreadsheet tool. Unit highlighted in red indicates the target formation. Blue indicates squares where data is inputted, grey are calculated and yellow indicates notes and justifications.

FACTOR	Release mechanism of hydrocarbon (H1)		Head gradient driving flow (H2)			
GEOLOGICAL UNIT	RANKNG	CONFIDENCE	RATING	CONFIDENCE	HAZARD SCORE	CONFIDENCE
Chalk Group			2	low	2	low
Gault Formation			2	low	2	low
Lower Greensand Formation			2	low	2	low
Weald Group			2	low	2	low
Purbeck Group			2	low	2	low
Portland Group			2	low	2	low
Kimmeridge Clay			2	low	2	low
Corallian Group			2	low	2	low
Kellaways and Oxford Clay Formations			2	low	2	low
Great Oolite Group			2	low	2	low
Inferior Oolite Group			2	low	2	low
Lias Group	1	high	2	low	2	low
NOTES						

Hazard score for the southeast England, conventional oil and gas, from the spreadsheet tool. Green squares indicates cell has been carried forward, orange is an option with a pull-down menu.

FACTOR	Vertical separation between source and base of receptor		Lateral separation between source and receptor		Mudstones and clays in intervening units between source and receptor	
WEIGHTING (w)	1.5		3		3.5	
CONFIDENCE	low		medium		medium	
GEOLOGICAL UNIT						
Chalk Group	5	7.5	0	0	2	7
Gault Formation	6	9	0	0	3	10.5
Lower Greensand Formation	7	10.5	0	0	3	10.5
Weald Group	8	12	2	6	4	14
Purbeck Group	8	12	4	12	5	17.5
Portland Group	8	12	4	12	5	17.5
Kimmeridge Clay	8	12	4	12	5	17.5
Corallian Group	7	10.5	0	0	2	7
Kellaways and Oxford Clay Formations	6	9	0	0	2	7
Great Oolite Group	4	6	0	0	1	3.5
Inferior Oolite Group	4	6	0	0	1	3.5
Lias Group	3	4.5	0	0	1	3.5
NOTES	Only upper three units are penetrated by boreholes					

Intrinsic vulnerability for units between the hydrocarbon source unit and potential receptor for southeast England, conventional oil and gas.

FACTOR	Groundwater flow mechanism in intervening units between source and receptor, including the receptor		Faults cutting intervening units and receptor		Solution features in intervening units and receptor		Anthropogenic features-mines close to site of interest		Anthropogenic features-boreholes close to site of interest		Intrinsic vulnerability score (V)
WEIGHTING (w)	3		4.5		2		8		4		
CONFIDENCE	medium		medium		medium		high		high		low
GEOLOGICAL UNIT											
Chalk Group	1	3	2	9	2	4	0	0	2	8	38.5
Gault Formation	1	3	2	9	1	2	0	0	2	8	41.5
Lower Greensand Formation	1	3	2	9	1	2	0	0	2	8	43
Weald Group	1	3	2	9	1	2	0	0	2	8	54
Purbeck Group	3	9	2	9	1	2	0	0	2	8	69.5
Portland Group	3	9	2	9	1	2	0	0	2	8	69.5
Kimmeridge Clay	3	9	2	9	1	2	0	0	0	0	61.5
Corallian Group	3	9	2	9	1	2	0	0	0	0	37.5
Kellaways and Oxford Clay Formations	3	9	2	9	1	2	0	0	0	0	36
Great Oolite Group	3	9	2	9	1	2	0	0	0	0	29.5
Inferior Oolite Group	3	9	2	9	1	2	0	0	0	0	29.5
Lias Group	3	9	2	9	1	2	0	0	0	0	28
NOTES			Fault possibly 1 km from activity		Portland group has potential for solution features, and evidence from BH log in chalk				Below target, no boreholes. Boreholes in village.		

Intrinsic vulnerability for units between the hydrocarbon source unit and potential receptor, and the potential receptor itself, for southeast England, conventional oil and gas.

GEOLOGICAL UNIT	RECEPTOR CLASSIFICATION	VULNERABILITY SCORE (V)	RISK SCORE (R)
Chalk Group	A	41.5	83
Gault Formation	D	41.5	83
Lower Greensand Formation	A	43	86
Weald Group	B	54	108
Purbeck Group	B	69.5	139
Portland Group	A	69.5	139
Kimmeridge Clay	D	61.5	123
Corallian Group	C	37.5	75
Kellaways and Oxford Clay Formations	D	36	72
Great Oolite Group	B	29.5	59
Inferior Oolite Group	B	29.5	59
Lias Group	C	28	56
CONFIDENCE		Low	Low

Risk score for potential receptors for southeast England, conventional oil and gas.

Appendix 2 – Oil and gas formations in England.

This chapter describes the main hydrocarbon bearing units in England. The units have been identified primarily from three BGS reports commissioned by DECC (the Department for Energy and Climate Change) in 2013 (DECC, 2013a; 2013b; 2013c), and three additional area-specific reports on shale gas prospectivity in the Bowland Shale (Andrews, 2013), the Weald (Andrews, 2014) and the Wessex area (Greenhalgh, 2016). This is not intended to be an exhaustive summary of the occurrence of hydrocarbon units in England, rather a high-level overview for hydrogeologists interested in the potential for groundwater contamination. If further information is required about the hydrocarbon characteristics of the units the reader should refer to the source documents (and references therein).

The reports identify units that have potential as conventional oil and gas reservoirs and source rocks (DECC, 2013a), for CBM (DECC, 2013b) and shale gas (DECC, 2013c, Andrews, 2013; 2014; Greenhalgh, 2016). There is no report for UCG and therefore coal units have been identified from DECC (2013b). Rock units within BGS' National Geological Model (NGM) (UK3D v2015 and Waters et al., 2016) were attributed with source rock properties using the associated Generalised Vertical Section (GVS) (model included in the digital data package for 3DGWV). Where the potential hydrocarbon unit cited was not indicated on the GVS it was mapped back to a parent unit (usually group or age-group and lithology) on the GVS, using the BGS Lexicon (http://www.bgs.ac.uk/lexicon/). The method for identifying the rock types with hydrocarbon potential differs slightly for each exploration method and is described in the relevant sections below. Note that not all formations will be prospective across all areas.

Each rock unit identified on the GVS is also summarised in Table A2.1 and described in this chapter. The different hydrocarbon attributions can be viewed when the attributed GVS is loaded into the NGM in LithoFrame Viewer. Each section can be queried to find unit positions relative to the Ordnance Survey National Grid and to Ordnance Datum (OD). It should be noted that often potential reservoir units are also groundwater-bearing units and vice-versa; possible oil/gas-water contacts within the units are not specified.

CONVENTIONAL HYDROCARBONS

Information on these units is sourced from DECC (2013a) unless otherwise indicated. There are two main petroleum systems in England:

- Southern England – Early Jurassic shales in southern England have matured to generate oil and some gas in the Wessex and Weald basins. Migration has occurred largely within Jurassic strata to the margins of both basins, into carbonate reservoirs. Younger, immature shales provide the seals to these reservoirs and very few shows are present above the Cimmerian (early Cretaceous) unconformity. Alpine inversion was more intense in the Wessex Basin, juxtaposing older (early Jurassic and Triassic) clastic reservoirs against the early Jurassic source rocks. The producing fields are located on Jurassic-early Cretaceous palaeo-highs concealed by strata deposited above the unconformity. Some later migration of hydrocarbons into Alpine structures has occurred, but many of the surface anticlines are dry. Surface shows are limited to where erosion has exposed Jurassic-early Cretaceous strata.
- Northern England –The southern part of the Pennine Hills contains the inverted Pennine Basin. In the Pennine Basin there are oil-prone source rocks in early Namurian shales and gas-prone source rocks, including Westphalian coals. Oil shows are almost wholly restricted to Carboniferous strata in the East Midlands. Farther north, oil has migrated into Triassic reservoirs, where shows are present in Mesozoic strata. Gas has probably been

generated from source rocks older than Westphalian age in the Cleveland and West Lancashire basins. This gas has been mainly trapped in Permian reservoirs.

Table A2.1Groups and formations identified as prospective for conventional oil and gas, CBM, shale oil and gas and UCG. Different colours show the different hydrocarbon sources for clarity. Groups might not be prospective in all areas; the location of prospective rock units and sources of the attribution are included in Section 3.1 to 3.4. Note the Quaternary is not identified in this version of UK3D and hence not in the GVS (seen here in grey). Lithological description of GVS codes are included below this table.

Period	GVS	GVS Unit	Unit with hydrocarbon potential	Conventional oil and gas	CBM	Shale gas and shale oil	UCG
Quaternary	Not modelled	Not modelled	Shirdley Hill Sand Formation	Reservoir			
Cretaceous	W-SDSL	Wealden Group	Wealden Beds, Tunbridge Wells Sand Formation	Reservoir			
	W-MDSS	Wealden Group		Reservoir			
Jurassic-Cretaceous	PB-LSMD	Purbeck Group	Purbeck Group	Reservoir			
Jurassic	PL-LMCS	Portland Group	Portland Sand Formation, Portland Group, Portland Stone Formation	Reservoir			
	KC-MDST	Kimmeridge Clay Formation	Kimmeridge Clay Formation	Source/ Reservoir			
	AMKC-MDST	Ampthill Clay Formation and Kimmeridge Clay Formation		Source/ Reservoir			
	CR-LSSM	Corallian Group	Corallian Group	Source/ Reservoir			
	KLOX-MDSS	Kellaways and Oxford Clay Formations (undifferentiated)	Oxford Clay Formation	Source			
	GOG-MDST	Great Oolite Group – mudstone	Fuller's Earth Formation, Frome Clay limestone, Forest Marble, Cornbrash Formation	Source/ Reservoir			
	GOG-SLAR	Great Oolite Group - sandstone, limestone and argillaceous rock		Source/ Reservoir			
	INO-SDLI	Inferior Oolite Group - sandstone, limestone and argillaceous rocks	Inferior Oolite Group	Source/ Reservoir			
	INO-LSSM	Inferior Oolite Group - limestone, sandstone, siltstone and mudstone	Inferior Oolite Group	Source/ Reservoir			

Period	GVS	GVS Unit	Unit with hydrocarbon potential	Conventional oil and gas	CBM	Shale gas and shale oil	UCG
	IOGO-SLAR	Inferior Oolite Group and Great Oolite Group (undifferentiated)	Inferior Oolite Group and Great Oolite Group, Fuller's Earth Formation	Source/ Reservoir			
Triassic-Jurassic	LI-MSLS	Lias Group - Mudstone, siltstone, limestone and sandstone	Bridport Sand Formation, Lias clays, Lower Lias Shales, Blue Lias Formation	Source/ Reservoir			
Triassic	MMG-MDSS	Mercia Mudstone Group - mudstone, siltstone and sandstone	Tarporley Siltstone Formation and Mercia Mudstone Group	Source/ Reservoir			
	OMS-SDST	Ormskirk Sandstone Formation	Ormskirk Sandstone Formation	Reservoir			
	WLSF-SDST	Wilmslow Sandstone Formation	Wilmslow Sandstone Formation	Reservoir			
	SSG-SDSM	Sherwood Sandstone Group - sandstone, siltstone and mudstone	Sherwood Sandstone Group	Reservoir			
	KNSF-SDST	Kinnerton Sandstone Formation	Kinnerton Sandstone Formation	Reservoir			
Permian	ZG-DLDO	Zechstein Group – Dolotimised limestone and dolomite	Roker or Seaham Formations, Kupferscheifer/Marl Slate	Reservoir			
	APY-SCON	Appleby Group - interbedded sandstone and conglomerate	Collyhurst Sandstone Formation	Reservoir			
	Not identified	Not identified	Yellow Sands Formation, Basal Permian Sands Formation	Reservoir			
Carboniferous	WAWK-SISDM	Warwickshire Group - siltstone and sandstone with subordinate mudstone	Halesowen Formation, Upper Coal Measures, Westphalian C-D	Source/ Reservoir			
	WAWK-MSCI	Warwickshire Group - mudstone, siltstone, sandstone, coal, ironstone and ferricrete		Source/ Reservoir			
	WAWK-SISDM2	Warwickshire Group - siltstone and sandstone with subordinate mudstone		Source/ Reservoir			
	PUCM-MSCI	Pennine Upper Coal Measures Formation	Pennine Coal Measures Group, Westphalian A-B	Source/ Reservoir			

Period	GVS	GVS Unit	Unit with hydrocarbon potential	Conventional oil and gas	CBM	Shale gas and shale oil	UCG
	PSMCM-MSCI	Pennine Middle Coal Measures Formation and South Wales Middle Coal Measures Formation (undifferentiated)		Source/ Reservoir			
	PSLCM-MSCI	Pennine Lower Coal Measures Formation and South Wales Lower Coal Measures Formation (undifferentiated) - mudstone, siltstone, sandstone, coal, ironstone and ferricrete		Source/ Reservoir			
	PCM-MDSS	Pennine Coal Measures Group		Source/ Reservoir			
	MARR-MDSD	Marros Group mudstone and sandstone	Marros Group				
	MG-MDSS	Millstone Grit Group	Silsden Formation, Pendleton Formation, Namurian Shales	Source/ Reservoir			
	AG-LSSA	Alston Formation - Limestone with subordinate sandstone and argillaceous rocks	Asbian and Brigantian substage rocks	Source/ Reservoir			
	CRAV-MDLM	Craven Group	Bowland Shale Formation, Lower Bowland Shales, Widmerpool Formation, Bee Low Limestone, Upper Bowland Shale Formation	Source			
	YORE-LSSA	Yoredale Group- limestone with subordinate sandstone and argillaceous rocks	Yoredale Group shales				
	DINA-LMST	Dinantian rocks	Asbian and Brigantian substage rocks, Woo Dale Limestone	Reservoir			
	CARB-ROCK	Carboniferous rocks undifferentiated	Pennine Coal Measures Group, Namurian Sandstones, Namurian	Source/ Reservoir			

Period	GVS	GVS Unit	Unit with hydrocarbon potential	Conventional oil and gas	CBM	Shale gas and shale oil	UCG
			Shales, Asbian and Brigantian substage rocks, Bowland Shale Formation, Lower Bowland Shales, Widmerpool Formation, Bee Low Limestone , Mid-Dinantian shales and Milldale Limestone, Craven Group, Yoredale Group				
	DINA-LSSA	Dinantian Rocks (Undifferentiated) – limestone with subordinate sandstone and argillaceous rocks	Asbian and Brigantian substage rocks, Bowland Shale Formation, Lower Bowland Shales, Widmerpool Formation, Bee Low Limestone , Mid-Dinantian shales and Milldale Limestone, Craven Group, Yoredale Group	Source/ Reservoir			
	DINA-SLAR	Dinantian Rocks (Undifferentiated) – sandstone, limestone and argillaceous rocks	Asbian and Brigantian substage rocks, Bowland Shale Formation, Lower Bowland Shales, Widmerpool Formation, Bee Low Limestone , Mid-Dinantian shales and Milldale Limestone, Onecote Sandstone, Minera Formation, Craven Group, Yoredale Group	Source/ Reservoir			

Lithological codes used in the GVS, see Table A2.1.

Lithology code	**Lithological description**
SDSL	Sandstone, siltstone
MDSS	Mudstone, siltstone and sandstone
LMSD	Interbedded limestone and mudstone
LMCS	Limestone and calcareous sandstone
MDST	Mudstone
SLAR	Sandstone, limestone and argillaceous rocks
SDLI	Sandstone, limestone and ironstone
MSLS	Mudstone, siltstone, limestone and sandstone
SDST	Sandstone
SDSM	Sandstone, siltstone and mudstone
DLDO	Dolomitised limestone and dolomite
SCON	Interbedded sandstone and conglomerate
SISDM	Siltstone and sandstone with subordinate mudstone
MSCI	Mudstone, siltstone, sandstone, coal, ironstone
MDSD	Mudstone and sandstone interbedded
LSSA	Mudstone with subordinate sandstone and argillaceous rocks
LMST	Limestone
LSSM	Limestone, sandstone, siltstone and mudstone

Conventional hydrocarbons are only expected to be found in five known basins in England; the Weald, Wessex, East Midlands, West Lancashire and Cleveland basins. These basins are broadly represented by current licensed areas. Groups/formations are not currently prospective outside these areas. An up to date map of licensed areas is available from the Oil and Gas Authority Website (https://decc-edu.maps.arcgis.com/apps/webappviewer/index.html?id=29c31fa4b00248418e545d222e57ddaa) and a shapefile of the DECC 14th Round of licence areas and existing licences is included in the 3DGWV digital dataset.

Oil and gas can migrate and accumulate in conventional reservoirs at any depth depending on the rock types and geological structure. A depth limit has also not been applied to source rocks, despite the necessity for burial to depths sufficient to achieve the oil or gas window, because of the possibility of widespread basin inversion in the UK onshore basins.

Shirdley Hill Sand Formation

The Late Pleistocene (Quaternary) **Shirdley Hill Sand Formation**, part of the British Coastal Deposits Group, is the shallow reservoir of the Formby Oilfield in the southeastern East Irish Sea Basin. It is also present in the West Lancashire Basin. This unit is not identified on the England-only GVS, which only covers bedrock.

Wealden Group

Sands of the Lower Cretaceous **Wealden Beds** (now the Wealden Group) of the Weald Basin have numerous shows of oil and gas (e.g. Bolney, West Sussex (Andrews, 2014)) and are possible reservoirs, although they are secondary, less predictable reservoirs than others in the basin. Enhancement of reservoir characteristics by fractures may provide additional or improved reservoir characteristics. Oil shows are found in exposures in Kent and Sussex in the **Tunbridge Wells Sand Formation,** part of the Wealden Group. These units are identified at the group level on the GVS, as both W-SDSL and W-MDSS.

Purbeck Group

Sands and limestones in the Upper Jurassic **Purbeck sequence** form a gas reservoir at Albury, on the northern margin of the Weald Basin. **Purbeck Group** inliers of the Weald basin are also reported to have indications of hydrocarbons. The Purbeck Beds produced gas at Heathfield, West Sussex, but quantities were insufficient for further development. This unit is identified at the group level as PB-LSMD (limestone and interbedded mudstone) on the GVS, and predominantly occurs in the Weald Basin.

Portland Group

The **Portland Sand Formation** of the Jurassic-aged Portland Group forms a local reservoir in the Wessex Basin. The **Portland Group** is largely represented by limestones in the Wessex-Channel Basin which have minor shows on the Isle of Wight. The **Portland Stone Formation** (previously Portland Limestone Formation) on Portland Island, Dorset, also has minor shows. Reservoir facies may be developed in the Weald Basin. Oil is produced at Brockham 1 and Godley Bridge, Surrey, and the unit is productive for gas at Crowden 2 in Kent. In Ashdown 1, East Sussex, there were gas shows in the Portland Beds (Andrews, 2014). This unit is identified at the group level on the GVS as PL-LMCS (limestone and calcareous sandstone), and is predominantly hydrocarbon bearing in the Weald Basin.

Kimmeridge Clay Formation

The **Kimmeridge Clay Formation** has source rock potential in the Wessex (such as at the Wytch Farm Oilfield) and Weald Basins. The Kimmeridge Clay is most mature along the axes of the sub-basins and enters the oil window in the Arreton 2 well on the Isle of Wight, but is thought to be immature regionally across the Wessex Basin (Greenhalgh, 2016). The mid-Kimmeridge micrites form the main reservoir for two recent hybrid-play oil discoveries in the Weald Basin. These are thickest in the centre of the basin, but pinch out towards the basin margins and do not extend into the Wessex area (Greenhalgh, 2016). The Kimmeridge Clay Formation is present throughout the Weald and Wessex Basins and is identified at formation level on the GVS as KC-MDST.

Ampthill Clay Formation and Kimmeridge Clay Formation

In this unit the Kimmeridge Clay Formation is not differentiated from the Ampthill Clay Formation. As described above, the **Kimmeridge Clay Formation** has source rock potential in the Wessex and Weald Basins. Since the unit is present directly adjacent to the Wessex Basin where the Kimmeridge Clay Formation is prospective, it has also been identified as a potential source rock on the GVS, as AMKC-MDST.

Corallian Group

A number of beds provide reservoirs in the Upper Jurassic **Corallian Group** in the Wessex Basin. Corallian limestone and sandstone form the reservoir of several conventional oil and gas fields in the northern and eastern parts of the Weald Basin. A lower limestone unit forms the reservoir in the Bletchingley discovery, Surrey, from which gas is being produced. The Palmers Wood Oilfield, south of London, produces from upper Corallian sandstone where the thickest sands are developed. There have been hydrocarbon indications at Edenbridge in Surrey and in Ashdown 1, East Sussex.

Some good source intervals are present in limestones of the Corallian in the Wessex Basin (Greenhalgh, 2016) and high TOCs have been recorded in the Corallian Group in the Weald Basin; the Corallian Clay may have contributed to various reservoirs here (Andrews, 2014).

This group is identified in the GVS as CR-LSSM (limestone, sandstone, siltstone and mudstone) and primarily occurs in the Weald and Wessex Basin, but also to a lesser degree in the northeast of England.

Kellaways Formation and Oxford Clay Formation (undifferentiated)

The **Oxford Clay Formation** has source rock potential in the Wessex and Weald Basins, particularly along the axes of sub-basins. The oil generating potential of the Oxford Clay Formation is variable, but it is mature in parts of the Weald and Wessex Basins. Oil has been encountered in fractures in the Oxford Clay in the Kimmeridge Oil field and might be actively recharging the Cornbrash reservoir (Greenhalgh, 2016). There were gas shows in the unit comprising the Oxford Clay and Kellaways Formation in Wareham 2, Wessex Basin (Greenhalgh, 2016). A small amount of oil was encountered in the Oxford Clay during drilling of the Coombe Keynes 1 well. The most significant organic-rich shales in the Weald Basin occur in the basal Oxford Clay (Andrews, 2014).

The mudstone-dominated Oxford Clay Formation and underlying Kellaways Formation are not differentiated. Since it is identified in the Wessex and Weald Basins, and has a mudstone, siltstone and sandstone lithology, the unit has been identified as a potential source rock on the GVS as KLOX-MDSS.

Great Oolite Group

Limestones of the Middle Jurassic Great Oolite Group, in particular the **Great Oolite limestone** (old name), are the main reservoir rock at the Humbly Grove Oilfield and other discoveries in the Weald Basin such as the Horndean, Stockbridge, Storrington, Goodworth and Singleton Oilfields and the Baxter's Copse and Lidsey discoveries. The **Frome Clay limestone** is a local reservoir in the Wessex basin. The **Cornbrash Formation** and **Forest Marble Formation** are also reservoirs in the Wessex Basin.

Occasionally, good source intervals are present in the **Frome Clay Formation** and **Fuller's Earth Formation** in the Wessex Basin (Greenhalgh, 2016).

The group is recognised as GOG-SLAR or GOG-MDST in the GVS.

Inferior Oolite Group

Minor gas shows have been found in the middle Jurassic **Inferior Oolite Group** in the Wessex basin. The discovery well in the Wareham Oilfield produced oil from the Inferior Oolite (along with the Bridport Sand Formation of the Lias Group) as did the Arreton 2 well, Wessex. The Inferior Oolite Group has also had shows in the Weald Basin.

Good source intervals are occasionally present within limestones of the Inferior Oolite Group (Greenhalgh, 2016).

In the Weald and Wessex Basins, this unit is identified as INO-LSSM and INO-SDLI on the GVS.

Inferior Oolite Group and Great Oolite Group (undifferentiated)

As described above, both the **Great Oolite Group** and **Inferior Oolite Group** could be reservoirs and source rocks. This unit has a similar lithology (sandstone, limestone and argillaceous rocks). The unit is identified in the north of the Weald Basin through Norfolk, and thus is identified on the GVS as IOGO-SLAR.

Lias Group – mudstone, siltstone, limestone and sandstone

The Lias clays have source rock potential in the Wessex and Weald Basins. The **Lower Lias** is the source rock for most oil to the south of the Purbeck-Isle of Wight monocline (Wessex Basin). It is the source of the Kimmeridge, Wytch Farm, Wareham and Humbly Grove oilfields. There may also have been contributions from younger formations in the Lias. Basin modelling predicts that the Lias falls within the zone of oil generation across much of the Wessex and Weald Basins, being over-mature in its deepest axial parts. The Lower Lias shales may also have entered the gas generation window in the deepest part of the Weald Basin, but they are not considered to have ever been sufficiently deeply buried to have generated significant amounts of gas onshore (Greenhalgh, 2016).

The **Bridport Sand Formation** of the Lias Group is a primary reservoir in the Wessex Basin, providing the main reservoir for smaller discoveries and contributing to oil produced in the Wareham Oilfield and Wytch Farm. There is only marginal prospectivity for this formation in the Weald basin.

The Lias Group is identified as LI-MSLS on the GVS.

Mercia Mudstone Group

Wells in the **Tarporley Siltstone Formation** of the Triassic Mercia Mudstone Group encountered oil at the Formby Oilfield, East Lancashire Basin. The **Mercia Mudstone Group** is also within the oil window in the Cheshire Basin. Here, the unit is identified both as a potential source and reservoir. Elsewhere, the Mercia Mudstone Group is neither a source nor a reservoir. This unit is identified as MMG-MDSS on the GVS.

Helsby (previously Ormskirk) Sandstone Formation

The **Helsby Sandstone Formation** of the Sherwood Sandstone Group is a potential reservoir in the West Lancashire Basin. Production was obtained from the Helsby (or Ormskirk) Sandstone play in the Formby Oilfield. This is also viewed as a secondary hydrocarbon source unit in the Cheshire basin, although exploration has so far been unsuccessful. This unit is identified as the Ormskirk Sandstone Formation, OMS-SDST, on the GVS.

Wilmslow Sandstone Formation

The **Wilmslow Sandstone Formation** of the Sherwood Sandstone Group is a potential reservoir in the Cheshire basin. This formation is identified as WLSF-SDST on the GVS.

The Sherwood Sandstone Group

The Helsby (Ormskirk) Sandstone Formation and Wilmslow Sandstone Formation of the Triassic **Sherwood Sandstone Group** are reservoirs in the West Lancashire Basin and Cheshire Basin, as described above. The Sherwood Sandstone aquifer is a major Triassic reservoir in the Wessex Basin, and light gas was found within it at the Wytch Farm Oilfield. There is some potential for oil in the west of the Weald Basin. This group is extensive across the country but its potential for hydrocarbon resources is limited even within the basins of interest. It is identified as SSG-SDSM in the GVS.

Kinnerton Sandstone Formation

The Early Triassic **Kinnerton Sandstone Formation** is a potential reservoir in the Cheshire basin. It is identified as KNSF-SDST on the GVS.

Zechstein Group

The upper Permian Zechstein Group limestones are a main reservoir in the Cleveland Basin, e.g. the Malton and Eskdale gasfields. These limestones were previously known as the Upper Magnesian Limestone and are currently known as the **Roker or Seaham Formations**. The Upper Magnesian Limestone (**Brotherton Formation**) also contains small amounts of gas in the East Midlands province. This group is identified as the ZG-DLDO on the GVS.

Appleby Group

The **Collyhurst Sandstone Formation** of the Permian Appleby Group is a potential reservoir in the Cheshire and West Lancashire basins. The reservoir at the Elswick Gasfield might also be in the Collyhurst Sandstone Formation. The group is identified as APY-SCON on the GVS.

Rotliegendes Group

The Rotliegendes Group (**Yellow Sands Formation** and **Basal Permian Sands Formation**) is not identified on the GVS. The group is a main reservoir in the Cleveland basin. The Yellow Sands Formation is productive in the Caythorpe gasfield.

Warwickshire Group

The **Halesowen Formation** of the Warwickshire Group is a known reservoir. There is an oil seep from Westphalian-aged sandstones near Ironbridge in the Cheshire basin. This unit is identified as the Warwickshire Group on the GVS consisting of a siltstone and sandstone with subordinate mudstone (WAWK-SISDM) overlying a mudstone, siltstone, sandstone, coal, ironstone and ferricrete (WAWK-MSCI) which overlies another siltstone and sandstone with subordinate mudstone (WAWK-SISDM2).

Pennine Coal Measures Group

There are gas prone source rocks in Westphalian-aged coals of the East Midlands Province, the **Pennine Coal Measures Group**, which have supplied gas to reservoirs in most northwest European countries. The Westphalian Coal Measures sandstones form the major reservoirs in the East Midlands Oilfields such as Eakring-Duke’s Wood, Gainsborough, Beckingham, Caunton, Egmanton, Corringham, South Leverton, Plungar, Bothamshall and Welton and East Glentworth. Production was possible from seepages in the Coal Measures at Riddings Colliery, Derbyshire in 1847.

All the main oil shows in the main part of the West Lancashire Basin were found in Westphalian Coal Measures. In the Cleveland Basin the Westphalian Coal Measures are only present to the east and are only marginally mature for gas generation. Shales and oil shales within the **Upper Coal Measures** of the Potteries Coalfield have been used for oil production.

This group is identified in the GVS as the Pennine Upper Coal Measures Formation (PUCM-MSCI), Pennine Middle Coal Measures Formation and South Wales Middle Coal Measures Formation (undifferentiated) (PSMCM-MSCI), Pennine Lower Coal Measures Formation and

South Wales Lower Coal Measures Formation (undifferentiated) - mudstone, siltstone, sandstone, coal, ironstone and ferricrete (PSLCM-MSCI), Pennine Coal Measures Group (PCM-MDSS).

Millstone Grit Group

The **Namurian sandstones** of the Carboniferous Millstone Grit are producing reservoirs in a number of oilfields in the East Midlands Province, including at Eakring-Duke's Wood, Gainsborough-Beckingham and Bothamsall. Production has also been obtained from Plungar, Egmanton, Corringham, South Leverton, Glentworth and Rempstone Oilfields. Non-economic quantities of oil and gas have been observed in Namurian sandstones in numerous boreholes. Gas is produced from the Upper and Lower Follifoot Grits (of the **Silsden Formation**) in the Kirby Misperton gasfield in the Cleveland basin. The Pendle Grit Member (of the **Pendleton Formation**), Grassington Grit (of the **Pendleton Formation**) and Red Scar Grit (of the **Silsden Formation**) of the Millstone Grit Group are potential reservoirs in the Cleveland Basin. The Millstone Grit Group is also a potential reservoir in the Cheshire Basin.

In the West Lancashire Basin and the East Midlands Province, the Sabden Shales (**Namurian shales**) of the Millstone Grit Group are extensions of the Holywell shale, a source in the East Irish Sea Basin.

These units are identified as the Millstone Grit Group – mudstone, siltstone and sandstone (MG-MDSS) on the GVS.

Alston Formation – limestone with subordinate sandstone and argillaceous rocks

Late Dinantian (Early Carboniferous) **Asbian** and **Brigantian** substage rocks, such as the Alston Formation, have undergone dolomitisation in places and might form reservoirs in the East Midlands Province. Brigantian basinal shales and shaly ramp carbonates are possible source rocks in the Cheshire Basin. This unit is identified as the Alston Formation – limestone with subordinate sandstone and argillaceous rocks (AG-LSSA) in the GVS.

Craven Group

The **Bowland Shale Formation** (previously Edale and Holywell Shale Formations) is part of the Craven Group and is thought to be the Carboniferous source rock of the East Midlands and East Irish Sea oilfields. Late Dinantian shales (lower **Bowland Shales** and the **Widmerpool Formation**) and limestones (**Bee Low Limestone**) are source rocks in the East Midlands Province. Mid-Dinantian shales and some limestones at outcrop may also be classed as source rocks (e.g. **Milldale Limestone**) in the East Midlands Province. The Bowland shales are considered the principal source rocks in the Craven Basin. Thick sequences of oil-prone late Dinantian shales occur in the Widmerpool, Edale and Gainsborough troughs. Dinantian-aged (previously the Worston Shale Group) shales are potential source rocks in the Cleveland Basin. In the Bowland, Cleveland, Edale, Gainsborough, Humber and Widmerpool basins, significant amounts of gas have been discovered in conventional plays (Andrews, 2013). The Namurian Holywell/Bowland Shales are source rocks in the Cheshire Basin. The Bowland Shales are considered the principal source rock in the West Lancashire basin and are at oil maturity in the Formby oilfield. These units are identified as the Craven Group on the GVS (CRAV-MDLM).

Dinantian Rocks

Dinantian rocks of limestone lithology (DINA-LMST) have been identified as potential reservoirs. This unit is extensive within basins of England from north to south. This unit could include rocks of the **Asbian** and **Brigantian substage** that have undergone dolomitisation in places and therefore might form reservoirs in the East Midlands Province. The **Woo Dale Limestones** (of the Dinantian Peak Limestone Group) are also possible reservoirs where they have been dolomitised in the East Midlands Province. The original discovery at Hardstoft, East Midlands Province was in a Dinantian Carboniferous reservoir and small quantities of oil have been produced from the top of the Dinantian Carboniferous Limestone (e.g. Hardstoft, Eakring, Duke's Wood, Plungar, Nocton). This is identified as DINA-LMST on the GVS.

Carboniferous Rocks (Undifferentiated)

This unit is found in the East Midlands Province. It could include rocks from any Carboniferous group present in the East Midlands province – **Pennine Coal Measures Group** (source and reservoir), **Namurian Sandstones** (reservoir), **Namurian Shales** (source), **Asbian and Brigantian substage rocks** (reservoir), **Bowland Shale Formation** (source), **Lower Bowland Shales** (source), **Widmerpool Formation** (source), **Bee Low Limestone** (source), **Mid-Dinantian shales and Milldale Limestone** (source). However it is only identified on a few sections. This unit is identified as CARB-ROCK on the GVS.

Dinantian Rocks (Undifferentiated) – limestone with subordinate sandstone and argillaceous rocks

This unit is identified throughout England. It could include rocks of the **Asbian** and **Brigantian substage** or the **Woo Dale Limestones** (of the Dinantian Peak Limestone Group) which have undergone dolomitisation in places and therefore might form reservoirs in the East Midlands Province; see descriptions above. In the Cheshire Basin, Dinantian Reservoirs include the **Onecote Sandstone** (productive at Nooks Farm) and sandstones of the **Minera Formation** of the Clwyd Group.

This unit might also contain the source rock **Bowland Shale Formation** of the Craven Group; see description above. This unit is identified as DINA-LSSA on the GVS.

Dinantian Rocks (Undifferentiated) – sandstone, limestone and argillaceous rocks

This unit is identified predominantly north of the English Midlands, in the north and west of England. It could include rocks of the **Asbian** and **Brigantian substage** or the **Woo Dale Limestones** (of the Dinantian Peak Limestone Group) which have undergone dolomitisation in places and therefore might form reservoirs in the East Midlands Province; see descriptions above. In the Cheshire Basin, Dinantian Reservoirs include the **Onecote Sandstone** (productive at Nooks Farm) and sandstones of the **Minera Formation** of the Clwyd Group.

This unit might also contain the source rock **Bowland Shale Formation** of the Craven Group; see description above. This unit is identified as DINA-SLAR on the GVS.

COAL BED METHANE (CBM)

Information on units with CBM potential is sourced from DECC (2013b). In England, south of the Stainmore-Cleveland Basin, coals are largely confined to strata of Westphalian age. Further north, a large number of coals also occur in the Namurian and Dinantian strata, but these are considered to be thin and mined-out. Neither the previous BGS pre-Permian subcrop map nor the coal mapping has attempted to predict the occurrence of Coal Measures beneath Variscan thrusts in southern Britain. There is a possibility that coals might exist at much greater depth than drilled in the Weald Basin, south of the Berkshire syncline and north of the Mendips. However, this would be too deep for CBM exploration. The Bude and Bideford formations of Westphalian age crop out in SW England. These were mined up to 1969 but no modern drilling or logging has taken place here (DECC, 2013b).

Coals are assigned ages in DECC (2013b) therefore coal-bearing units with CBM potential have been identified according to their age. It should be noted that CBM exploration is still at an early stage in the UK and much of the information about their potential originates from the USA.

CBM exploration from virgin seams is likely to be constrained to depths of 200-1200 m bgl (below ground level) (Jones, et al. 2004). CMM will be restricted to the depth of planned mines, whereas AMM will be restricted to the depth of existing mines, generally both < 1200 m in the UK (Jones, et al. 2004).

Westphalian-aged Coal Measures

Formations similar to Westphalian coals are found in the Black Warrior Basin, Alabama and the Appalachian Foreland Basin. Coal fields in the Black Warrior Basin lie within the oil window (i.e. within the temperature range at which oil is generated and expelled from source rocks). The Black Warrior Basin coals are comparable to North-Staffordshire-Lancashire coals in terms of their gasiness.

CBM potential varies across the country. Estimated volumes of methane in coal seams are 3 m^3/t (or less) for South Staffordshire and the South Midlands, up to 9 m^3/t for the East Midlands, 11 m^3/t for South Lancashire and up to 15 m^3/t for North Staffordshire. Generally, older and deeper coals have been shown to have a greater gas content since gas content increases with maturity. There is a progressive increase in the gas content of coals northwards, from Oxfordshire towards the Pennine Basin margin in Warwickshire and South Staffordshire and the depocentre of the Pennine Basin, in Lancashire. There is also a slight increase in gas content southwards from Oxfordshire to the Carboniferous foreland basin in Kent and probably into Somerset.

Two Westphalian-aged coal measure groups are identified:

Warwickshire Group

This group comprises coal in the Pennine Basin in Staffordshire, Warwickshire, Shropshire, Lancashire, Nottinghamshire and South Yorkshire. The Group is thick at outcrop in the Warwickshire Coalfield and in the subsurface to the south. Maturity and gas content are low where measured, as the basin straddles the Wales-Brabant Massif. Maturities may increase near the southern boundary but no gas content measurements were acquired here. A shallow well has been drilled for exploration in the west of the Warwickshire coalfield. In the Somerset Coalfield naked-light working was common in these Coal Measures suggesting low methane. These Coal Measures are identified as the Warwickshire Group on the GVS with either siltstone and sandstone with subordinate mudstone (WAWK-SISDM); mudstone, siltstone, sandstone, coal, ironstone and ferricrete (WAWK-MSCI) or siltstone and sandstone with subordinate mudstone (WAWK-SISDM2).

Pennine Coal Measures Group (Westphalian A-B)

This group is from Langsettian to Westphalian B in age and comprises units previously known as the Coal Measures Group.

This group is present in central and northern England. CBM exploration is underway in this group in the Midlands and northwest England. There has been drilling at the Keele University Campus in North Staffordshire. A gas content of 6-9 m^3/t is indicated in the Cheshire-Staffordshire Basin and a permeability of < 5 mD. The Doe Green CBM pilot production site has produced electricity from the Lancashire Coalfield.

The Cumbria-Canonbie coalfields have a high gas content. A large subsurface area between the two coalfields has never been mined. This area is being explored for CBM.

Eastern England coalfields have lower gas contents than those west of the Pennines, despite being part of the same basin. However, small conventional oil and gas fields indicate that porosity and permeability of units adjacent to CBM reservoirs are adequate for production. The Selby coalfield has an estimated methane gas potential of 13.3 x 10 m^3/km^2, with an assumed gas content of 5.3 m^3/t. In the Yorkshire and Nottinghamshire coalfield gas content and total thickness of the Westphalian coals increase to the northwest. This area is being explored by three companies.

Thick coals occur beneath the Warwickshire Group in the Warwickshire Coalfield. While coals are present in the Kent Coalfield, no part is considered to have ‘good’ coalbed methane potential although more gas measurements need to be made to confirm this. In the Somerset Coalfield extensive problems with methane were encountered during mining of this group, but no measured gas contents are available.

This group is identified in the GVS as the Pennine Upper Coal Measures Formation (PUCM-MSCI), Pennine Middle Coal Measures Formation and South Wales Middle Coal Measures Formation (undifferentiated) (PSMCM-MSCI), Pennine Lower Coal Measures Formation and South Wales Lower Coal Measures Formation (undifferentiated) - mudstone, siltstone, sandstone, coal, ironstone and ferricrete (PSLCM-MSCI) and the Pennine Coal Measures Group (PCM-MDSS).

SHALE GAS AND OIL

This information is from DECC (2013c) and includes potential shale gas and oil units that are of interest in the current licensing round (March 2016). The report states that the lowest (economic) risk shale gas exploration is where shale gas prospects are associated with conventional hydrocarbon fields. In England this includes the Upper Bowland Shale of the Pennine Basin, the Kimmeridge Clay of the Weald Basin, and possibly the Lias of the Weald Basin. It was recommended that deeper Dinantian shales also be tested in the Pennine Basin.

Similar to conventional hydrocarbons, shale gas is only expected to be found in five known basins in England; the Weald, Wessex, East Midlands, West Lancashire and Cleveland basins. These basins are broadly represented by current licensed areas. Groups/formations are not currently prospective outside these areas. An up-to-date map of licensed areas is available from the Oil and Gas Authority Website (https://decc-edu.maps.arcgis.com/apps/webappviewer/index.html?id=29c31fa4b00248418e545d222e57ddaa) and a shapefile of the DECC 14th Round of licence areas and existing licenses is included in the 3DGWV digital dataset.

Older shales such as those from the Upper Cambrian on the Midlands Microcraton are higher risk hydrocarbon source units because they have not been found to source conventional fields and are therefore not currently of prospective interest. In addition, where prospective shales occur in the Variscan fold belt the risks are considered too high. These shales have been discounted from the summary and GVS attribution because they are not currently licensed.

In the USA shale gas and oil is generally exploited from between 1000 to 3,500 m bgl. The 2015 Infrastructure Act states that fracking in the UK cannot take place at < 1000 m bgl (http://www.legislation.gov.uk/ukpga/2015/7/contents/enacted) or at < 1200 m bgl in protected areas (http://www.legislation.gov.uk/uksi/2016/384/note/made).

Purbeck Group

Shales of the Jurassic-Cretaceous **Purbeck Group** may have been a source of some oil and gas shows in several wells of the Weald Basin. A Purbeck Group oil-shale outcrops in the Purbeck inlier in the Wealden anticline. Source richness has been identified in the Purbeck Group but these are not considered prospective in the Wessex Basin due to their basin-wide immaturity (Greenhalgh, 2016). This unit is identified at the group level on the GVS as PB-LSMD (limestone and interbedded mudstone), and predominantly occurs in the Weald Basin.

Kimmeridge Clay Formation

The **Kimmeridge Clay Formation**, part of the Ancholme Group in onshore eastern and southern England, is potentially prospective for shale oil and biogenic gas because it contains ubiquitous oil-shale beds. The Kimmeridge Clay of the Weald basin is associated with conventional hydrocarbon fields and therefore has one of the best shale gas potentials in the onshore UK. Five basins show thickening in response to syn-sedimentary faulting (Weald, Wessex, English Channel, Cleveland and Lincolnshire-Norfolk). However, the unit is immature for thermogenic gas generation onshore and only marginally mature for oil generation in the Weald Basin depocentre.

After the first OPEC oil price increase in 1973, Kimmeridge Clay oil-shales were assessed for resource potential but deemed uneconomic because of the thin beds and high sulphur content. This might now be overcome by horizontal drilling and opportunities to exploit thinner beds. The English Channel Basin, particularly south of Purbeck and on the southern Isle of Wight, contains more mature source rocks than in the area near the Wytch Farm oil field. There are already precedents for deviating wells from onshore to offshore to access the main part of this basin for shale gas (DECC, 2013a). Shows of oil and gas in several Weald Basin wells indicate a Kimmeridge Clay or Purbeck shale source. There are also some small gas fields and gas discoveries in a line along the northern Weald Basin (Albury, Bletchingley, Lingfield and Cowden), and with the Godley Bridge, Baxter's Copse and Heathfield fields in the centre and south of the basin. This mudstone formation is present in the Weald and Wessex Basins and is identified as KC-MDST.

Ampthill Clay Formation and Kimmeridge Clay Formation

As described above, the **Kimmeridge Clay Formation** has some shale oil and gas potential. In this mudstone unit, the Kimmeridge Clay Formation is not differentiated from the Ampthill Clay Formation; both belong to the Ancholme Group. Since it is identified directly adjacent to the region with the Kimmeridge Clay Formation, to the north of the Wessex Basin, this unit has also been identified as a potential oil shale and gas rock on the GVS as AMKC-MDST.

Kellaways Formation and Oxford Clay Formation (undifferentiated)

The **Oxford Clay Formation** has a relatively high Total Organic Carbon (TOC) content (7.83%) in the Weald Basin and lies within the oil window at the basin's depocentre. Shelly horizons in the Oxford Clay Formation in the Wytch Farm Oilfield contain free oil, although this might represent migrated oil. A bituminous horizon is present at the base of the formation in southern and central England, but this is absent in Yorkshire. In central England TOC's are over 4% but they are immature for oil generation.

In this mudstone unit the Oxford Clay Formation is not differentiated from the Kellaways Formation. Both formations belong to the Ancholme Group in the south of England. Since this unit is identified in the Wessex and Weald Basins, and has a mudstone, siltstone and sandstone lithology, it has been identified as a potential source rock on the GVS as KLOX-MDSS.

Great Oolite Group - mudstone

The **Fuller's Earth Formation** in the Great Oolite Group has good TOC values in the Weald Basin but it has only reached oil maturity in the basin's depocentre. The unit GOG-MDST has been identified as having shale gas and oil potential on the GVS because it is dominated by mudstone.

Great Oolite Group – sandstone, limestone and argillaceous rock

As above, the **Fuller's Earth Formation** in the Great Oolite Group has good TOC values in the Weald Basin but it has only reached oil maturity in the basin's depocentre. The unit GOG-SLAR has been identified as having shale gas and oil potential on the GVS because it comprises argillaceous rocks which might contain the Fuller's Earth mudstones in places.

Inferior Oolite Group and Great Oolite Group (undifferentiated)

As described above, the **Fuller's Earth Formation** in the Great Oolite Group has good TOC values in the Weald basin but it has only reached oil maturity in the basin's depocentre. While mostly identified to the north of the Weald Basin through Norfolk, it has also been identified at the northern boundary of the Weald Basin. The unit IOGO-SLAR has been identified as having shale gas and oil potential on the GVS because in places it comprises argillaceous rocks which might contain the Fuller's Earth mudstones.

Lias Group – Mudstone, siltstone, limestone and sandstone

Shales in the Lower Jurassic **Lias Group** of the Weald Basin may have some shale gas and oil potential. The Lias Group is the source rock for the Weald Basin petroleum system and the Wessex Basin, with migration into three different reservoirs in the Wytch Farm oil field. The **Lower Lias Shales** lie within the oil window over a wide area; maturity is lower on former highs of syn-sedimentary faults. However, sampled TOCs are not high throughout. The area of Liassic source rock within the gas window is believed to be >467 km^2 at exploitable drilling depths between 2750 and 3950 m. The mid-case resource estimate is 10 tcf (trillion cubic feet) plus condensate.

Bituminous shales at the base of the **Blue Lias** in Dorset contain 3.9-7% carbon and laminated marls 8% carbon. Lias oil-shale is present at Kilve on the southern side of the Bristol Channel but both sides of the channel are immature for oil. The Lias is immature for shale gas in all of these areas. In the Cleveland Basin the Lias is within the oil window and there are extensive oil shows, but no gas, in its iron-ore mines. In the Godley Bridge 1 well, gas readings in the Lias were fairly low. The Lias Group is identified as LI-MSLS on the GVS.

Zechstein Group

The Kupferschiefer/Marl Slate of the Zechstein Group is a basal upper-Permian unit with a very high organic and metal content for shale. Samples from Durham show that these are correlated. This unit is unlikely to be prospective as it is thin and would need to be treated more like a coal in CBM than a shale. This is identified as the ZG-DLDO on the GVS.

Marros Group

The Namurian aged Marros Group shales are equivalent to the Lower and Upper Bowland shales in the Pennine Basin (see below). These shales are in the South Wales-Bristol Basin and have high gamma-ray responses on geophysical logs, indicating a high organic content, such as in the Ashton Park borehole. However the shales are interbedded with thick sandstones. It is thought that the shales thicken to the south thus could be a realistic shale gas hydrocarbon source unit. This group is identified as MARR-MDSD on the GVS.

Millstone Grit Group

In the West Lancashire Basin and the East Midlands Province the **Sabden Shale Formation** (Namurian shales) of the Millstone Grit Group are extensions of the **Holywell Shale Formation**, a source in the East Irish Sea Basin. The Sabden Shale is not sufficiently deeply buried onshore to be considered as a source of shale gas (Andrews, 2013). These units are identified as the Millstone Grit Group – mudstone, siltstone and sandstone (MG-MDSS) on the GVS.

Craven Group

The late Dinantian to Namurian **Bowland Shale Formation** (with local names of Bowland, Edale, Holywell shales, top part of Craven Group), belonging to the Craven Group in the Pennine Basin, offers the best potential for shale gas in the UK because they have previously sourced hydrocarbons and have a high TOC. These shales are also more extensive than younger Dinantian-aged shales. A combined resource estimation was made by Andrews (2013) for the Bowland Shale Formation and Hodder Formation. The organic content of these shales is typically in the range 1-3%, but can reach 8%. Where they have been buried to sufficient depth for the organic material to generate gas, they have the potential to form a shale gas resource analogous to the producing shale gas provinces of North America. Where they have been less deeply buried, there is potential for a shale oil resource (but there is inadequate data to estimate the oil-in-place) (Andrews, 2013). The Bowland-Hodder unit is divided into two; a lower, syn-rift unit, largely undrilled, and an upper post-rift unit which is more prospective. A large volume of gas has been identified in this unit (P90 23.3, P50 37.6 and P10 54.6 tcm (trillion cubic metres)) but not enough is known to estimate the potential reserves (Andrews 2013).

The Bowland Shale Formation is a source rock for the southern East Irish Sea gas and oil fields and also the Formby oil field. Gas is sourced from Namurian shales at the Elswick Gasfield, in the West Lancashire Basin and gas in other basins may have originated from Namurian strata, for example at the Nook Farm and the Marishes to Malton gas fields along the southern margin of the Cleveland Basin.

The Craven Group has been shown to be within the gas window in boreholes drilled in the Cheshire Basin, southeast of Milton Green and in the Gainsborough 2 borehole in the Gainsborough Trough. These units are identified as the Craven Group on the GVS (CRAV-MDLM).

Yoredale Group – limestone with subordinate sandstone and argillaceous rocks

The late Dinantian to early Namurian **Yoredale Group** and **earlier formation** shale rocks may have some shale gas potential in the Northumberland and Stainmore Troughs because they have high TOCs in a largely gas-prone facies. However, these shales tend to be thin in the basins. A possible play was indicated by the Errington well and thicker, shalier sequences might occur. This group is identified as YORE-LSSA on the GVS.

Carboniferous Rocks (Undifferentiated)

This unit is identified in a small region of the East Midlands Province. It could include rocks from any Carboniferous group present in the East Midlands province; **Bowland Shale Formation** of the Craven Group or Yoredale Group. This unit is identified as CARB-ROCK on the GVS.

Dinantian Rocks (Undifferentiated) – limestone with subordinate sandstone and argillaceous rocks

This unit is identified primarily in the centre-northeast of England. It might contain the source rock **Bowland Shale Formation** of the Craven Group, see description above. This unit is identified as DINA-LSSA on the GVS.

UNDERGROUND COAL GASIFICATION (UCG)

There has been no individual assessment for UGC potential from the UK Government or BGS. Therefore, all Coal Measures have been included, as for the CBM. For UCG, seams of 2 m or thicker are required, at assumed depths of between 600 and 1200 m from the surface (Jones et al., 2004). It should be noted that UCG exploration is considered unlikely in the coming years.

Appendix 3 – Defining groundwater

DEFINING GROUNDWATER STATUS

Groundwater status, defined in Article 2.19, is

> "the general expression of the status of a body of groundwater, determined by the poorer of its quantitative status and its chemical status",

and **good groundwater status**, Article 2.20 means

> "the status achieved by a groundwater body when both its quantitative status and its chemical status are at least good".

Good groundwater chemical status, Article 2.25 is defined as

> "the chemical status of a body of groundwater, which meets all the conditions set out in table 2.3.2 of Annex V",

and **available groundwater resource**, Article 2.27 is defined as

> "the long-term annual average rate of overall recharge of the body of groundwater less the long-term annual rate of flow required to achieve the ecological quality objectives for associated surface waters specified under Article 4, to avoid any significant diminution in the ecological status of such waters and to avoid any significant damage to associated terrestrial ecosystems".

Further characterisation of groundwater bodies, or groups of bodies, Annex 2, section 2.2. of the WFD consists of the following activities:

- "geological characteristics of the groundwater body including the extent and type of geological units";
- "hydrogeological characteristics of the groundwater body including hydraulic conductivity, porosity and confinement";
- "characteristics of the superficial deposits and soils in the catchment from which the groundwater body receives its recharge, including the thickness, porosity, hydraulic conductivity, and absorptive properties of the deposits and soils";
- "stratification characteristics of the groundwater within the groundwater body";
- "an inventory of associated surface systems, including terrestrial ecosystems and bodies of surface water with which the groundwater body is dynamically linked";
- "estimates of the directions and rates of exchange of water between the groundwater body and associated surface systems";
- "sufficient data to calculate the long term annual average rate of overall recharge", and
- "characterisation of the chemical composition of the groundwater, including specification of the contributions from human activity. Member States may use typologies for groundwater characterisation when establishing natural background levels for these bodies of groundwater".

COMMON IMPLEMENTATION OF THE WFD

After the WFD was adopted, a Common Implementation Strategy (CIS) (EC, 2001) was developed and agreed in May 2001. This established a mechanism for developing a common understanding of approaches to, and implementation of, the WFD, as well as examples of good practice. Working groups were convened to exchange information and experience related to the implementation of the WFD. In 2003 the working group on water bodies produced a guidance document (EC, 2003) on the identification of water bodies. The following is a summary of the salient points from the guidance that was also re-iterated in the technical report on groundwater body characterisation and risk assessment issued by Working Group C (the groundwater-specific working group of the EC) in December 2005 (EC, 2005).

The CIS guidance notes that:

> "a body of groundwater must be within an aquifer or aquifers. However, not all groundwater is necessarily within an aquifer".

It goes on to note that:

> "the environmental objectives of preventing deterioration of, and protecting, enhancing and restoring good groundwater status apply only to bodies of groundwater. However, all groundwater is subject to the objectives of preventing or limiting inputs of pollutants and reversing any significant and sustained upward trend in the concentration of any pollutant".

The document, for the first time, sets out more detailed guidance on the implementation of the WFD, indicating how to delineate groundwater bodies, including their upper and lower boundaries. The guidance notes that the first step to identifying groundwater bodies is to interpret the WFD definition of aquifers, i.e.

> "in respect of what constitutes a significant flow of groundwater" and "what volume of abstraction would qualify as a significant quantity [of groundwater]".

The guidance defines a significant flow of groundwater as one that

> "were it [prevented] from reaching an associated surface water body or a directly dependent terrestrial ecosystem, would result in a significant diminution in the ecological or chemical quality of that surface water body or significant damage to the directly dependent terrestrial ecosystems" and a significant quantity of groundwater as "abstraction of more than 10 m^3 of drinking water a day as an average" or "or sufficient to serve 50 or more people".

If either of these criteria is satisfied then the geological strata should be regarded as an aquifer.

With regard to delineation of groundwater bodies, the guidance states that:

> "this does not mean that a body of groundwater must be delineated so that it is homogeneous in terms of its natural characteristics, or the concentrations of pollutants or level alterations within it. However, bodies should be delineated in a way that enables an appropriate description of the quantitative and chemical status of groundwater"

and that delineation must be undertaken in such a way that

> "any groundwater flow from one groundwater body to another (a) is so minor that it can be ignored in water balance calculations; or (b) can be estimated with adequate precision [such that it] will facilitate the assessment of quantitative status."

Finally, with respect to the identification of upper and lower boundaries to groundwater bodies, the guidance recommends that:

> "groundwater bodies should be delineated in three dimensions"; and that "the depth of groundwater within an aquifer or aquifers that needs to be protected and, where necessary,

> enhanced through its inclusion in a body of groundwater should depend on the risks to the Directive's objectives".

The guidance notes that the latter

> "is a matter for Member States to decide based on their assessments of groundwater characteristics and the risks to the Directive's objectives. It should be noted that all groundwater is subject to the 'prevent or limit' objective [Article 4.1(b)(i)] whether or not it is identified as being part of a body of groundwater".

More generally, the guidance notes that:

> "although most pressures will affect the relatively shallow component of a groundwater flow, groundwater flow [and chemical status] at depth can still be important to surface ecosystems - even though this may be over an extended timescale. Human alterations to groundwater flow [and chemical status] at depth can affect shallow groundwater and thus potentially the chemical and ecological quality of connected surface ecosystems. Deep groundwater may also be an important resource for drinking water or other uses. However, Member States would not be expected to identify deep groundwater as water bodies where that groundwater (a) could not adversely affect surface ecosystems; (b) are not used for groundwater abstraction; (c) was unsuitable for drinking water supply because of its natural qualities or because its abstraction would be technically unfeasible or disproportionately expensive; and (d) could not place the achievement [of] any other relevant objectives at risk".

In addition, it notes that

> "the Directive's definitions of aquifer and body of groundwater … permit groundwater bodies to be identified either (a) separately within different strata overlying each other in the vertical plane, or (b) as a single body of groundwater spanning the different strata. This flexibility enables Member States to adopt the most effective means of achieving the Directive's objectives given the characteristics of their aquifers and the pressures to which they are subjected. For example, where there are major differences in status of the groundwater in strata at different depths, it may be appropriate to identify different bodies of groundwater (i.e. one on top of another) to ensure the status of groundwater can be accurately described, and the Directive's objectives appropriately targeted. Similar criteria should be applied in defining the upper and lower boundaries of the groundwater body as to the geographical boundaries ... . In other words, to facilitate the estimation of quantitative status, the upper and lower boundaries should be based first on geological boundaries and then on other hydraulic boundaries such as flow lines."

In conclusion, the Guidance (EC, 2003) recommended that an iterative, hierarchical approach be adopted to identifying aquifers and the boundaries to groundwater bodies. It recommended that some combination of geological boundaries,

> "the starting point for identifying the geographical boundaries of a groundwater body should be geological boundaries to flow, unless the description of status and the effective achievement of the Directive's environmental objectives for groundwater require sub-division into smaller groundwater bodies"

and groundwater highs or divides

> "sub-divisions of an aquifer or aquifers that cannot be based on geological boundaries should be based initially on groundwater highs or, where necessary, on groundwater flow lines"

and flowlines should be used. However, the details of how this was done was to left to individual Member States to decide according to best local practice. Specifically it was stated that:

> "The degree of subdivision of groundwater into bodies of groundwater is a matter for Members States to decide on the basis of the particular characteristics of their River Basin Districts. In making such decisions, it will be necessary for Member States to balance the requirement to adequately describe groundwater status with the need to avoid the fragmentation of aquifers into unmanageable numbers of water bodies"

In 2009 the European Commission published Guidance Document 22 (EC, 2009) which sets out the common implementation strategy for the Geographical Information System (GIS) elements of reporting related to EU water policy, including the WFD and Groundwater Directive. Appendix 13.3 to report No. 22 (EC, 2009) specifically dealt with issues associated with reporting of geographical data including the reporting of 3D groundwater bodies. Appendix 13.3 notes that under the WFD the following data are requested as a minimum to be provided for each groundwater body: a unique identification code, name of groundwater body, x (longitude) co-ordinate of the centroid of the body, y (latitude) co-ordinate of the centroid, and size (surface area, m^2). However, reporting information about groundwater horizons and whether or not overlying groundwater bodies exist is optional.

Annex 15 of Appendix 13.3 notes that

> "GWBs [groundwater bodies] are three-dimensional entities; however the representation of the feature will be as 2-D polygons … it is necessary in case of more groundwater bodies above them with not identical boundaries to distinguish them in different horizons (layers). Groundwater bodies like this overlay each other and should be differentiated through horizon code or separated files. Some countries delineated groundwater bodies in this way (alluvial deposit horizon (layer), main horizon (layer), deep horizon (layer), thermal or mineral water horizon (layer) etc.)"

LATERAL BOUNDARIES TO GROUNDWATER BODIES

UKTAG (2011) extends the CIS guidance (EC, 2003) on the identification of groundwater lateral boundaries by proposing that lateral boundaries to groundwater bodies can be identified using the following features:

- "Groundwater flow divides, using surface water catchments and geological boundaries as proxies where information is limited";
- "Pressure variations, where these are significant at a river basin level and where they require variations in management";
- "Natural chemistry variations, where they impose a limit on the value of the resource for potable abstraction, or where they influence the susceptibility to, and management of, pressures. For example, groundwater is considered to have limited resource value where its natural salinity exceeds the limit for human consumption, and is considered to have no resource value where it exceeds that of seawater"; and,
- "Coastline, unless there is specific evidence to suggest that groundwater beyond the coastline has a resource value".

It is also noted that

> "hydraulic boundaries should be used wherever feasible to avoid the requirement under WFD to calculate flows between groundwater bodies".

EXAMPLES OF INTERNATIONAL BEST PRACTICE

European Union

Despite the development of a common implementation strategy (CIS), the manner in which the WFD and Groundwater Directive has been applied in relation to the identification of aquifers, and in particular the identification of the boundaries of deep groundwater bodies varies between Member States. However, details of how Member States have gone about the process of identifying deep groundwater cannot be assessed systematically as they are not obliged by the Commission to publish the detailed methods that have been used. There is some limited information, obtained primarily through grey literature or through a few peer-reviewed papers in academic journals, related to the processes by which individual Member States have identified the boundaries of aquifers and defined groundwater bodies. The table below provides links to some of the limited information related to how individual Member States undertake such tasks.

Generally, since groundwater systems and groundwater bodies are invariably defined in the first instance on the distribution of rock types within a region or country, differences in the way Member States have defined boundaries to aquifers and groundwater bodies reflects the wide range of hydrogeological contexts and settings across Europe. The following are some selected, non-systematic, examples and illustrations of how Member States have, or have not, defined deep groundwater systems.

For some Member States and regions within Europe, deep groundwater systems have not been considered at all due to the hydrogeological setting. For example, on relatively small island states such as Cyprus and Malta, groundwater systems are typically relatively shallow. Aquifer and groundwater boundaries are controlled not just by the extent of geological formations but by the location of coastlines and the extent and nature of the resulting interfaces between fresh water and seawater. For example, in Cyprus half of the groundwater bodies "have a connection with the sea", and most of these are subject to significant seawater intrusion (Republic of Cyprus, 2016). Another example is the Maltese islands which are composed of two porous fractured limestone aquifers, the Upper Coralline Limestone and the Globigerina-Lower Coralline Limestone separated by a sequence of clays and marls (Maltese Resources Authority, 2016).

A second group of Member States where deep groundwater systems, deep aquifers and groundwater bodies are not important features of their groundwater resources are in Scandinavia, such as Sweden and Finland. Groundwater bodies in this hydrogeological setting are typically restricted to shallow weathered basement systems or fluvioglacial deposits in connection with numerous small, often isolated surface water bodies. For example, Sweden has about 3000 groundwater bodies primarily in small Quaternary deposits of sand and gravel throughout the country (McCarthy and Gustafsson, 2011; Lang et al., 2011) although some sedimentary bedrock groundwater bodies have been identified. In this setting, the base of the groundwater bodies is the base of the Quaternary deposits where it rests on the underlying metamorphic or igneous basement and is typically very shallow.

However, across much of Europe aquifers are present over a wide range of depths. Member States have used a variety of information sources, criteria and procedures to define the extent of aquifers and groundwater bodies. Information used may include data on geological units, and the hydrogeological characteristics of those units - including hydraulic conductivity, water chemistry, and degree and nature of confinement, as well as evidence for hydraulic boundaries or groundwater divides and flow lines (as recommended in EC, 2003). What is typically lacking is any description of the criteria or procedures that have been used to define groundwater bodies and particularly deep groundwater systems. Even when there is some information about how aquifer and groundwater bodies have been defined it is typically restricted to the identification of lateral boundaries and rarely is the identification of the base of aquifers explicitly addressed.

For example, Czarniecka-Januszczyk et al. (2011) and Sanchez et al. (2009) presented graphical representations of how groundwater bodies are defined in Poland and in Malaga, Spain based on a combination of considerations related to geology and hydrogeological characteristics. In both cases the conceptualisations focus on identification of lateral boundaries of groundwater bodies based on changes in geology or hydrogeological divides at or near the land surface. However, in both cases the base of the lowest aquifer / groundwater body is undefined in the schematic cross-sections and no criteria have been set to define the base of the system within the wider studies. The lack of an explicit definition of the base of an aquifer or groundwater body is a common deficiency in the description and characterisation of European groundwater systems.

In France, the principles for defining the groundwater bodies closely follow the Groundwater Directive and CIS Guidance. For example, Barraque et al (2010) describe the process used as follows:

- “geologic and hydrogeologic criteria, a groundwater body is one (or part of a) hydrogeologic unit, decomposed into 6 types of aquifers (alluvial/bedrock/volcanic/ mostly non alluvial sedimentary/mountain composite hydrogeological systems intensely folded/impervious systems but locally containing small disjoint aquifer units);
- the limits of groundwater bodies are stable and not variable in time (impervious geologic limits, stable piezometric tops; flow lines);
- all boreholes giving more than 10 m^3/d of drinking water or used for producing drinking water for more than 50 people must belong to a groundwater body, therefore in practice all aquifers are considered;
- deep groundwater, unconnected to rivers or surface ecosystems, in which there is no withdrawal and which cannot be used for drinking water supply because of its poor quality or for technical-economical reasons may be excluded from the list of groundwater bodies;
- groundwater bodies may exchange water as long as this can be understood/quantified;
- for large groundwater bodies, they may have spatially variable heterogeneity of their hydrogeological characteristics and quantitative or qualitative status;
- subdividing groundwater bodies for taking into account human pressure must be limited; it is acceptable only for particular problems (e.g. point pollution plumes from

> industrial sites, active or not, piezometric depressions linked to overexploitation; this subdividing can only be made if the zone of interest needs that specific objectives be defined, different from the rest of the groundwater body, with a different management"

Note that deep groundwater systems are specifically excluded from the groundwater body designation on the grounds of lack of connection with rivers and surface ecosystems and an absence of abstraction for drinking water because of poor quality or for technical or economic reasons. However, no specific criteria related to these considerations, for example thresholds for quality or abstraction are noted by Barraque et al. (2010).

Another example of how groundwater bodies have been defined for a Member State can be found in the report by the Umwelt Bundesamt (2007) on the implementation of the WFD in Bulgaria, and specifically for the Osan and Vit sub-basins of the Danube River Basin.

The following summary of how the boundaries of groundwater bodies have been defined is given:

> "the boundaries of the groundwater bodies are placed in 4 layers. Without applying a strict stratigraphic sequence, the first layer contains mainly Quaternary aquifers, the second Neogene and Paleogene aquifers, the third mostly Karst aquifer massifs and basins and the fourth is the location of the most deeply located water bodies. The denomination of the bodies follows the largely used denomination of aquifers in the specialized literature ... when the GWB consists of two or more layers, a focus is given to the overlaying and/or the most productive one. The basic materials used are a geological map [and] hydrological maps."

It is primarily based on pre-existing hydrostratigraphic mapping, with aquifers and groundwater bodies ranging from alluvial sediments with an average thickness of about 10 m and a transmissivity of 60 to 1100 m^2/d, to suites of sandy marls down to depths of 2500 m with spring discharges of about 1 l/s. However, there is no indication of how the base of any of these units is defined based on hydrostratigraphic criteria.

The lack of any explicit criteria to define the base of groundwater bodies, or even the conceptualisation of deep groundwater systems, appears to be a common failing throughout Member States. Although some Member States do have explicit criteria for the designation of the lower boundary of groundwater bodies, such as Croatia (Brkic, 2008) where the base of Groundwater Bodies is defined by groundwater temperatures of greater than 20°C and mineralisation >1000 mg/l. Although it is also noted that

> "Aquifers of thermal [sic] and mineral water is not included in groundwater bodies because there is not enough data".

Other states who have also given some consideration to the regulation of deep groundwater systems, even if it is not clear if there are specific criteria related to the delineation of deep groundwater bodies, are those with relatively deep karst systems that are used for both water supply and for the production of geothermal energy. For example, Sanchez et al. (2009) describe how the effective exploitation depth of a deep limestone aquifer, the Sierra de Mijas aquifer from Malaga, Spain is used to define the base of the Groundwater Body as follows:

> "Sierra de Mijas groundwater body is made up of Triassic marbles partially covered by Neogene and Quaternary detrital deposits belonging to the Bajo Guadalhorce groundwater body. In this area the abstraction boreholes are rarely deeper than 500 m … when the depth to the Sierra de Mijas aquifer is greater than 500 m, pumping wells are not deep enough to abstract water from it and then only one groundwater body (the upper one) is considered."

Another example of regulation of deep karst systems is Hungary where licences for abstraction of thermal waters down to 2500 m below ground level are granted, but not below 2500 m (Szocs, 2013).

Australia

As part of the national water quality management strategy for Australia, guidelines for groundwater quality protection (Australian Government, 2013) state that a risk-based approach should be used, the concepts of intergenerational equity, polluter pays and precautionary principles should all be applied, and that:

> "The process for managing the protection of groundwater quality is one of risk assessment that identifies where action is required, followed by implementation of management measures to protect groundwater quality "

and that as part of this process it is noted that

> "understanding the groundwater system to be protected is an important initial step in applying the risk-based framework".

This initial understanding should be based on a conceptual model of the groundwater system and include consideration of the system boundaries, stratigraphy, geological structure, groundwater flow paths, hydraulic properties of the aquifers and other factors including

> "historical, current and expected future groundwater uses and demands"

And although no details are provided as to how this initial conceptualisation should be undertaken reference is made to the Australian Groundwater Dependent Ecosystems Toolbox (NWC, 2011). There is no specific reference in the guidance (Australian Government, 2013) to the identification of deep groundwater systems, but the following observations are pertinent to deep systems:

> "In data poor environments many components of the conceptual model may not be known. These knowledge gaps can be dealt with in two ways: either further research/investigation should be undertaken to address the knowledge gaps, or they should be identified as areas of uncertainty to which the precautionary principle is applied in the groundwater quality protection plan. A lack of knowledge concerning the potential impacts of a hazard should not be used to justify a delay in establishing groundwater protection measures. Rather, the knowledge gaps should be identified and addressed through adaptive management where necessary within a risk-based approach. The level of risk will assist in determining the most appropriate course of action where data is limited, as high risk areas may warrant further investment to fulfil knowledge gaps, while in lower risk areas acknowledgment of the uncertainties and application of precautionary measures may be sufficient."

The Environmental Value concept of a groundwater system is the key tool used to set water quality objectives (Australian Government, 2013) as follows:

> "An Environmental Value is a particular value or use of the groundwater that is important for the maintenance of a healthy ecosystem or for public benefit, welfare, safety or health, and which requires protection from the effects of contamination, waste discharges and deposits. Different Environmental Values are values or uses of the groundwater that support aquatic ecosystems, primary industries, recreation and aesthetics, drinking water, industrial water, and cultural and spiritual values."

When introducing a framework for assigning environmental value categories to groundwater systems, the guidance cites the Victorian State Environment Protection Policy (EPA Victoria, 1997) which gives examples of how total dissolved solids (TDS) can be used to determine appropriate environmental value categories for groundwater, and notes that

> "This approach recognises that salinity often determines the possible uses of groundwater. The policy also includes provision for precluding certain beneficial uses if another background quality indicator will be detrimental to the beneficial use (determined based on salinity); if aquifer yields cannot sustain a particular beneficial use; or if an existing polluted groundwater zone has been identified".

Note that the indicated maximum TDS for acceptable potable water supply of 1000 mg/l is the same as used by Croatia to define their groundwater bodies (Brkic, 2008) and considered unpalatable by the WHO (2011).

Commentary on the application of the Environmental Value categories does, however, include a consideration of potentially deep groundwater sources, as follows:

> "Physical constraints on groundwater extraction may cause some Environmental Value categories to be disregarded through community consultation, for example where aquifer yields or soil characteristics mean groundwater cannot be extracted for industrial or agricultural use. ... Similarly, aquifer depth is not a sufficient reason to disregard certain Environmental Value categories since the economics of water supply could make deep groundwater sources viable in the future. Potential use of the groundwater in the future should also be a determinant of Environmental Value"

and

> "There may be circumstances where a groundwater system has no obvious current or future Environmental Value category, due to its depth, remote location or poor quality water. An example of this is where a deep confined aquifer in a stable geological formation contains extremely poor natural quality water (for example due to high salt or radionuclide levels) and there are no current users of the aquifer. This confined aquifer may be sought to be developed as a long term depository for wastes. As a consequence, an Environmental Value of industrial water use would apply and this would set the baseline for future groundwater quality protection measures. Another example is the extraction of poor quality groundwater associated with coal seam gas extraction. In such situations, these guidelines should be applied, particularly the precautionary principle, to ensure that changes in pressure and quality do not result in deterioration of the assigned Environmental Values of overlying or adjacent aquifers. The long timeframes involved in contaminant transport in deep confined groundwater systems mean that impacts may not be observed for a long time, are difficult to predict, and remediation may not be possible. Waste disposal and further degradation of aquifers must be assessed with a strong emphasis on the precautionary, intergenerational equity and polluter pays principles. These principles imply that an aquifer should not be further degraded if there is a chance of significant future problems or if the potential to assign certain Environmental Value categories in the future could be precluded."

North America

The Clean Water Act (CWA, 2002) established the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters only. Groundwater in the United States of America is subject to regulation and protection through the Safe Drinking Water Act (SDWA) of 1974 which protects drinking water sources including rivers, lakes, reservoirs, springs and groundwater wells (with the exception that it does not regulate private wells that serve fewer than 25 individuals). A summary of the regulations and a history of amendments to the Act can be found on the United States Environmental Protection Agency (US EPA or just EPA) website at:

https://www.epa.gov/sites/production/files/2015-04/documents/epa816f04030.pdf .

Essential components of the SDWA include protection and prevention, whereby States and water suppliers must conduct assessments of water sources to see where they may be vulnerable to contamination. Water suppliers may also voluntarily adopt programs to protect their watershed or wellhead, and states can use legal authorities from other laws to prevent pollution.

The SDWA is designed to prevent threats to what is termed 'Underground Sources of Drinking Water (Section 1421(b)), where EPA regulations (40 CFR 144.3) define a USDW as follows: an aquifer or its portion: which supplies any public water system; or which contains a sufficient quantity of ground water to supply a public water system; and that currently supplies drinking water for human consumption or contains fewer than 10,000 mg/l TDS; and which is not an exempted aquifer. Note that there is no guidance on how to define the lateral or vertical extent of aquifers.

Individual states and federal agencies define freshwater as typically in the TDS range <1,000 mg/l to <3,000 mg/l (Kang and Jackson, 2016).

Exemptions to the Act remove the protection to groundwater and are regulated by the EPA. To grant an exemption, the EPA must determine that the proposed exemption area is not a current or future source of drinking water following the criteria at 40 CFR 146.4 (more details regarding exemptions and the framework for the EPA Underground Injection Control (UIC) program to control the injection of wastes into groundwater can be found at https://www.epa.gov/uic/aquifer-exemptions-underground-injection-control-program). The EPA and States implement the UIC program, which sets standards for safe waste injection practices and bans certain types of injection altogether.

Additional regulation of groundwater includes the ‘Ground Water Rule’ or GWR which came into force in 2006 and which provides protection against microbial pathogens in public water systems using groundwater sources (see https://www.epa.gov/dwreginfo/ground-water-rule for more information).

In this context, the EPA provides oversight, guidance and regulation related to shale gas and environmental protection summarised here https://www.epa.gov/hydraulicfracturing#providing. Specifically with respect to groundwater protection, the EPA provide technical recommendations for protecting USDWs for a range of well-based activities including (Calls II) oil and gas related injection wells, with specific technical guidance when diesel fuels are used in fracturing fluids or propping agents (https://www.epa.gov/uic/diesel-fuels-hydraulic-fracturing-dfhf). Their current position is summarised in their recent report – ‘Assessment of the Potential Impacts of Hydraulic fracturing for Oil and Gas on Drinking Water Resources (US EPA, 2015).

SELECETED SOURCES OF INFORMATION ON DEFINITIONS OF GROUNDWATER AND GROUNDWATER BODIES IN EU MEMBER STATES

Member States	References & sources of information
Austria	"Implementation of the EU Water Framework Directive (WFD) in Austria - Groundwater quality aspects – procedures applied and current state" by Sebastian Holub www.sepa.gov.rs/download/ETCWater/GW_WFD_in_AT.ppt Groundwater management in Large River Basins edited by Milan Dimkic, Heinz-Jurgen Brauch, Michael C. Kavanaugh http://www-naweb.iaea.org/napc/ih/documents/2015_Symposium/Session7/KralikViennaBasinIAEA_150514_v1.pdf
Belgium	http://carto1.wallonie.be/webgis_escaut_public_en/pdf/EN_MESO.pdf EC Report on the implementation of the Water Framework Directive River Basin Management Plans, SWD (2015) http://ec.europa.eu/environment/water/water-framework/pdf/4th_report/MS%20Annex%20-%20Belgium.pdf
Bulgaria	Groundwater bodies in Bulgaria: Identification & delineation practices. http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Presentation_04_spasov_pdf.pdf?__blob=publicationFile&v=2 See also http://www.inweb.gr/workshops2/Workshop_Thessaloniki_June_08/presentation_pdf/Bulgaria_2.pdf Implementation of the WFD in the Bulgarian part of the Danube catchment http://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3346.pdf 178 GW bodies defined in 7 layers based on porous, karstic and fissured rock types. Uncertainty in transition zone from fresh to mineralised deep groundwater bodies identified as a difficulty. Work on groundwater bodies in the Danube catchment in Bulgaria includes definition of deep groundwater bodies down to 2500m associated with spring discharges of up to 1dm³/s.
Croatia	Initial characterisation of groundwater bodies in Croatian karst (Brkic, 2008) https://www.unece.org/fileadmin/DAM/env/water/meetings/karst_croatia_2008/Brkic_et_al_Initial%20characterization%20of%20groundwater%20bodies%20in%20Croatian%20karst.pdf Approach to groundwater body delineation in Croatia http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies_2011/poster_02_brkic_pdf.pdf?__blob=publicationFile&v=3 Groundwater bodies in the Croatian part of the Danube river basin http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Poster_02_Croatia_pdf.pdf?__blob=publicationFile&v=2 Groundwater bodies in the Sava river Basin http://www.savacommission.org/dms/docs/dokumenti/srbmp_micro_web/backgroundpapers_final/nnno_2_background_paper_gwbs_in_the_sava_rb.pdf Lower boundaries of Croatian Karst defined by temperatures of <20 deg. C and 'mineralisation of <1000 mg/l (Brkic, 2008)
Cyprus	Cyprus water resources http://www.moa.gov.cy/moa/wdd/Wdd.nsf/resources_en/resources_en GW Body status http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies_2011/poster_03_constantinou_pdf.pdf?__blob=publicationFile&v=2 Water Resource Management in Cyprus http://brawa.uest.gr/uploads/dodou.pdf
Czech Republic	http://www.geology.cz/rebilance/english
Denmark	http://www.danishwaterforum.dk/Research/Annual%20meeting%202015/Presentations/Session-4/L%20Thorling%20GEUS.pdf and https://prezi.com/vf743tlpypn_/modelling-a-spatial-database-for-danish-groundwater-bodies/ and http://web.natur.cuni.cz/luwq2015/download/poster/223_sessionE_Danish%20groundwater%20status.pdf
Estonia	https://www.unece.org/fileadmin/DAM/env/water/meetings/Assessment/Kiev%20workshop/Presentations/basin%20presentations/Presentation_2ndAssessment_Kiev_Groundwater_Riismaa_EE.pdf and file:///C:/Users/jpb/Downloads/veepoliitika_aruanne_eng.pdf
Finland	http://www.borenv.net/BER/pdfs/ber13/ber13-381.pdf
France	http://www.easac.eu/fileadmin/PDF_s/reports_statements/France_Groundwater_country_report.pdf
Germany	http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Presentation_03_thomas_walter_ppt.pdf;jsessionid=D219EC4F55420AA2B962C56C555EA04D.1_cid284?__blob=publicationFile&v=2 and http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Presentation_05_schenk_pdf.pdf;jsessionid=D219EC4F55420AA2B962C56C555EA04D.1_cid284?__blob=publicationFile&v=2 Water Resource Management in Germany (Parts 1 & 2) https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/wawi_teil_01_englisch_barrierefrei.pdf and https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3771.pdf
Greece	http://www.easac.eu/fileadmin/PDF_s/reports_statements/Greece_Groundwater_country_report.pdf

Member States	References & sources of information
Hungary	Groundwater governance in Hungary and regional overview http://www.fao.org/fileadmin/user_upload/groundwatergovernance/docs/Hague/Presentations/Day1/P4-Szocs_GroundwaterGov_pres.pdf Groundwater in Hungary http://www.kvvm.hu/szakmai/karmentes/kiadvanyok/fav2/fav2_eng.pdf and http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Poster_10_Hungary_pdf.pdf;jsessionid=D219EC4F55420AA2B962C56C555EA04D.1_cid284?__blob=publicationFile&v=2 Regulation of groundwater down to 2500m for abstraction of thermal waters
Ireland	http://www.wfdireland.ie/Documents/Characterisation%20Report/Background%20Information/Analaysis%20of%20Characters/Groundwater/GW2%20Groundwater%20Body%20Delineation.pdf and http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Poster_16_Ireland_MainPoster_A0.pdf.pdf;jsessionid=D219EC4F55420AA2B962C56C555EA04D.1_cid284?__blob=publicationFile&v=2
Italy	http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Poster_11_Italy_Lucio_Martarell_pdf.pdf;jsessionid=D219EC4F55420AA2B962C56C555EA04D.1_cid284?__blob=publicationFile&v=2
Latvia	http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Presentation_07_kadunas_pdf.pdf?__blob=publicationFile&v=2
Lithuania	http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Presentation_07_kadunas_pdf.pdf;jsessionid=D219EC4F55420AA2B962C56C555EA04D.1_cid284?__blob=publicationFile&v=2
Malta	http://mra.org.mt/hydrogeology/wfd/wfd-identification-of-groundwater-bodies/
Netherlands	http://www.wfd-croatia.eu/userfiles/file/presentations%20download/Dutch_Groundwater_delineation(1).pdf The Netherlands has delineated 23 fairly large groundwater bodies (average size 1804 m²). Delineation was based on hydraulic characteristics (subsurface, top zone), salinity and usage (coastal aquifers), and administrative borders
Poland	http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies_2011/poster_04_czarniecka_pdf.pdf?__blob=publicationFile&v=2
Portugal	http://www.easac.eu/fileadmin/PDF_s/reports_statements/Portugal_Groundwater_country_report.pdf and http://www.easac.eu/fileadmin/PDF_s/reports_statements/Easac_Groundwater_WebVersion.pdf SEUMS report notes only 91 GW Bodies identified in Portugal but ~700 in Spain so "This raises questions about methodology and whether the differences reflect differences in geology or in the definitions of aquifer boundaries."
Romania	https://www.unece.org/fileadmin/DAM/env/water/meetings/Assessment/Kiev%20workshop/Presentations/basin%20presentations/Presentation_2ndAssessment_Kiev_groundwater_Bretotean_RO.pdf and http://sgem.org/sgemlib/spip.php?article2761
Slovakia	Water Plan of Slovak Republic http://old.vuvh.sk/download/RSV/00_VPS/Water_Plan_of_the_Slovak_Republic.pdf
Slovenia	Groundwater bodies in the Sava river Basin http://www.savacommission.org/dms/docs/dokumenti/srbmp_micro_web/backgroundpapers_final/nnno_2_background_paper_gwbs_in_the_sava_rb.pdf
Spain	Overview of groundwater resources in Spain http://www.rac.es/ficheros/doc/00587.pdf and http://www.umweltbundesamt.at/fileadmin/site/umweltthemen/wasser/Grundwasser/conference/Abstracts_Presentations/2_4_Varela.pdf and http://www.easac.eu/fileadmin/PDF_s/reports_statements/Spain_Groundwater_country_report.pdf and good paper describing GW Body delineation in Malaga http://www.sciencedirect.com/science/article/pii/S0301479708003186 (deep aquifers defined by pumping depth max of ~500m) Hernandez-Mora et al (2010) note "A precise estimate of the total volume of water stored in Spain's aquifers would not be easy to calculate. Depending on the study, estimates vary between 150,000 Mm3 and 300,000 Mm3 . However, actual reserves are probably much higher, since the existing calculations only take into account the volume stored to 100–200 m depth and do not consider unofficial hydrogeological units, which now are clearly included in the new definition of groundwater bodies, and whose reserves can be significant. In any case, groundwater reserves present a much higher storage than surface water infrastructures, whose full capacity is about 53,000 Mm³ . Of these, on average only 37,425 Mm³ are annually available for use."
Sweden	Groundwater bodies in Sweden http://www.geozentrum-hannover.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies_2011/poster_08_mccarthy_pdf.pdf?__blob=publicationFile&v=2 and http://www.bgr.bund.de/EN/Themen/Wasser/Veranstaltungen/workshop_gwbodies/Poster_13_Sweden_pdf.pdf?__blob=publicationFile&v=2 Primarily from Quaternary (shallow) deposits with ~50% of all groundwater abstraction for public water sup[ply based on artificial recharge

GROUNDWATER QUALITY IN ENGLAND

TDS-depth as a function of lithology

Based on data from the Geothermal catalogues.

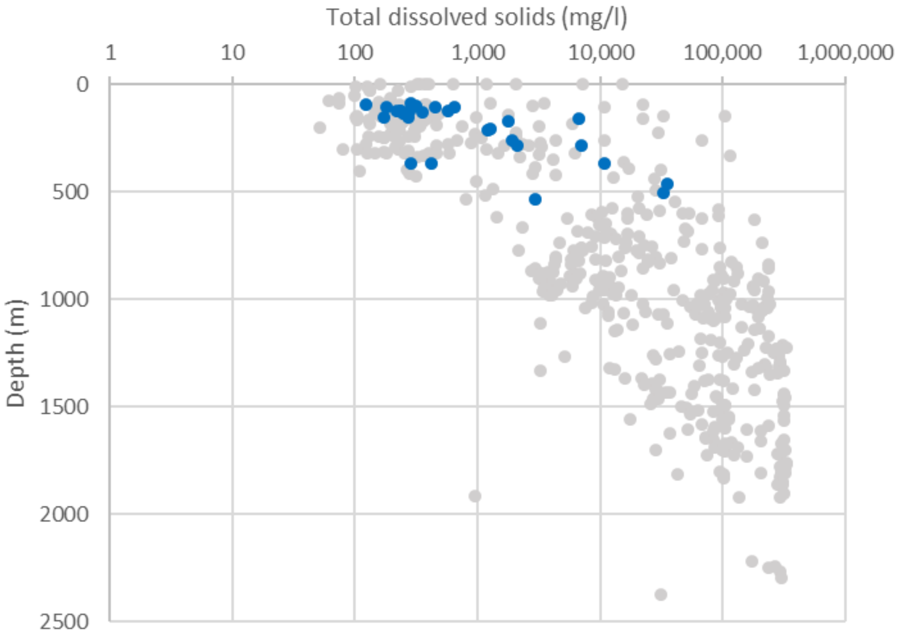

Figure A3.1 TDS and depth for Chalk (blue dots) and all formations combined (grey dots), from BGS Catalogues of Geothermal Data (Burley et al., 1984; Rollin, 1987).

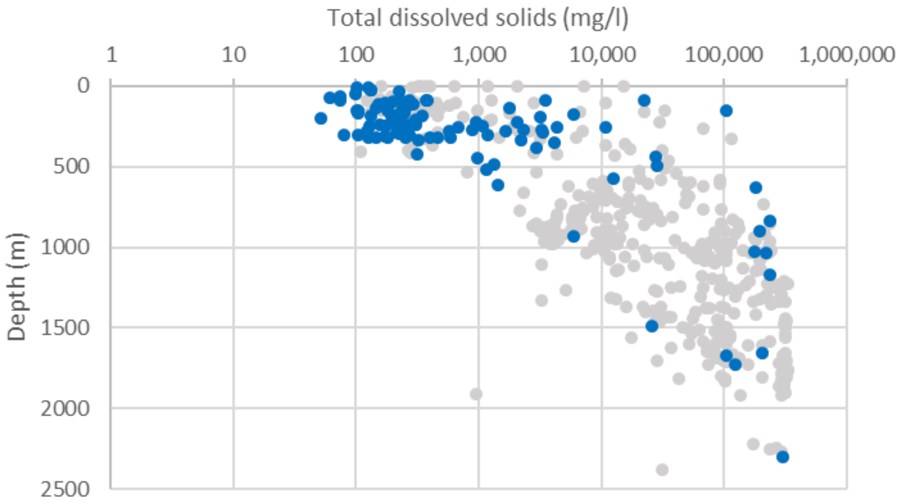

Figure A3.2 TDS and depth for Sherwood Sandstone (blue dots) and all formations combined (grey dots), from Geothermal Catalogues (Burley et al., 1984; Rollin, 1987).

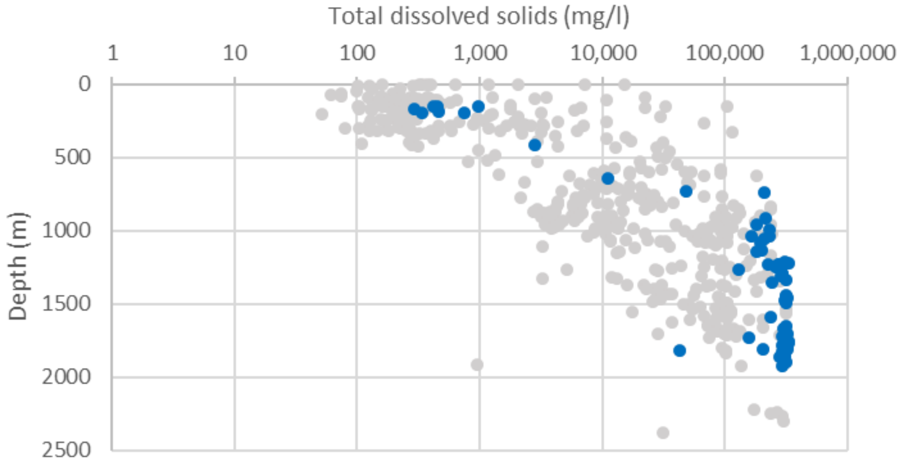

Figure A3.3 TDS and depth for the Zechstein Group (blue dots) and all formations combined (grey dots), from Geothermal Catalogues (Burley et al., 1984; Rollin, 1987).

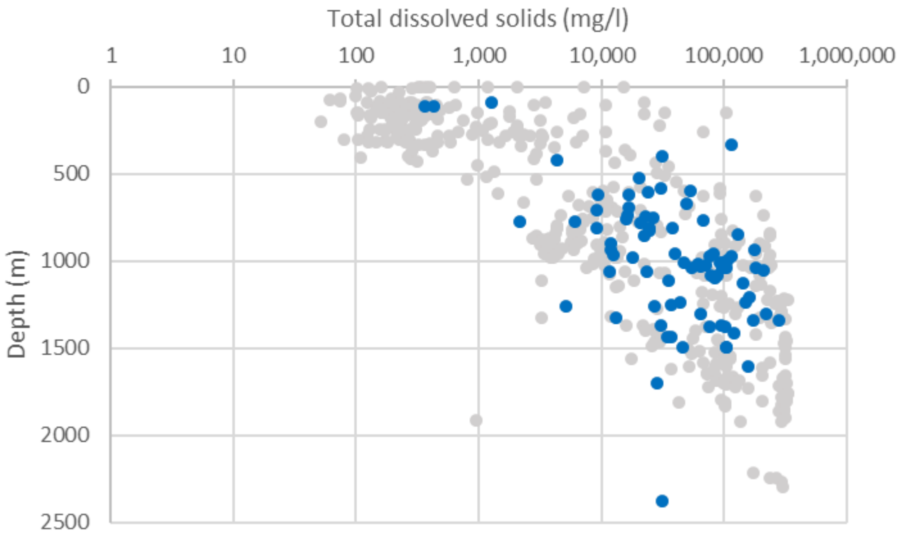

Figure A3.4 TDS and depth for the Coal Measures (blue dots) and all formations combined (grey dots), from Geothermal Catalogues (Burley et al., 1984; Rollin, 1987).

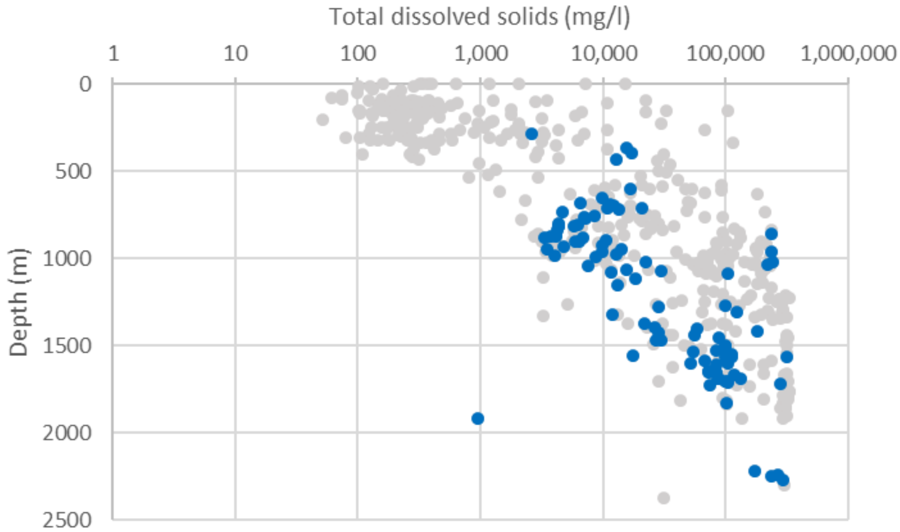

Figure A3.5 TDS and depth for the Millstone Grit (blue dots) and all formations combined (grey dots), from Geothermal Catalogues (Burley et al., 1984; Rollin, 1987).

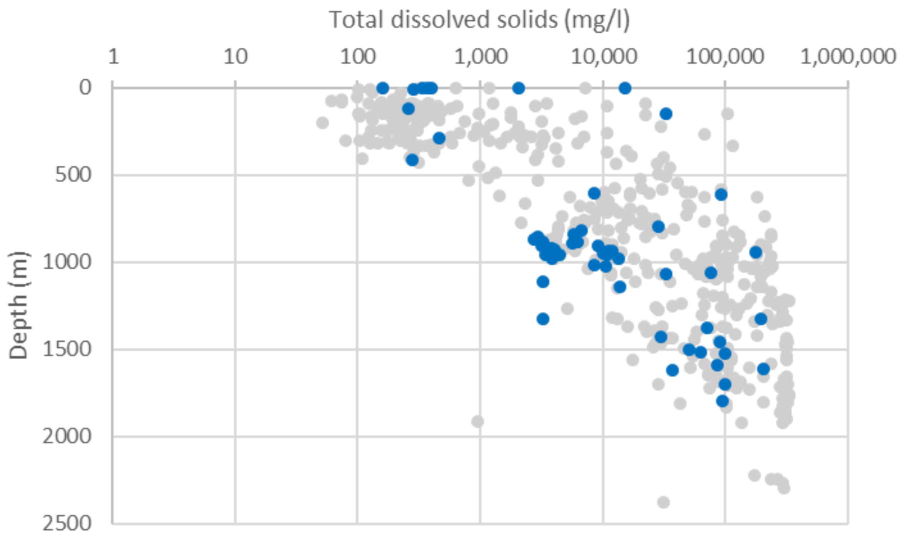

Figure A3.6 TDS and depth for the Carboniferous Limestone (blue dots) and all formations combined (grey dots), from Geothermal Catalogues (Burley et al., 1984; Rollin, 1987).

Maps of deep groundwater chemistry data from geothermal catalogues

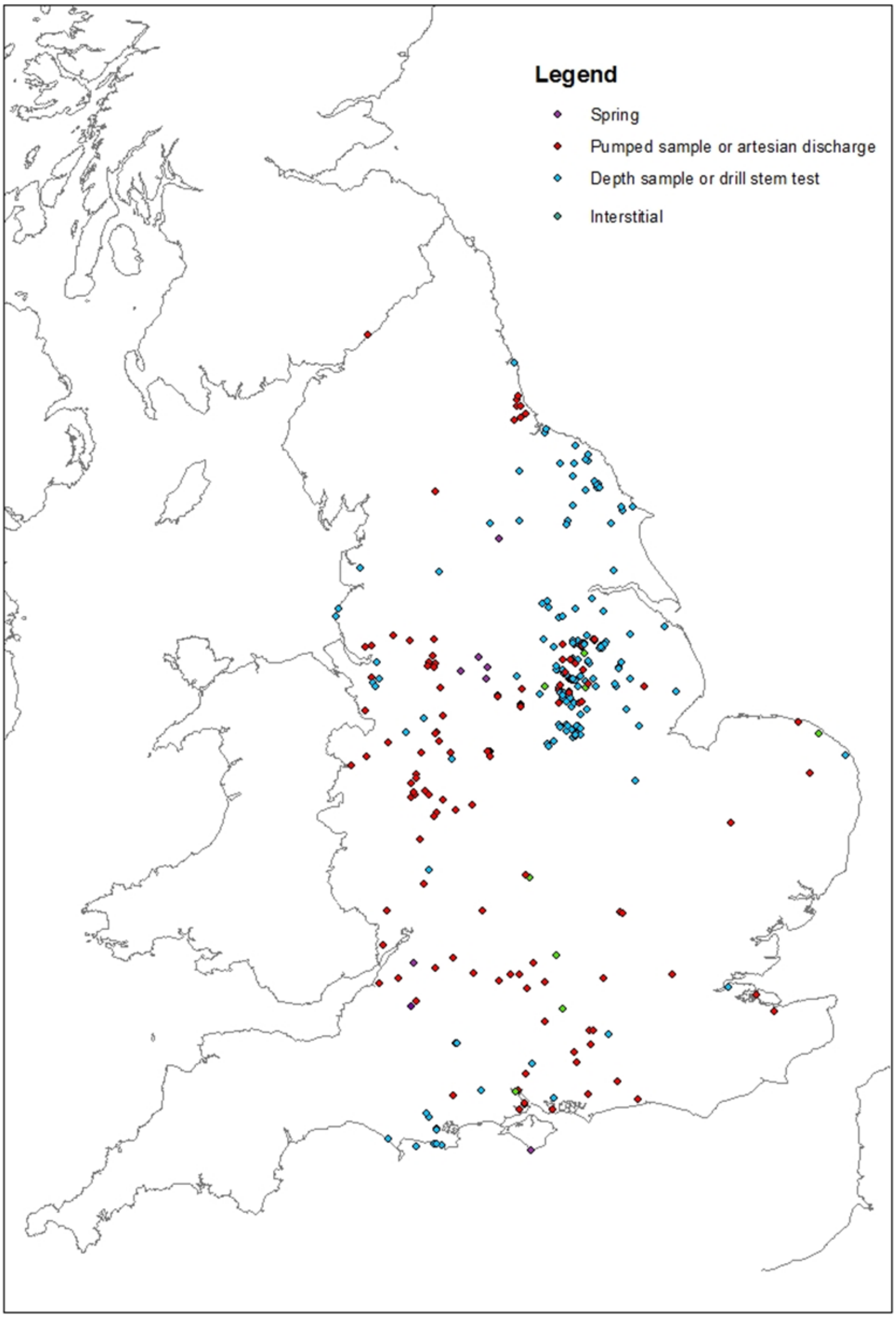

Figure A3.7 Distribution of groundwater chemistry data for England from Geothermal Catalogues (Burley et al., 1984; Rollin, 1987) data by type of sample.

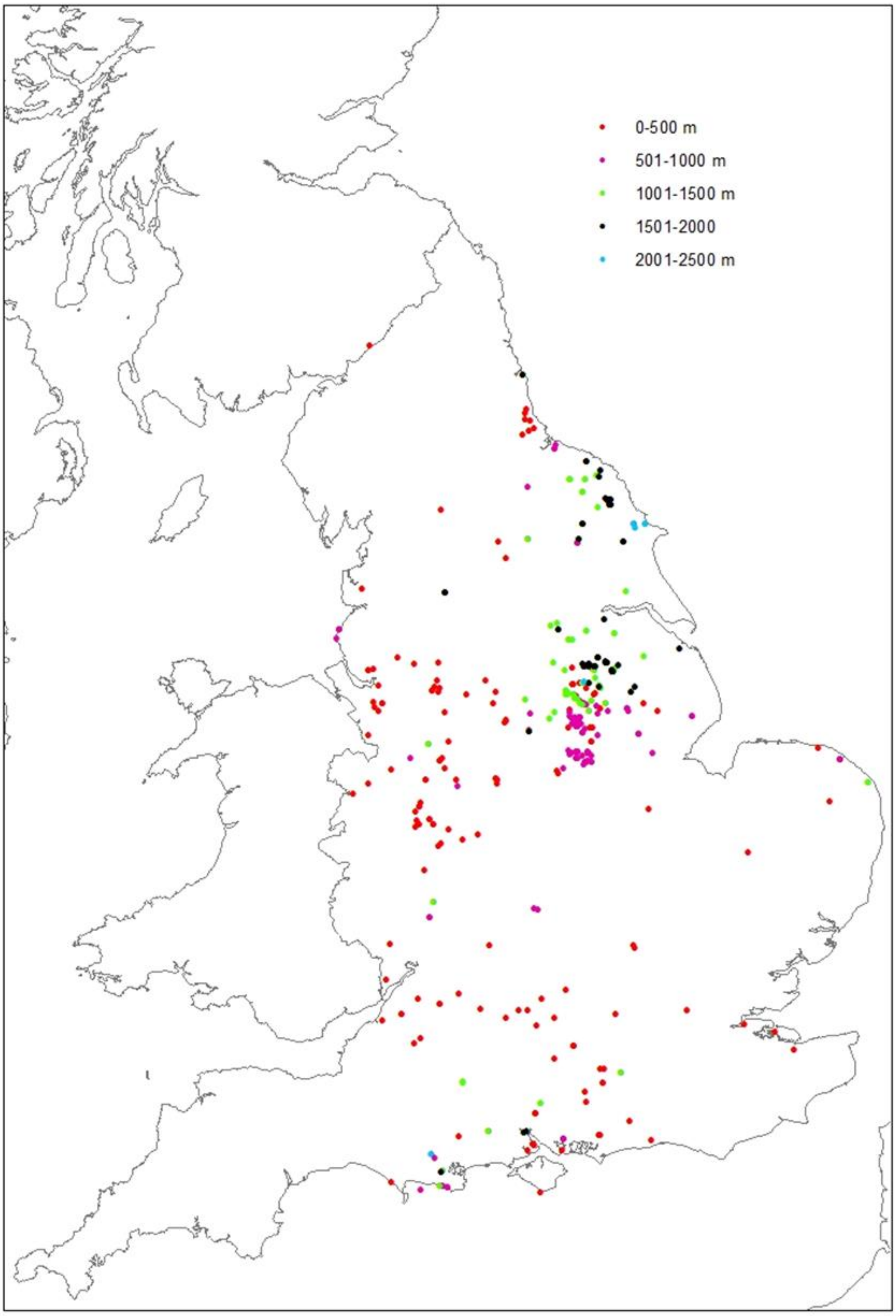

Figure A3.8 Distribution of groundwater chemistry data for England from Geothermal Catalogues (Burley et al., 1984; Rollin, 1987) data by depth of sample.

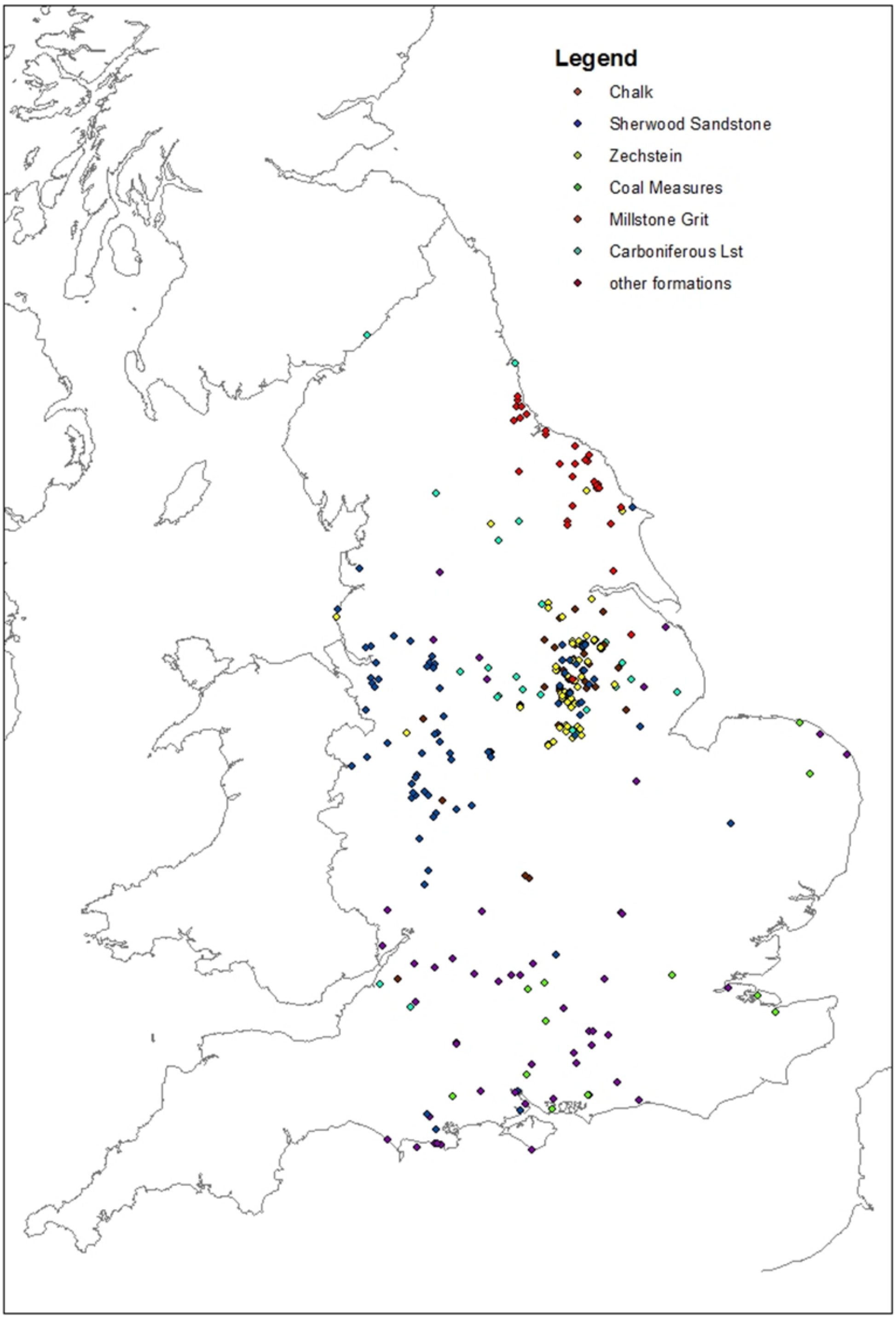

Figure A3.9 Distribution of groundwater chemistry data for England from Geothermal Catalogues (Burley et al., 1984; Rollin, 1987) data by aquifer.

Appendix 4 – Areas with important solution features

From Farrant (2008)

- Chalk; well-developed karst occurs in Dorset, near Salisbury, around Newbury and Hungerford and in many parts of the Chilterns (particularly along the Palaeogene margin between Beaconsfield and Hertford).
- Purbeck Group, Jurassic Limestone and Corallian Group; particularly in some of the Portlandian and Purbeck limestones in Dorset and Wiltshire.
- Cornbrash and Corallian limestones; around Oxford and on the southern flank of the North York Moors.
- Lincolnshire Limestone; karst developed south of Grantham.
- Mercia Mudstone; where halite is present – mainly within the Triassic strata of the Cheshire Basin, and to a lesser extent in Lancashire, Worcestershire and Staffordshire. Subsidence has affected the main Triassic salt fields including Cheshire, Staffordshire (Stafford), Worcestershire (Droitwich), coastal Lancashire (Preesall).
- Permian rocks; halite of north-east England. Where the saliferous Triassic rocks come to outcrop, most of the halite has dissolved and the overlying and interbedded strata have collapsed or foundered producing a buried salt karst. These areas commonly have saline springs, indicative of continuing salt dissolution.
- Permian salt; present at depth beneath coastal Yorkshire and Teeside. Here the salt deposits and the karstification processes are much deeper than in the Triassic salt. Some dissolution mining subsidence has occurred.
- Gypsum karst; occurs in relatively small areas and is present mainly in a belt 3 km wide and about 100 km long in the Permian rocks of eastern and north-eastern England. Karstification thicknesses are enhanced by the thickness of gypsum in the Permian sequence and the fact that it has interbedded dolomite aquifers. Significant thicknesses of gypsum also occur along the eastern side of the Vale of Eden. Gypsum palaeokarst features also occur, especially along the coast of north-east England
- Gypsum karst locally occurs in the Triassic strata, but the effects of karstification are much less severe than in the Permian rocks. Mainly present in weakly permeable mudstone sequences. Active subsidence occurs in many places, especially around the town of Ripon, and to a lesser extent in the eastern part of Darlington; it also occurs in several other locations along the outcrop.
- Zechstein Group dolomites; less soluble than pure limestones so karstic features are less-well developed. However the dolomites are closely associated with gypsum. Numerous small cave systems are present along the outcrop from near Mansfield in the south to Sunderland in the north. Some sinking streams are present as are numerous springs, but very few sinkholes occur. However, numerous open joints, incipient conduit systems on bedding planes, palaeokarst, and sediment infilled fissures can be identified in road cuttings and quarries.
- Limestone-rich Permo-Triassic conglomerates; in Mendip, and parts of Devon, host cave systems, perhaps the most famous example being Wookey Hole in Somerset.
- Carboniferous Limestone; hosts the best developed karst and longest cave systems in the country. Karst features are present on and within the majority of the outcrop. Particularly well-developed karst occurs in the Mendip Hills, in the Derbyshire Peak District and in the Yorkshire Dales and adjacent areas, running up into the northern Pennines. Less well known karst areas include the Forest of Dean, and around the fringes of the Lake District. In all these areas, well-developed karstic drainage systems, sinkholes and extensive cave systems are common.

- Limestones of Devonian age; known well developed cave systems in Plymouth, Buckfastleigh and Torbay, in addition to stream sinks, karstic springs, sinkholes and areas of irregular rockhead.
- Limestones of Silurian age; in the West Midlands and Welsh Borders, but no significant cave systems are known.

Appendix 5 – Characteristics of sub-surface hydrocarbon activities

Oil and gas have been typically extracted from 'conventional' systems whereby they have migrated from the source rock and accumulated in a permeable reservoir. Low permeability 'traps', such a geological fault or rock unit, prevent the oil and gas from migrating further. Recent improvements in extraction technology and an increase in economic viability have allowed for the extraction of hydrocarbons from low permeability rocks, which may be 'tight' rocks within conventional reservoirs or alternatively may be the hydrocarbon source rock, such as coal (CBM and UCG) and shales (shale gas and oil). These are known as 'unconventional hydrocarbons'.

Below is a summary of the extraction techniques referred to in Section 5, specific vulnerability.

Conventional Hydrocarbons (Figure 5.1)	
Background	There has been onshore drilling for conventional hydrocarbons in the UK since the mid-1800s when oil was discovered in Scotland, followed by gas in England in 1896. There are currently 120 sites with 250 operating wells producing between 20,000 and 25,000 barrels of oil equivalent a day (UKOOG, 2016).
Geological setting	Sedimentary basins. The hydrocarbon source rock ranges from a few metres to hundreds of metres in thickness and the thickness of reservoir rocks is also variable.
Depth of exploitation	Reservoirs in the UK range from between 50 m bgl in the Formby Oilfield (DECC, 2013a) and 1550 m at Wytch Farm, Dorset, but are typically between 800 and 1200 m in depth. Elsewhere, exploitation depths can range from 0 to 9 km (Hu et al., 2013).
Boreholes	Vertical boreholes are typical, but directional boreholes can be used where required, for example, at Wytch Farm, Dorset to gain access to resources away from the borehole location.
Stimulation	When reservoir pressure decreases, oil and gas can be pumped to the surface (BGS, 2011). Secondary, or Enhanced Oil Recovery (EOR) uses reinjected water to displace and drive out remaining oil or to maintain reservoir pressure (BGS, 2011). Hydraulic fracturing is not commonly required (AMEC, 2013) but has been conducted from vertical wells since the 1940s. Thermal recovery or chemical injection can also be used for reservoir stimulation, although this has not been used in the UK (BGS, 2011).
Lifetime	In the range of 10-30 years, with an average of 20 years (AMEC, 2013).
Footprint	Often, multiple boreholes will be drilled into the reservoir but borehole density is lower than for unconventional hydrocarbons (US EPA, 2016). For the UK, AMEC (2013) estimated a future density of three to six well pads per site, with two wells per pad and up to three Ha land per pad. AMEC (2013) used a minimum separation distance between well pads of five km. The sub-surface footprint depends on the size of the reservoir, for example, Wytch Farm has 13 well sites and > 100 boreholes. Boreholes here may be < 100 m apart.

Shale gas and oil (Figure 5.3)	
Background	Widespread in the U.S. since the mid-2000s due to technological advances. Initially, explosives or acid etching were used to increase flow from vertical wells (Gallegos and Varela, 2015). Fracking with water began in 1953, and with slick water soon after. Tight oil production began in the U.S. in the 1980s (EIA, 2016). By 1999 nearly one million fracking operations had been applied to vertical wells (Gallegos and Varela, 2015). Directional drilling was developed in the 1980s, maturing in the 1990s and becoming cost-effective in conjunction with hydraulic fracturing in 2001 (US EPA, 2016). In 2000, 6% of hydraulically fractured boreholes were horizontal whereas in 2010 this was 42% (Gallegos and Varela, 2015). Between 25,000 and 30,000 new boreholes are estimated to have been drilled and hydraulically fractured in the U.S. annually between 2011 and 2014 (for tight gas and oil, CBM and shale combined) (US EPA, 2016). In 2015, more than 50 % of

	oil and nearly 70% of gas in the U.S. was produced with the benefit of hydraulic fracturing (US EPA, 2016). There is currently no shale gas production in the UK or Europe. Several countries in Europe have announced moratoria or bans on shale gas, including Scotland, Northern Ireland and Wales. There is active exploration in England for the Bowland-Hodder shale formations in the Fylde of Lancashire and the Vale of Pickering, Yorkshire. A test hydraulic fracture at the Preese Hall site, Lancashire in 2011 was halted due to unexpected induced seismicity (see Clarke et al., 2014).
Geological setting	In the UK, shales and tight formations with the potential for shale/tight gas are often found in sedimentary basins. In North America, tight oil and gas can be found in halo plays, around the edges of historical production sites, or in larger geostratigraphic plays (CSUR, 2016). Shale and tight oil and gas formations can be characterised as clastic depositional systems with sandstone, siltstone, mudstone and shale or carbonate systems with limestone, dolomite, shale and halite/anhydrite. The Bowland-Hodder shale formations are locally interbedded with sandstones and/or thin limestones (Harvey et al., 2016). In the UK, the basin and formation structure is likely to be complex (Ward et al., 2015; Harvey et al., 2016) due to the age and deformation history of the rock units. The thickness of shales with gas resources is variable; for example, the Marcellus shale is less than 110 m in thickness (US EPA, 2016), and other formations similar to UK shales are only tens of metres in thickness (Harvey et al., 2016). The thickness of tight formations is variable for oil but for gas plays they are commonly located in deep basins and are very thick with continuous gas saturation (Aguilera & Harding, 2008). In England, potential shale gas units such as the Carboniferous Bowland-Hodder formations are nearly 4 km in thickness in basins and 100 m on platforms. The thicknesses of shales in the Weald Basin are much smaller, from 19 to 300 m in total (Harvey et al., 2016).
Depth of exploitation	Variable: In the U.S., the average depths of large gas-producing reservoirs in shales are between 2 km (Marcellus shale) and 3.7 km (Haynesville-Bossier shale). The minimum and maximum depths of exploitation range from 200 m in New Albany to 4.12 km in Haynesville-Bossier. 16 % of boreholes in the U.S. are < 1.6 km deep (US EPA, 2016). Tight oil formations are typically exploited from 1-3 km depth and gas from deep (> 4.5 km) basins. Biogenic gas can be < 1 km bgl (Naik, 2003). Hybrid plays can be shallow, such as the Antrim biogenic gas play (430 m bgl) and the Niobraran shale oil resource (305 m bgl) (Monaghan, 2014). In the UK, Andrews (2013) used a depth cut-off of 1.5 km for shale gas estimations in the Bowland-Hodder formations and Andrews (2014) used a depth cut-off of 1 km for the Weald. Monaghan (2017) used a shale gas depth cut-off of 805 m bgl in central Scotland – relating to pressure and flow rates and well sample maturity. Shale oil has been found between 67 and 550 m bgl (Andrews et al., 2014). However, the UK 2015 Infrastructure Act states that high volume hydraulic fracturing (more than 1000 m^3 fluid at each stage or more than 10 000 m^3 of fluid in total) cannot take place < 1 km bgl (http://www.legislation.gov.uk/ukpga/2015/7/contents/ enacted) or < 1.2 km bgl in protected areas such as National Parks (http://www.legislation.gov.uk/uksi/2016/384/note/made). In the DECC (2013c) report, shale oil resources were assessed from surface to a depth of 1000 m and to 3,500 m for shale gas.
Boreholes	Extracted via a borehole, which may be deviated or have horizontal sections within the shale (Gallegos and Varela, 2015). By drilling multilateral horizontal boreholes into the shale, a greater rock volume can be accessed (DECC, 2013c) and boreholes are now being drilled with longer horizontal sections and closer spacing (US EPA, 2016).

Stimulation	High volume hydraulic fracturing (fracking) is used to increase the permeability of the shale, allowing gas to flow from the shale to the borehole in commercial quantities. A high volume of frack fluid (water with chemical additives) is injected into the borehole under a very high pressure in order to create hydraulic fractures in the rock surrounding the borehole. Fractures increase the shale porosity from 1-10%, to 35% (Brownlow et al., 2016). Fractures are kept open using a proppant (sand or ceramics) while the borehole is subsequently depressurised so that the gas flows out of the shale, into the borehole and to the surface (The Royal Society, 2012). Hydraulic fracturing is not always required for oil production from tight formations (US EPA, 2016). The volumes of water and pressures required for high volume hydraulic fracturing depend on the geological conditions and composition of the hydraulic fracturing fluid, but are relatively large. In the U.S., the average water volume injected per horizontal borehole in 2014 was nearly 20,000 m^3 (typically between 10,000 to 25,000 m^3, AEA (2012)) per well for gas and up to 16,000 m^3 for oil (Gallegos et al., 2015). The volumes required for vertical boreholes are much lower, with medians of < 2,000 m^3 and < 1,000 m^3 for gas and oil respectively (Gallegos et al., 2015), and generally reflect the length of the borehole (Gallegos et al., 2015). Between 40-80 % of injected fluids flow back to the surface as flowback (Prpich et al., 2015). In the Marcellus and Haynesville Shales, injection pressures range from 13.8 MPa to 82 MPa (US EPA, 2016).
Lifetime	Hydraulic fracturing activities can last from one day to several weeks (US EPA, 2016). If the horizontal wells are too long to maintain pressure along their length, plugs can be used to fracture the well in stages (The Royal Society, 2012). Re-fracturing or re-completions are sometimes required in wells, but this is thought to be for < 2 % boreholes (US EPA, 2016). The overall lifetime of shale gas wells is not well known because the industry is still immature (US EPA, 2016). AMEC (2013) estimated an average lifetime of 20 years and Prpich et al. (2015) estimated a lifetime of up to 30 years. However, there are some estimates that the production phase in tight gas reservoirs may be from 40 to 60 years, or from 5 to 70 years in shale (US EPA, 2016).
Footprint	In some cases, more than 20 boreholes can originate from a single well pad (Jackson et al., 2013a). Multi-borehole pads have an average area of 1.4 ha during hydraulic fracturing operations and 0.24 ha during production (NYSDEC, 2011). AMEC (2013) estimated that the minimum distance between well pad sites in the UK would be 5 km. For the 13 years following the start of shale gas development in the UK, they estimate that between 30 and 120 well pads could be developed for low and high activity scenarios, respectively. Each well pad could have 6 to 24 wells and be two to three ha per production pad, resulting in 80 to 2880 wells in total (AMEC, 2013).

Coal bed methane (Figure 5.5)	
Background	CBM is well established in the US, Australia, China, India and Canada. Gas has been produced from high rank coals since the 1970s and low rank coals since mid-1990s (Moore, 2012). Commercial production began in the USA in the early 1980s. In 2001, there were 3655 CBM boreholes in the Powder River Basin alone. Production has been ongoing in Australia since 1996 and India since 2009 (Moore, 2012). In the UK, CBM exploration wells have been drilled in the Vale of Clwyd, South Wales and South Lancashire. In Airth, Midland Valley, Scotland, significant, but not economic, gas and water production has been established (Jones et al., 2004). CMM has been exploited in the UK since the 1950s, and all working mines (as of 2004) drained methane (Jones, 2004). AMM was produced at the Old Boston colliery, Lancashire, between 1957 and 1967 at an average rate of 52 l/s and up to 300 l/s (Jones et al., 2004). The Avon Colliery pumped gas to South Wales in 1971 (Ren, 2004). There are also AMM sites in North Staffordshire, the East Midlands and Yorkshire (Jones et al., 2004). Methane is also being extracted for electricity generation from the mine complex at Stillingfleet, Selby, Yorkshire (Younger, 2016).
Geological setting	Organic material forming coal seams was often deposited in sedimentary basins (US EPA, 2016) cyclically with other sedimentary rocks. Therefore, coal seams are generally interbedded with other rock types including mudstones, sandstones, siltstones, conglomerate and limestone (e.g. the Coal Measures and Warwickshire groups in England). In England, coal is predominantly found

	in basins of Carboniferous age and has often subsequently been uplifted and inverted. Structural features such as faulting and folding in the coal bearing units are thus common. Coal units are sometimes overlain by Permo-Triassic principal aquifers in sedimentary basins in England (Jones et al., 2004). Virgin coal seams in England are only several metres in thickness in comparison to those in the USA and Australia, which may be up to 43 m in thickness (US EPA, 2016).
Depth of exploitation	CBM basins in the US range from 0 to > 2000 m depth (e.g. in the Black Warrior and Powder River Basins, respectively) (US EPA, 2016). Jones et al. (2004) and Gow et al. (2016) considered Coal Measures in the UK to have potential for CBM between 200 to 1200 m bgl. It is thought that there is a possible increase in methane content with depth (EA, 2014). Shallow workings with opencast sections are not considered to have potential for CBM due to the possibility of major air ingress. CMM and AMM resources are in areas with existing and abandoned mines with methane.
Boreholes	CBM boreholes may have many subsurface horizontal or multilateral side tracks drilled from one surface location in order to penetrate more coal (DECC, 2013b). Horizontal sections of wells are often 1-3 km in length (The Scottish Government, 2014). There may also be multiple pads per production operation (EA, 2014).
Stimulation	Where permeability of coal is low, hydraulic fracturing can be used to improve connectivity between the borehole and the cleat system. Pressures required for hydraulic fracturing are 50-70% lower than for shale gas, often of the order of 24-34 MPa, although this is depth dependent (EA, 2014). The volume of fluid injected for fracturing is also smaller than for shale gas, between 200 m^3 – 1500 m^3 water per borehole (EA, 2014) due to shorter well lengths (US EPA, 2016). Injected fluids include water, water and sand or nitrogen foam with proppants and other additives (EA, 2014). In the UK, estimated produced water volumes are 1-40 m^3/day per well and the water can often be highly saline (EA, 2014). Hydraulic fracturing is not a requirement for CMM or AMM.
Lifetime	The lifetime of a CBM operation depends on a range of factors such as adjacent wells and the amount of gas available, but is poorly understood at present. Most producers in the Powder River Basin, USA, can produce for 10 to 12 years though it is thought that stimulation could increase lifetimes by 10 to 30 years (De Bruin et al., 2016). For CMM there is typically 6 to 12 months of gas production before mining can take place (Karacan et al., 2011). Production in an AMM project in Pittsburgh declined after 2.7 years (Karacan et al., 2011).
Footprint	Multiple lateral wells can allow drainage of 7.2 km^2 from a single well pad, whilst only 0.3 km^2 may be drained from a single vertical well (Al-Jubori et al., 2009). The subsurface footprint of CMM and AMM depends on the size of the pre-existing mines.

Underground Coal Gasification (Figure 5.7)	
Background	There have been more than 50 UCG trials and larger schemes over the last half century (Jones et al., 2004). Early trials were small-scale and at relatively shallow depths. In 1959, the Newman Spinney trials were conducted south of Sheffield, UK, within the Fox Earth Coal at a depth of 75 m for one to two months at a time. From 1978-1986, trials were conducted on a thin seam at a depth of 1000 m at Thulin in Belgium. The El Temedal European trial in Spain (1993-1998), confirmed technical feasibility at depths between 500 and 700 m bgl. Further afield, UCG has been taking place in Kuzbass, Siberia, at the Yuzhno-Abinskaya gasification plant since 1955 in a coal seam 1.3 to 3.9 m thick, and at the Angren mine in Uzbekistan within lignite seams 2-20 m in thickness and at depths of 130 to 350 m. A test site at Hanna, Wyoming, involved extensive site characterisation and monitoring for hydrogeological and environmental variables but projects in Wyoming were not found to be commercially viable (Jones et al., 2004). Large-scale air-blown schemes have been undertaken more recently in Russia and Uzbekistan and also at Chinchilla, Australia in 1999, where syngas was produced at 300°C and at a depth of 140 m, though this scheme was mothballed by 2003. Since 1990, there have been 16 known trials in

	China. Feasibility studies have also been undertaken in Canada, India, Pakistan, Russia, Slovenia and the Ukraine.
Geological setting	Organic material forming coal seams was often deposited in sedimentary basins (US EPA, 2016) cyclically with other sedimentary rocks. Therefore coal seams are generally interbedded with other rock types including mudstones, sandstones, siltstones, conglomerate and limestone (e.g. the Coal Measures and Warwickshire groups in England). In England, coal is predominantly found in basins of Carboniferous age and has often subsequently been uplifted and inverted. Structural features such as faulting and folding in the coal bearing units are thus common. Coal units are sometimes overlain by Permo-Triassic principal aquifers in sedimentary basins in England (Jones et al., 2004). It is generally thought that coal units need to be > 2 m in thickness for UCG (Jones et al., 2004; Burton et al., 2006; Gow et al., 2016) but coal seams are typically thinner than this in Europe, and seams of 0.5 m in thickness may be feasible (Shafirovich and Varma, 2009). Geological structural complexity is not a significant concern for UCG, strata dips of 5 to 30^{o} are preferable (Jones et al., 2004) and horizontal coal seams would need to be compartmentalised (Olness and Gregg, 1977).
Depth of exploitation	UCG operations are considered shallow between the surface and 350 m bgl and deep from 600 to 1300 m bgl (Burton et al., 2006; Shafirovitch and Varma, 2009). They are generally located below the water table in order to control burns (e.g. Hoe Creek, Burton et al., 2006). In England, Jones et al. (2004) suggest that UCG is more likely to occur at depths of between 600 m and 1200 m bgl, based on the depths required to reduce environmental impacts and the normal limits for mining. For similar reasons, UCG typically takes place deeper in the subsurface in Europe (Burton et al., 2006).
Boreholes	At least two boreholes are required for injection and extraction, with between 10 and 60 m separation. Thicker coal seams require fewer boreholes (Burton et al., 2006). Directional drilling enables improved control of the gasification process and although it is not necessary (Shafirovitch and Varma, 2009), it is common in deeper seams (Burton et al., 2006).
Stimulation	Permeability can be increased artificially with stimulation techniques such as reverse combustion and hydraulic fracturing (Bhutto et al., 2003; Burton et al., 2006; Shafirovitch and Varma, 2009). UCG also requires a strong, dry, impermeable roof rock (Jones et al., 2004). In deeper UCG operations steam is injected at pressures of up to 80 MPa. In shallower sites pressures of only 324 kPa may be required. The optimum ‘blast’ intensity is suggested to be around 5000 m^3/hr, but experiments have ranged from 1500 to 7000 m^3/hr with higher intensities improving production (Burton et al., 2006). Temperatures exceeding 200^{o}C have been found to minimise pollutant by-products (Burton et al., 2006) with temperatures of up to 300^{o}C used in Chinchilla, Australia (Jones et al., 2004).
Lifetime	The lifespan of a UCG operation is variable; for example, a site in Uzbekistan has been operational for 50 years but others in the former USSR were operational for between 5 and 17 years (Burton et al., 2006).
Footprint	Subsurface footprint is variable, dependent on the coal resource and cavity size. However, little control can be exerted over the cavity size (Burton et al., 2006).

Appendix 6 – Case studies

CASE STUDY 1: CONVENTIONAL OIL AND GAS, SOUTHEAST ENGLAND

Hydrocarbon source and extraction method

Portland Group, East Sussex (Figure A6.1), conventional oil and gas reservoir approximate location shown by the letter 'T' in Figure A6.1 and Figure A6.2 .

AOI

Extending to 2 km from vertical borehole

Geological setting

The AOI lies on the boundary between the Weald Basin and the Wessex Basin, on the north side of the South Downs. In the Wessex Basin a thin (~50 m in thickness) layer of the Triassic-aged Mercia Mudstone Group overlies a basement of Dinantian (Carboniferous) and Devonian-aged rocks, which decrease in depth southwards from ~1600 m below OD beneath the Weald Basin to ~1000 m below OD beneath the South Downs and the English Channel. Sedimentary rocks of Jurassic to Cretaceous age (Lias Group to Wealden Group) overlie the Mercia Mudstone Group. The Wealden Group rocks crop out in the Weald Basin. The thickness of the Cretaceous is about 1600 m. This sequence becomes thinner (600 m in thickness beneath the English Channel) and shallower (base of sequence 1000 m below OD beneath the English Channel) to the south. Here, the Wealden Group and Purbeck Group are truncated by an unconformity and covered by younger Cretaceous rocks (Lower Greensand to Chalk Group). While the Lias Group to Kimmeridge Clay Formation are relatively horizontal over the basement platform, the Lower Greensand Formation, Wealden Group and Chalk Group dip to the south (Figure A6.2). There are a number of large scale faults in the area particularly those associated with large scale east-west monoclines in the Wessex Basin.

Conceptual model

The conceptual geological model for the AOI across (north-northeast – south-southwest) and along (west-northwest – east-southeast) strike, is shown in Figure A6.3. Vulnerability and risk have been assessed for both the overlying and the underlying units in this AOI because the activity would be < 1200 m bgl. The AOI lies along the LFV section UK_Reg8_Sec220 (Figure A6.1). A number of boreholes (1 km to the southwest, 4 km to the west and 2 km to the north) terminate in the Lower Greensand, thus providing some evidence regarding the depth and thickness of the Chalk and Gault. These borehole records indicate that there is little variability in the thickness of these units across the AOI, although the topography impacts the Chalk thickness (it is thicker under higher topography). No boreholes in the area penetrate the base of the Lower Greensand, thus the conceptual model from the top of this formation downwards is based on the LFV cross section. Consequently, there is some uncertainty regarding the geometry of units beneath the base of the Gault. Nevertheless, similar to the top two units, there appears to be little variation along or across strike in the AOI. A general geological sequence and unit descriptions are shown in Table A6.1.

A number of large-scale faults (marked on the 1:625,000 geological map) strike west-northwest – east-southeast about 6 km to the northeast of the centre of the AOI. These faults cut the Wealden Group outcrop, between the Weald and Wessex Basins. The AOI also lies approximately along-strike of an east–west trending fault which appears to have offset the Wealden Group. On the 1:10 000 geological map there is a 2 km long north-northeast–south-southwest striking fault which is mapped as having offset the Chalk Group laterally by about 80 m (vertical throw <= 10 m to west – thus, this could be a normal fault or a strike-slip fault) in the southeast of the AOI. This is drawn as having ~50 m vertical throw in the conceptual model in Figure A6.3 because the cross section is beyond the mapped surface extent of the fault and the vertical throw cannot be determined from the map. A number of other, north-northwest–south-southeast striking faults mapped as about 600 m in length, but with a similar horizontal displacement of the Chalk Group, could cross the along-strike conceptual section in the east but there is no map evidence for these crossing into the AOI.

Baseline methane

Bell et al. (2016) sampled for methane concentrations in aquifers in the southeast as part of the methane baseline survey of Great Britain. Six sites were sampled within the area shown in Figure A6.1; two from the Chalk and four from the Wealden Group (Hasting Subgroup; Tunbridge Wells Sand Formation and the Ashdown Formation). One location is about 8 km west of the AOI, along strike. It was found that methane concentrations were above the detection limit in the region and lower in the Chalk than in the Wealden Group. Two samples from the same borehole in the Wealden Group (the sample was repeated) in the northeast of the region shown in Figure A6.1 were over the groundwater equivalent LEL for methane (Section 6.1). The authors describe a known zone of shallow methane in this region and hydrocarbon well logs report significant gas in the shallow Cretaceous sandstones of this area. While additional analysis implied a thermogenic source it was not possible to clarify using isotopic investigations. The authors conclude that given the shallow nature of the gas, the methane could be thermogenic, having migrated up from depth, or biogenic, having formed from thin lignite layers in the Weald Clay. They state that the spatial distribution, source and hydrogeological controls on this methane occurrence are poorly understood.	
Potential receptors	**Classification**
Aquifer designations were obtained from the LFV, based on EA aquifer designations (Figure A6.4). Where model units were classified as variable aquifers (Wealden, Portland, Corallian and Lias groups), EA aquifer designation maps were used to identify the designation in this particular region and with a comparable lithology. In this instance the outcrops of these units were predominantly along the coast to the west of the AOI, from the Isle of Wight to Charmouth. These units have the same lithologies, despite being up to 160 km from the AOI (for the Lias). For the Wealden Group, the outcrop is much closer, in the Weald Basin, but there are multiple aquifer designations for this group depending on the formation. This is also the case for the Lias in the Charmouth area. Where there are multiple designations, the most sensitive designation has been applied to the whole unit.	
Chalk	A – principal aquifer < 400 m bgl, a record from a borehole 1 km to the south of the AOI drilled into the Chalk to a depth of 13 m indicates a groundwater TDS of 583 mg/l. Another borehole drilled to 39 m bgl had a measured TDS of 412 mg/l.
Gault	D – unproductive strata
Lower Greensand	A – principal aquifer < 400 m bgl, borehole record in the south of the AOI indicates a TDS of 447 mg/l in this unit.
Wealden Group	B – secondary aquifer < 400 m bgl
Purbeck Group	B – secondary aquifer < 400 m bgl
Portland Group	A – principal aquifer < 400 m bgl
Kimmeridge Clay	D - unproductive strata
Corallian Group	C – secondary aquifer > 400 m bgl
Kellaways and Oxford Clay	D – unproductive strata
Great Oolite Group	B – principal aquifer > 400 m bgl
Inferior Oolite Group	B – principal aquifer > 400 m bgl
Lias	C - secondary aquifer > 400 m bgl
Hazard	**Score**
Release mechanism of hydrocarbon	No permeability enhancement (passive) for conventional oil and gas.
Head gradient driving flow	Incomplete picture of groundwater head distributions in the AOI, or region, at depth. The Hydrogeological Map of the South Downs and adjacent parts of the Weald (IGS, 1978) shows that shallow groundwater heads in the Chalk Group largely follow topography, suggesting groundwater flow in this unit is broadly towards the centre of the upper cross section and to the west in the lower cross section (Figure A6.3). Groundwater head contours for the Lower Greensand appear to be less variable locally, and suggest groundwater flow from the north-east to south-west.

	Borehole records 4 km west and 6 km northeast of the AOI indicate that there can be upwards head gradients leading to artesian conditions in the Lower Greensand. It is not known from what depth this upward gradient applies so an upwards gradient from the source (hydrocarbon source unit) to overlying potential receptors cannot be ruled out. There is also a lack of evidence regarding the direction of head gradients from the hydrocarbon source unit reservoir to the underlying units, so a downwards gradient from the hydrocarbon source unit to these units is also not excluded.
Intrinsic vulnerability	
Vertical separation distance between source and base of receptor	Depth of the Chalk and the Gault potential receptor units are relatively well known due to their limited lateral variability and availability of records from a number of boreholes. There are no borehole records below the Gault, and greater uncertainty associated with the depth of these potential receptors. Nevertheless, the limited area (diameter 4 km) and the little variability across the LFV sections indicate there is probably little variability across the AOI. The vulnerability assessment has been performed for the centre of the AOI. The confidence is low due to the unknown depth to potential receptors beneath the Lower Greensand and to the hydrocarbon source unit itself.
Lateral separation distance between source and receptor	A fault 1 km to the east, across-strike (Figure A6.3), could bring the Wealden Group into contact with the Portland Group hydrocarbon source unit. Small-scale variability could also bring the vertically adjacent units (Purbeck Group and Kimmeridge Clay) into contact with the hydrocarbon source unit and can also be considered laterally connected. The thickness of the Kimmeridge Clay is too great to allow for lateral connectivity of the Corallian Group and the hydrocarbon source unit across the fault. The confidence is medium because there is little variability in depth and thickness of units across the AOI. However, the throw on the fault is not known.
Mudstones and clays in intervening units between source and receptor	The composition of the Chalk, Gault and Lower Greensand were assessed from borehole records. Units underlying this do not have borehole records in the region so their lithology was identified from the geological sheet memoir (Lake et al., 1987). Units directly above or below the hydrocarbon source unit are not separated by any intervening units. Above the hydrocarbon source unit, the Purbeck Group (limestone and mudstone) and Wealden Groups (mudstone, sandstone and siltstone) are estimated to be 50% mudstone, the Lower Greensand predominantly sandstone (estimated 0 % mudstone from borehole records) and the Gault 100% mudstone (although there are occasional sandstone beds). The cumulative mudstone thickness increases up the sequence with distance from the hydrocarbon source unit, with the class ‘A’ potential receptors – the Lower Greensand and the Chalk expected to have about 98 and 178 m of mudstone, respectively, between their bases and the top of the hydrocarbon source unit formation. There are a number of thick mudstone units in the geological sequence underlying the hydrocarbon source unit, including the Kimmeridge Clay directly beneath the hydrocarbon source unit (203 m mudstone), and the Kellaways and Oxford Clay formations (221 m mudstone). The confidence level for this factor is medium because there are no borehole logs nearby which indicate the unit lithologies below the Lower Greensand and confidence of the correct assignment of these is only moderate.

Groundwater flow mechanism in intervening units between source and receptor, including the receptor	The Portland and Purbeck Groups are carbonates, thus there is potential for these units to have solutionally-enhanced fracture networks which are well connected. Permeability in the Wealden Group is likely to be low and dominated by intergranular flow. The Wealden Group will dominate the cumulative flow type above the hydrocarbon source unit at this point (> 50% intergranular flow) because of the large expected thickness (140 m). The Lower Greensand also has high intergranular permeability. The Gault is not a potential receptor class A to C and therefore is not included in the cumulative flow type. The Chalk also has a potential for solutionally enhanced fracture networks and is therefore likely to have well connected fractures but this will not alter the cumulative flow type of the interval above the hydrocarbon source unit due to its limited thickness in comparison to the units dominated by intergranular flow. Beneath the hydrocarbon source unit, the Kimmeridge Clay and the Kellaways and Oxford Clay Formations are not included in the groundwater flow assessment because they are not potential receptors A to C. The Corallian, Great and Inferior Oolite groups are likely to have well connected fracture networks. The Lias is expected to be fractured but not generally well connected. Beneath the hydrocarbon source unit the cumulative flow type is > 50 % well connected fractures. The confidence level for this factor is medium because there is no borehole information for most of the units.
Faults cutting intervening units and receptor	The AOI lies approximately along-strike of an east–west trending fault which appears to have offset the Wealden Group. On the 1:10,000 geological map there is a 2 km long north-northeast–south-southwest striking fault which is mapped as having offset the Chalk by about 80 m along-strike (thus this could be a normal fault or a strike slip-fault) in the southeast of the AOI. This is shown as having ~50 m vertical throw in the conceptual model in Figure A6.3 because the cross section is beyond the mapped extent of the fault and the vertical throw cannot be determined from the map. This fault is about 1 km from the hypothetical hydrocarbon activity. A number of other, north-northwest – south-southeast striking, 600 m long, faults with a similar horizontal displacement of the Chalk could cross in the far east of the along-strike cross section but there is no mapped evidence for them crossing into the AOI and they are therefore considered > 2 km from the lateral extent of the activity. There is no evidence to suggest whether the fault 1 km from the activity is transmissive. The confidence level for this factor is medium because the maps point to some evidence for faults; however they are not mapped directly within the AOI, and there is no information regarding their hydraulic properties.
Solution features in intervening units and receptor	Many of the geological units have potential for developing solution or karst features (Farrant, 2008) in the AOI due to their predominantly carbonate-based compositions. These include the hydrocarbon source unit – the Portland Group – and the Purbeck, Chalk and the Corallian groups. There are records of karst features in the Chalk Group from a nearby borehole at 56 m bgl where chippings were lost into a fracture system. Because there is no evidence to support this factor for most of the units, the confidence is medium.
Anthropogenic features-mines close to site of interest	No recorded mines in AOI. The confidence for this factor is high.

Anthropogenic features-boreholes close to site of interest	Because the hydrocarbon source unit is only 335 m below OD in the AOI, even shallow (< 100 m bgl) boreholes within the area of interest are within 600 m vertically of the hydrocarbon source unit, although no boreholes in the AOI extend to within 200 m of the hydrocarbon source unit. Three boreholes are within 0.5 km laterally of the hydrocarbon activity (the drill location). The confidence level in this factor is high.			
Potential receptor	Intrinsic vulnerability score	Specific vulnerability score	Risk group	Confidence
Chalk	41.5	83	Medium/low	Low
Gault	41.5	83	Low	
Lower Greensand	43	86	Medium/low	
Wealden Group	54	108	Low	
Purbeck Group	69.5	139	Low	
Portland Group	69.5	139	Medium/low	
Kimmeridge Clay	61.5	123	Low	
Corallian Group	37.5	75	Low	
Kellaways and Oxford Clay	36	72	Low	
Great Oolite Group	29.5	59	Low	
Inferior Oolite Group	29.5	59	Low	
Lias	28	56	Low	

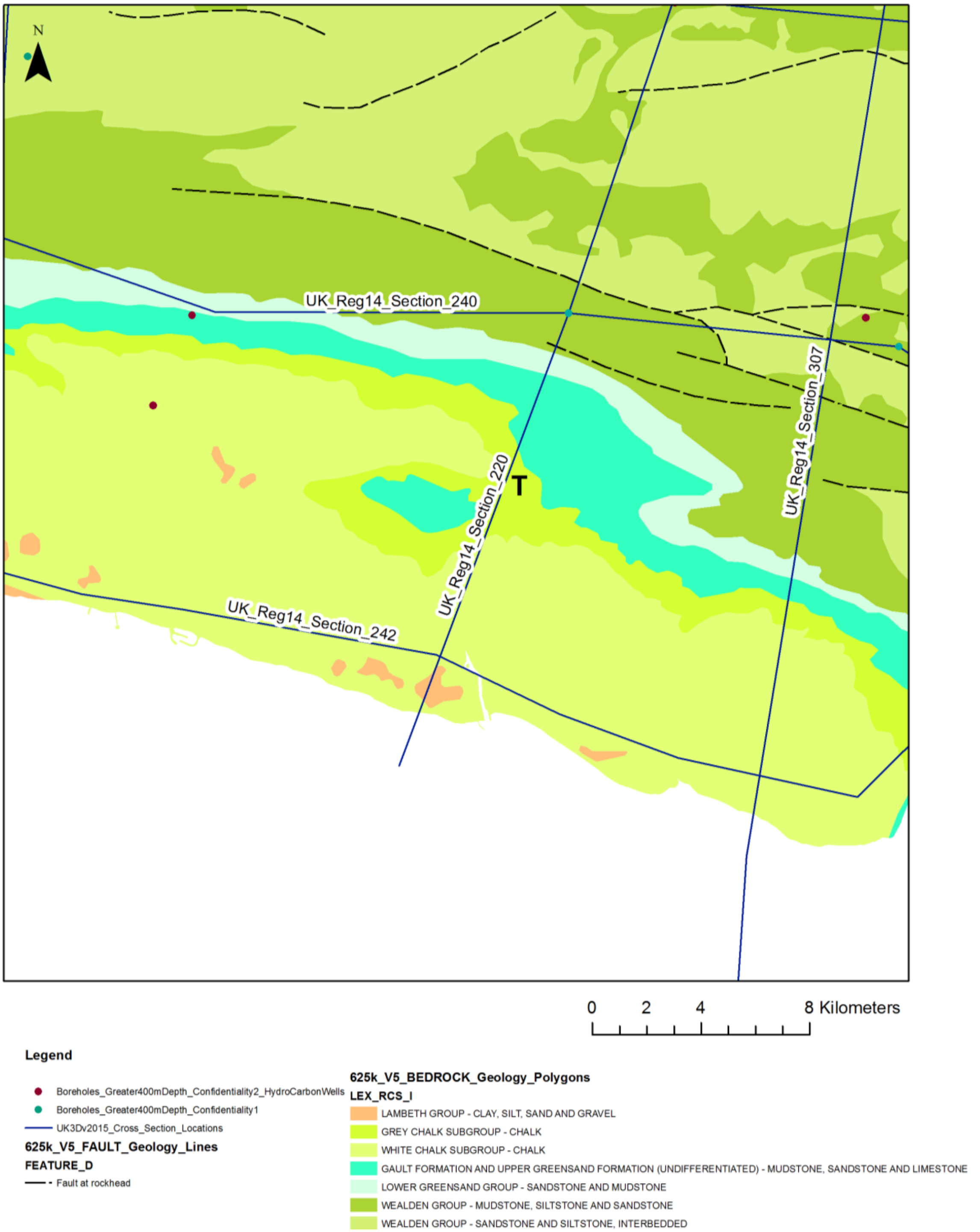

Figure A6.1 Hypothetical location of conventional hydrocarbon extraction in East Sussex with geology and LFV sections in the region. T indicates the approximate location for the hydrocarbon source unit.

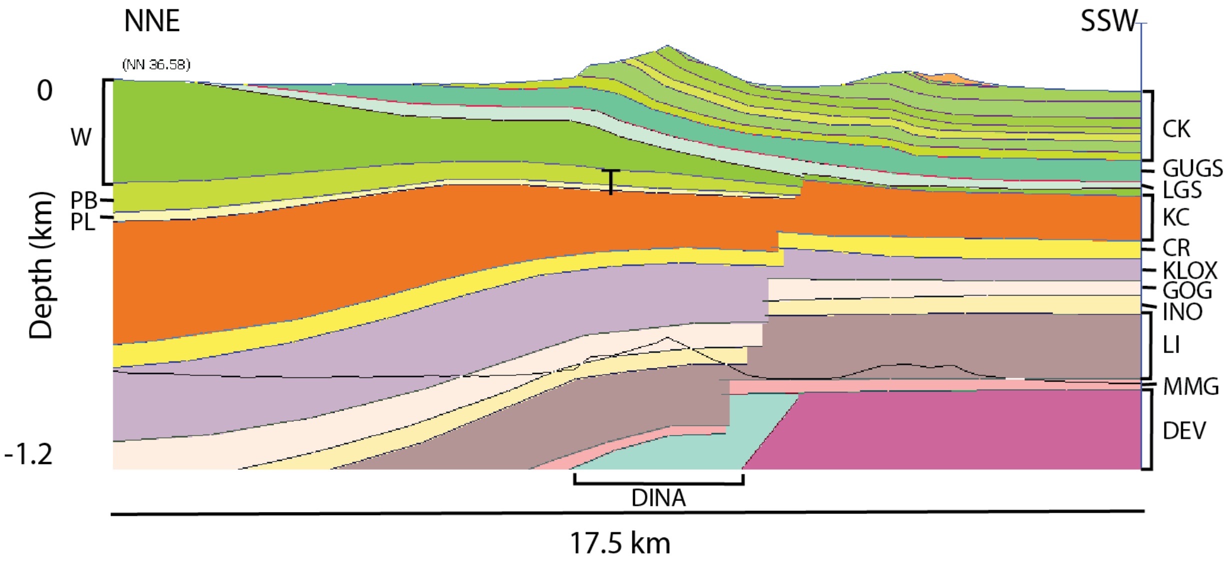

Figure A6.2 Cross section UK_Reg14_Sec220 from LithoFrame Viewer with the approximate location of the hypothetical hydrocarbon source unit area shown by 'T'. Cross section location is shown in Figure A6.1 and is across strike of the basin structure. The near horizontal black line indicates 1000 m bgl – the shallowest level allowed for shale gas activities in England and Wales. Rock codes are described in Table A6.1.

Model Unit	Age	Description
Chalk (CK)	Cretaceous	White Chalk is chalk with flint, the Grey Chalk is marly chalk.
Gault Formation (GUGS, stands for Gault and Upper Greensand formations)	Cretaceous	In this region only the Gault Formation is present, comprising clay and is silty in parts.
Lower Greensand (LGS)	Cretaceous	Glauconitic silts and sands.
Wealden Group (W)	Cretaceous	Comprises Weald Clay; clay with thin limestones and sands. Hastings Beds Subgroup; Tunbridge Wells Sands, Wadhurst Clay and Ashdown Beds.
Purbeck Group (PB)	Jurassic/ Cretaceous	Purbeck Beds, mudstones and limestones with gypsum and anhydrite at base.
Portland Group (PL)*	Jurassic	Mudstones, siltstones, sandstones and limestones.
Kimmeridge Clay Formation (KC)	Jurassic	Mudstones and cementstones.
Corallian Group (CR)	Jurassic	Mudstones, siltstones and argillaceous limestones.
Kellaways and Oxford Clay Formations (KLOX)	Jurassic	Predominantly Oxford Clay (mudstone), with underlying sandstone with silt and mudstone.
Great Oolite Group (GOG)	Jurassic	Limestones and oolites overlying argillaceous beds.
Inferior Oolite Group (INO)	Jurassic	Oolitic limestone.
Lias (Li)	Jurassic	Predominantly the Lower Lias mudstones and limestones in this area, with the Middle and Upper Lias comprising mudstones and siltstone.
Mercia Mudstone Group (MMG)	Triassic	Calcareous mudstone, mudstone and silty mudstone with subsidiary anhydrite-stone, gypsum stone, halite, sandstone and siltstone and trace breccia **.
Dinantian Rocks (DINA)	Carboniferous	Limestone and sandstone with subsidiary dolostone and mudstone .
Devonian Rocks (DEV)	Devonian	Conglomerate, limestone and mudstone**.

Table A6.1 Rock units present in the hypothetical Southeast AOI. Descriptions are from the regional guide, colours correspond with those used in the LFV section (Figure A6.2) and the AOI conceptual model (Figure A6.3). * indicates the hydrocarbon source unit. ** indicates description from BGS Lexicon, otherwise descriptions are from the BGS sheet memoir (Lake et al., 1987).

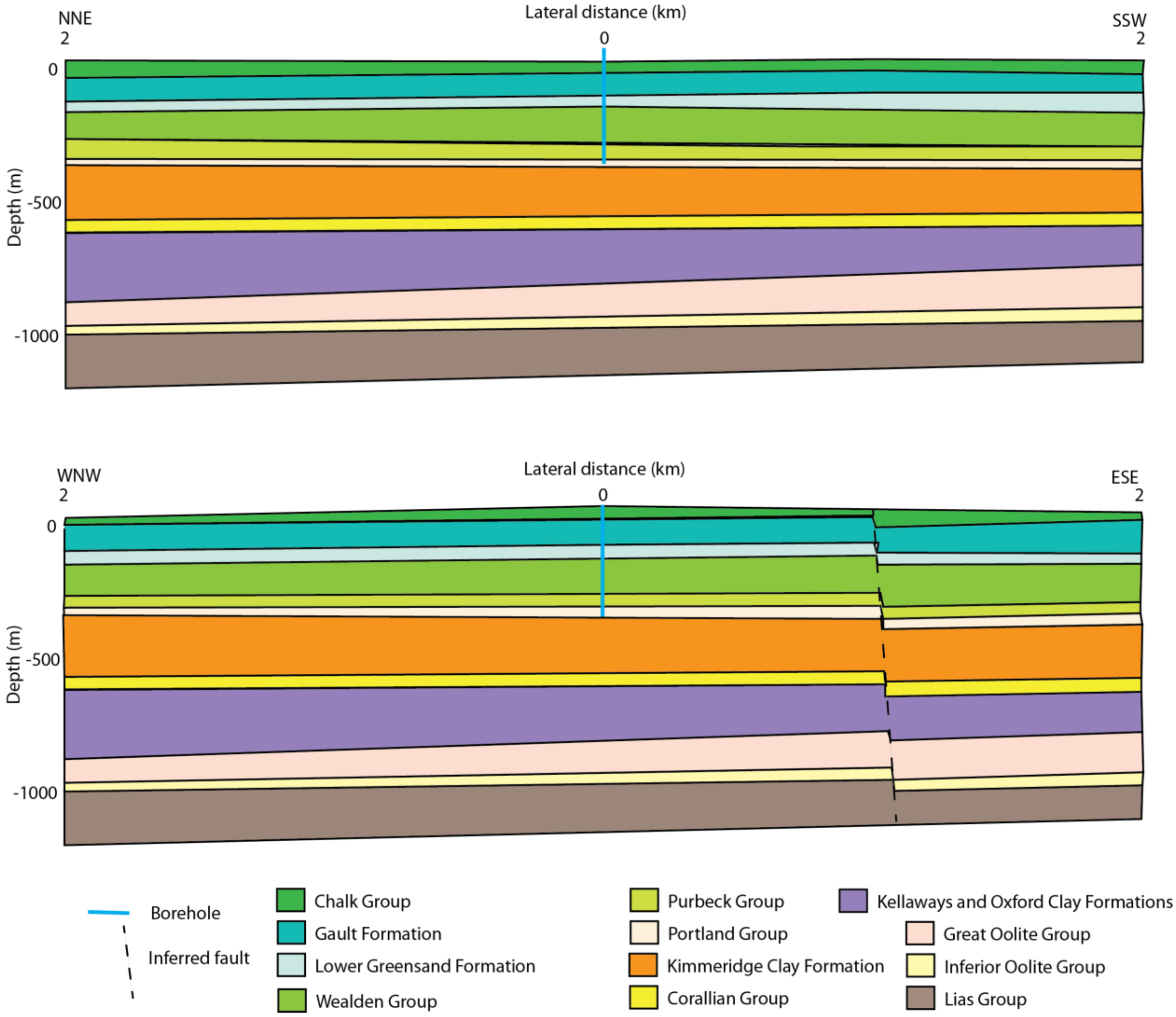

Figure A6.3 Conceptual model of the AOI for the hypothetical conventional oil and gas site in the Southeast. The hydrocarbon source unit is the Portland Group.

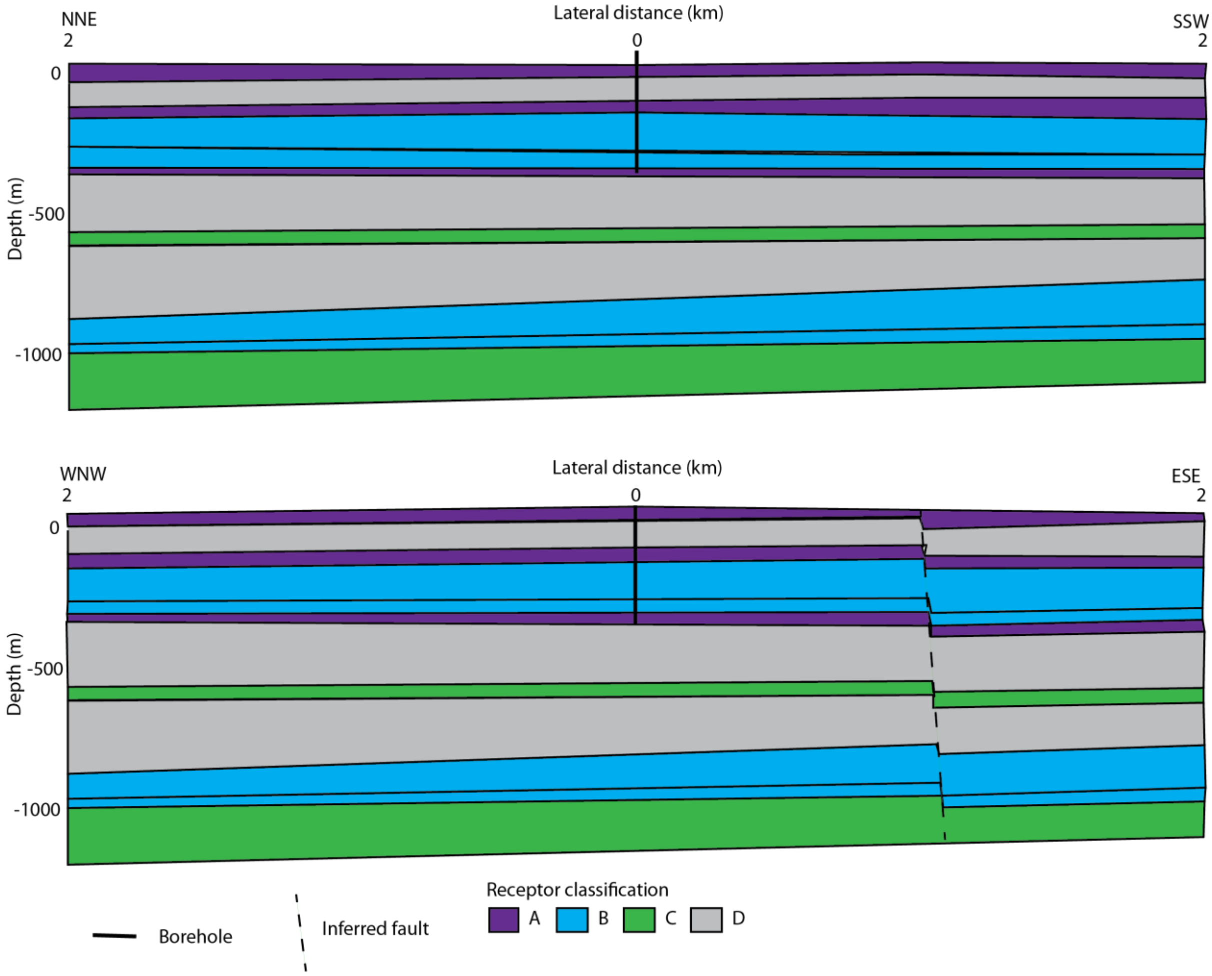

Figure A6.4 Potential receptor classifications for units within the conceptual model of the AOI.

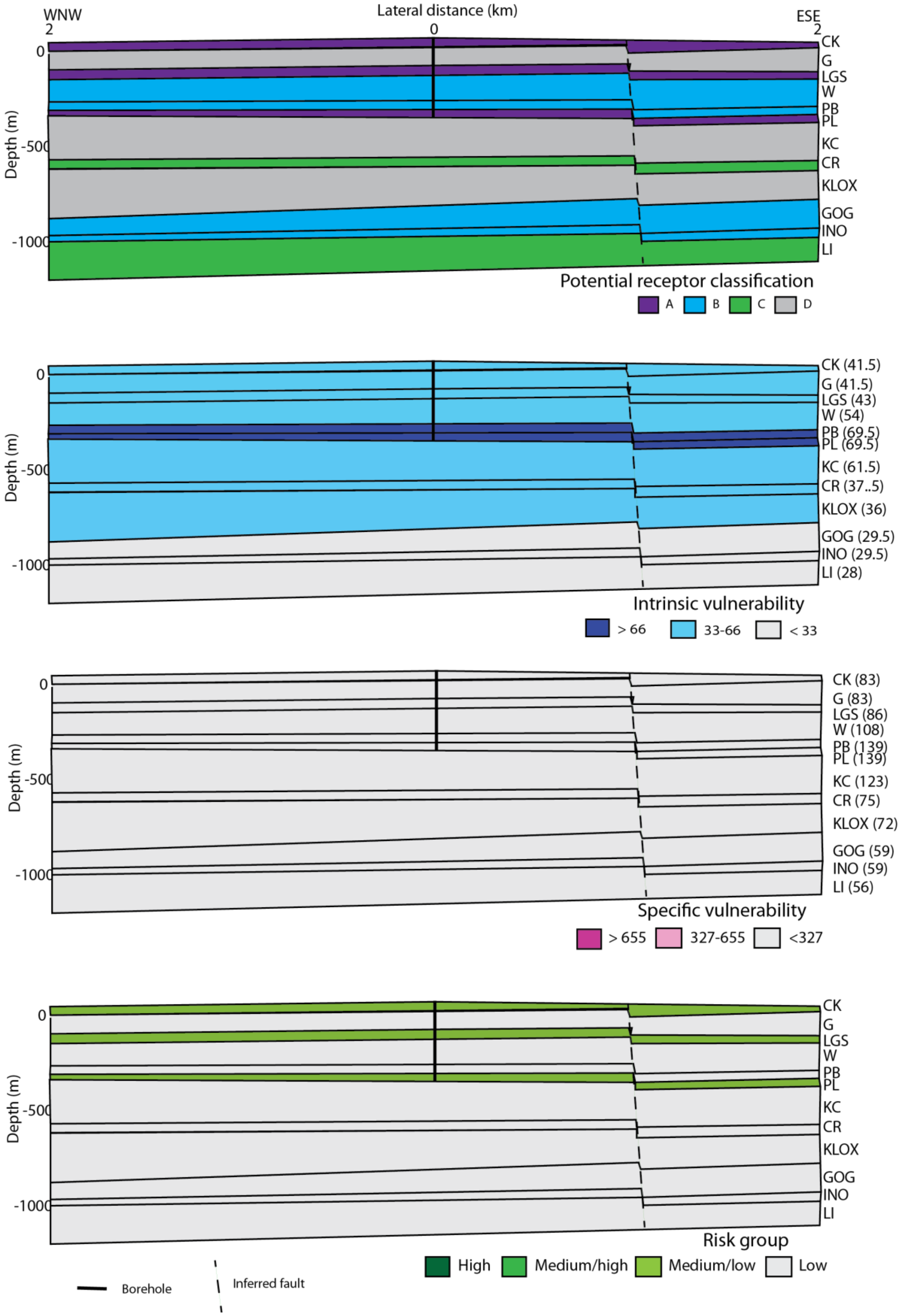

Figure A6.5 Conceptual model for the AOI in the southeast of England for potential oil and gas extraction from the Portland Group. Top to bottom; potential receptor classifications, intrinsic vulnerability scores, specific vulnerability scores and risk group for each potential receptor. See Table A6.1 for unit code translations. The confidence for this assessment is low. Boundaries used for intrinsic and specific vulnerability and risk groups are used for preliminary purposes.

Summary of case study 1: Conventional oil and gas in the southeast

- Important potential receptors are found at a range of depths, interspersed with units with lower potential receptor classifications. The hydrocarbon source unit (Portland Group) remains a potential receptor class ‘A’ as there is no information to the contrary. Nevertheless, if it is a hydrocarbon source unit the water quality within this unit is unlikely to be potable and would therefore be downgraded to a ‘B’ or, more likely, ‘C’. Large distances between the AOI and the outcrop of many of the potential receptors (up to 160 km away for the Lias) suggests that groundwater quality is likely to be relatively poor thus if there were groundwater quality data it is expected that their classification would be down-graded, and consequently also the risk group. More local information regarding the rock properties and water quality of potential receptors needs to be obtained to be confident about their classifications.
- Intrinsic vulnerability scores for the potential receptors are quite varied, ranging from 28 to 69.5 – about average for all of the case studies. The intrinsic vulnerability of units underlying the hydrocarbon source unit are lower (between 37.5 and 28), primarily due to the absence of anthropogenic disturbance by boreholes at these depths. A fault could provide a potential contamination pathway for all of the units within the AOI.
- The specific vulnerability scores for the potential receptors are low (56 to 139) as a result of the expected low hazard nature of conventional hydrocarbon extraction activities compared to other technologies. This is despite an assumed head gradient from the source to the potential receptors both above and beneath the hydrocarbon source unit. In the AOI, the risk group, which considers both the potential receptor classification and the specific vulnerability score, is medium/low for the potential receptors classified as ‘A’; the Chalk and Lower Greensand and the Portland Group. This is the lowest risk group possible for a class ‘A’ potential receptor and recognises that there is always an element of risk when interacting with the subsurface. It is important to improve the understanding of water quality of these potential receptors, since the downgrading of the units, particularly in the case of the Portland Group, to B or C would lower the risk group, which is more realistic for this unit based on the assumption that it is likely to already contain hydrocarbons. The risk group for all other potential receptors is low, due to their low specific vulnerability scores.
- The confidence level in the intrinsic vulnerability scores is low because of the uncertainty associated with the depths and thicknesses of units below the Gault. To increase the overall confidence, it would be advisable to use additional information from new boreholes, or to improve understanding of the variability of thicknesses and depths of units within the geological sequence in the region. The confidence in the head gradient is also low.
- The National Methane Baseline Survey (Bell et al., 2015) indicated that there are some naturally occurring areas of high methane concentrations in the region, specifically in the Wealden Group. It is currently unclear as to the source of this methane (biogenic or thermogenic), and it could be the Wealden Group, but methane might also have travelled from greater depth. This should be investigated further because, if the latter case, it might indicate that there are migration pathways in the region and in the AOI.

CASE STUDY 2: COAL BED METHANE, WEST MIDLANDS

Hydrocarbon source and extraction method
Pennine Coal Measures Group with 2 km lateral wells assumed in any direction. The release mechanism has been specified as CBM. Coal beds are towards the top of the Coal Measures Group.
AOI
Extending to 2 km from lateral borehole, total radius of 4 km
Geological setting
The AOI lies at the northern margin of the Cheshire Basin, north West Midlands, the approximate location is shown by the letter 'T' in Figure A6.6 and Figure A6.7. The Cheshire Basin is a deep basin underlying most of Cheshire, and towards the north under Manchester and south under Shropshire. The basin fill is primarily Permian and Triassic sandstones and mudstones, with some halite beds. The Permo-Triassic infill reaches up to 4 km depth in some places. Coal Measures of variable thickness underlie the Permian-aged rocks across much of the basin and are at outcrop around the margins of the basin. Along the northern margin of the basin the Coal Measures can be more than 1300 m in thickness. At the location of the AOI the Coal Measures are covered by Triassic aged-rocks and have a regional dip to the southeast, towards the centre of the basin. The 1:625,000 geological map shows that rocks in the area are cut by numerous north-northwest–south-southeast trending faults (Figure A6.6). The Cheshire Basin has a history of oil and gas exploration, with many formations belonging to the Sherwood Sandstone having potential as oil reservoirs (DECCa, 2013). The Mercia Mudstone (present across the centre of the basin) has been identified as having potential as an oil reservoir and source rock. The Halesowen Formation of the Warwickshire Group is a known reservoir. There is an oil seep from Westphalian-aged sandstones near Ironbridge in the Cheshire basin. The Millstone Grit is also a potential reservoir in the Cheshire basin. The Namurian Holywell/Bowland Shales of the Craven Group are source rocks in the Cheshire Basin.
Conceptual model
The geological sequence was determined from cross sections in the 3D LFV project and a number of deep boreholes north of the centre of the AOI (Figure A6.6). There were no deep boreholes to the south of the AOI and there is consequently lower confidence in the depth and thickness of units in the south. There is a high variability in the thickness and depth of geological units in the sequence which introduces greater uncertainty as to their depth and thickness. The general geological sequence and lithological descriptions are shown in Figure A6.8 and Table A6.2. The Sherwood Sandstone outcrops across the AOI. The Mercia Mudstone crops out for 0.5 km of the southerly part of the AOI. Throughout the AOI the hydrocarbon source unit and overlying units dip to the south-southeast. In the north, the hydrocarbon source unit is at depths < 400 m below OD and in the south > 1500 m below OD. The hydrocarbon source unit thickness is ~ 500 m throughout the AOI. The overlying Warwickshire Group is about 50 m in thickness, the Permian Appleby Group (Collyhurst Sandstone) is 150 m thick in the north to 300 m thick in the south, the Cumbrian Coast Group (Manchester Marls) is 100 m thick in the north to 150 m thick in the south, and the Sherwood Sandstone is from 20 m thick in the north to 1000 m thick in the south. From the west to east cross-section it can be seen that the centre of the AOI lies in a small graben. Units are shallower to the west than the east; the hydrocarbon source unit is at about 500 m below OD in the west and 1000 m below OD in the east. A number of borehole logs document faults at depth, including the fault to the west of the centre of the AOI which has about 300 m throw recorded. The Permian Appleby Group is ~50 m thinner in the west than the east, and it thickens (to ~ 300 m) into the fault immediately east of the centre of the AOI. The Warwickshire Group decreases in thickness west to east across the central graben. A number of large faults (marked on the 1:625,000 geological map) cross the AOI in a north-south direction, and are shown to cut all of the units. Two of these are also identified in borehole logs. To the west and east of the centre the faults possibly bring the Collyhurst Sandstone into horizontal contact

with the hydrocarbon source unit. Another fault runs approximately east-west about 2 km north of the AOI, the throw is thought to be smaller on this fault. The vulnerability assessment is made for the hydrocarbon source unit towards the potential receptor units overlying the hydrocarbon source unit. Due to the variability an assessment has been made for the north, centre and south of AOI.	
Baseline methane	
Bell et al. (2015) sampled two sites within the area shown in Figure A6.6, from the Sherwood Sandstone. One location is about 30 km south of the AOI and the other 25 km northeast, both of these were from the unconfined aquifer. It was found that methane concentrations were above the detection limit in the region, although well below the groundwater equivalent LEL (Section 6.1). The highest methane concentration recorded in the region was to the northeast, although this site is close to central Manchester and beneath a cover of 6 m boulder clay that could cause reducing conditions in the aquifer. However, the maximum recorded methane is well below other areas.	
Potential receptors	**Classification**
The Warwickshire Group and Cumbrian Coast Group (Manchester Marls) were classified as variable aquifers but both are designated secondary aquifers in this region. A borehole record immediately to the east of the north-south trending fault which is east of the graben (centre) records water that 'overflowed at the surface and is very saline'. A borehole in the central graben (but only 300 m from the estuary) also recorded slightly saline water (SEC at 25°C of > 7300 µS/cm, thus TDS approximately 4000 mg/l). The first borehole is 1.2 km away from the estuary. Across the fault to the west of the central graben, a borehole record states a TDS of 316 mg/l from a depth of about 60 m bgl. This suggests that there could be separation of groundwater flow across the western fault, and it may be acting as a barrier to cross-fault flow. While the evidence for differing flow systems across the north-south trending faults is limited, this conceptual model will be used to demonstrate the process and impacts of down-grading potential receptors based on groundwater chemistry. Here, potential receptors classified as 'A' on the east of the western fault have been downgraded to potential receptor class 'B'. Evidence suggests that this would not be appropriate west of the fault, and the salinity of groundwater north of the east-west trending fault is not known therefore potential receptors have not been downgraded here either (Figure A6.9).	
Mercia Mudstone Group	B – secondary aquifer, < 400 m bgl
Sherwood Sandstone Group	A – principal aquifer, < 400 m bgl but B east of western fault due to recorded salinity
Cumbrian Coast Group	B – secondary aquifer, < 400 m bgl
Appleby Group	A – principal aquifer, < 400 m bgl but B east of western fault due to recorded salinity
Warwickshire Group	C secondary aquifer, > 400 m bgl
Pennine Middle Coal Measures Group	C (secondary aquifer, > 400 m bgl)
Millstone Grit Group	C (secondary aquifer, > 400 m bgl)
Craven Group	C (secondary aquifer, > 400 m bgl)
Hazard	**Score**
Release mechanism of hydrocarbon	Water table lowering and depressurisation (CBM)
Head gradient driving flow	A borehole record from the east of the eastern north-south fault states that groundwater 'overflowed at surface and is very saline' (the formation is not stated). Although the source of this water is not known, there could be upwards flow from the hydrocarbon source unit formation towards the overlying potential receptors.

	Downing et al. (1987) state that the Permo-Triassic sandstone of the Mersey Valley (which the AOI is located within) is one of the main outlets for groundwater in the northwest of England. However there is limited direct evidence for flow from the Upper Palaeozoic rocks into the Permo-Triassic sandstones. There is also no evidence for a heat flow anomaly in the Cheshire Basin, suggesting that there is not significant rising groundwater. This supports the hypothesis that the regional groundwater flow in the Cheshire Basin is primarily around deeper parts of the basin in essentially horizontal directions towards outlets in the Mersey Estuary (Downing et al., 1987). However, the AOI is on the north side of the Mersey Estuary, and groundwater is more likely to flow from the north. It is also possible that the fault between the borehole and the site of interest leads to different groundwater flow patterns. It is not clear if groundwater flow is still in an upwards direction from the underlying potential receptors to the source. Therefore, a worst case scenario with, groundwater head direction from the hydrocarbon source unit towards potential receptors, is assumed.
Intrinsic vulnerability	
Vertical separation distance between source and base of receptor	There are better controls on the depth of the units in the north of the AOI than in the south due to the presence of a number of boreholes in the Coal Measures. However, there is a lot of variability in the depth and thickness of units in the AOI due to a number of faults, and the impact of these is not completely known. There is a large difference in the depth and thickness of units from the north to the south, and so the vulnerability assessment was conducted in the centre, the north and the south of the AOI. In the north of the AOI, the hydrocarbon source unit occurs at shallower depths than in the centre (500 m below OD versus 1000 m below OD). Therefore, an assessment has also been made for the underlying Millstone Grit in the north. In this case, vertical separation is calculated between the base of the hydrocarbon source unit and the top of the Millstone Grit. Here, it is 0 m because the Millstone Grit directly underlies the hydrocarbon source unit. The confidence levels attributed to the assessments in the centre and north of the AOI are medium, since there is some borehole control, but also a high degree of variability. However, the confidence attributed to the assessment in the south of the AOI is low because of a lack of borehole information and assumed high variability.
Lateral separation distance between source and receptor	The Cumbrian Coast, Appleby, Warwickshire groups and Upper Coal Measures Formation are brought to the same horizontal level as the hydrocarbon source unit within 0.2 km of the sub-surface activities due to the regional dip to the south (Figure A6.8). The other units are not expected to be at the same horizontal level within the AOI. The confidence level for this factor is medium and is dependent on the conceptual model.
Mudstones and clays in intervening units between source and receptor	The composition of the units was assessed from borehole records and the regional guide. Units directly above or below the hydrocarbon source unit are not separated by any intervening units. Above the hydrocarbon source unit, the Upper Coal Measures and Warwickshire Group have been assessed as being approximately 50% mudstone. The Appleby Group in this area comprises the

	Collyhurst Sandstone – a coarse-grained sandstone. The Cumbrian Coast Group comprises the Manchester Marl. The Sherwood Sandstone comprises predominantly sandstones. There are no boreholes penetrating the Millstone Grit, and it is assumed from regional information that this unit is 50% mudstone. In the centre of the AOI, the Sherwood Sandstone has up to 350 m mudstone in the intervening unit between it and the hydrocarbon source unit, resulting from the thick Manchester Marls and the variable composition of the Coal Measures (including the Warwickshire Group). In the north of the AOI, the intervening mudstone thickness is only 230 m. The confidence level for this factor is medium because there are a number of borehole logs nearby which indicate the unit lithologies but this factor is also dependent on the thickness of the units.
Groundwater flow mechanism in intervening units between source and receptor, including the receptor	The Sherwood Sandstone and Appleby Group (Collyhurst Sandstone) are expected to be dominated by intergranular flow. The finer grained and older units (the Cumbrian Coast, Coal Measures and the Millstone Grit groups) are likely to be dominated by poorly connected fracture flow. The dominant flow type changes from > 50% fractured, poorly connected or mixed fracture and intergranular flow below the Sherwood Sandstone to > 50% inter-granular flow for the Sherwood Sandstone.
Faults cutting intervening units and receptor	A number of large faults (marked on the 1:625 000 geological map) cross the AOI in a north-south direction, and are shown to cut all of the units. Two of these are identified in borehole logs. Another fault runs approximately east-west about 2 km north of the AOI; the throw is thought to be smaller on this fault. The closest mapped fault is about 0.5 km to the east of the centre. The confidence level for this factor is high.
Solution features in intervening units and receptor	The only unit which is specified as having potential solution features in the AOI is the Mercia Mudstone. This is known to contain halite and gypsum in the Cheshire Basin. However, this is only present at the southern boundary of the AOI and will not impact the units below. A borehole record at the northern boundary of the AOI reports a cavity within the Bunter (Sherwood) Sandstone. The cause of this cavity is not reported and it is not clear from the log whether halite or gypsum are present, although these are a possibility in Triassic units. It will, therefore, be assumed that there could be solution features in this unit but this will have a low confidence level.
Anthropogenic features-mines close to site of interest	There are mines recorded in the northern part of the AOI. The confidence in this factor is high.
Anthropogenic features-boreholes close to site of interest	There are many boreholes within 0.5 km of the AOI including one within 200 m vertical distance from the hydrocarbon source unit, as determined from the borehole layer in the GIS project. The confidence level in this factor is high.

Potential receptor	Intrinsic vulnerability score	Specific vulnerability score	Risk group	Confidence
		North		
Sherwood Sandstone Group	57.5	230	Medium/low	Low
Cumbrian Coast Group	58	232	Low	
Appleby Group	76.5	306	Medium/low	
Warwickshire Group	76.5	306	Medium/low	

Pennine Upper Coal Measures Group	85	340	Low	
Millstone Grit Group	85	340	Low	
South				
Mercia Mudstone Group	44.5	178	Low	Low
Sherwood Sandstone Group	51	204	Low	
Cumbrian Coast Group	51.5	206	Low	
Appleby Group	68.5	274	Medium/low	
Warwickshire Group	70	280	Medium/low	
Pennine Upper Coal Measures Group	85	340	Low	

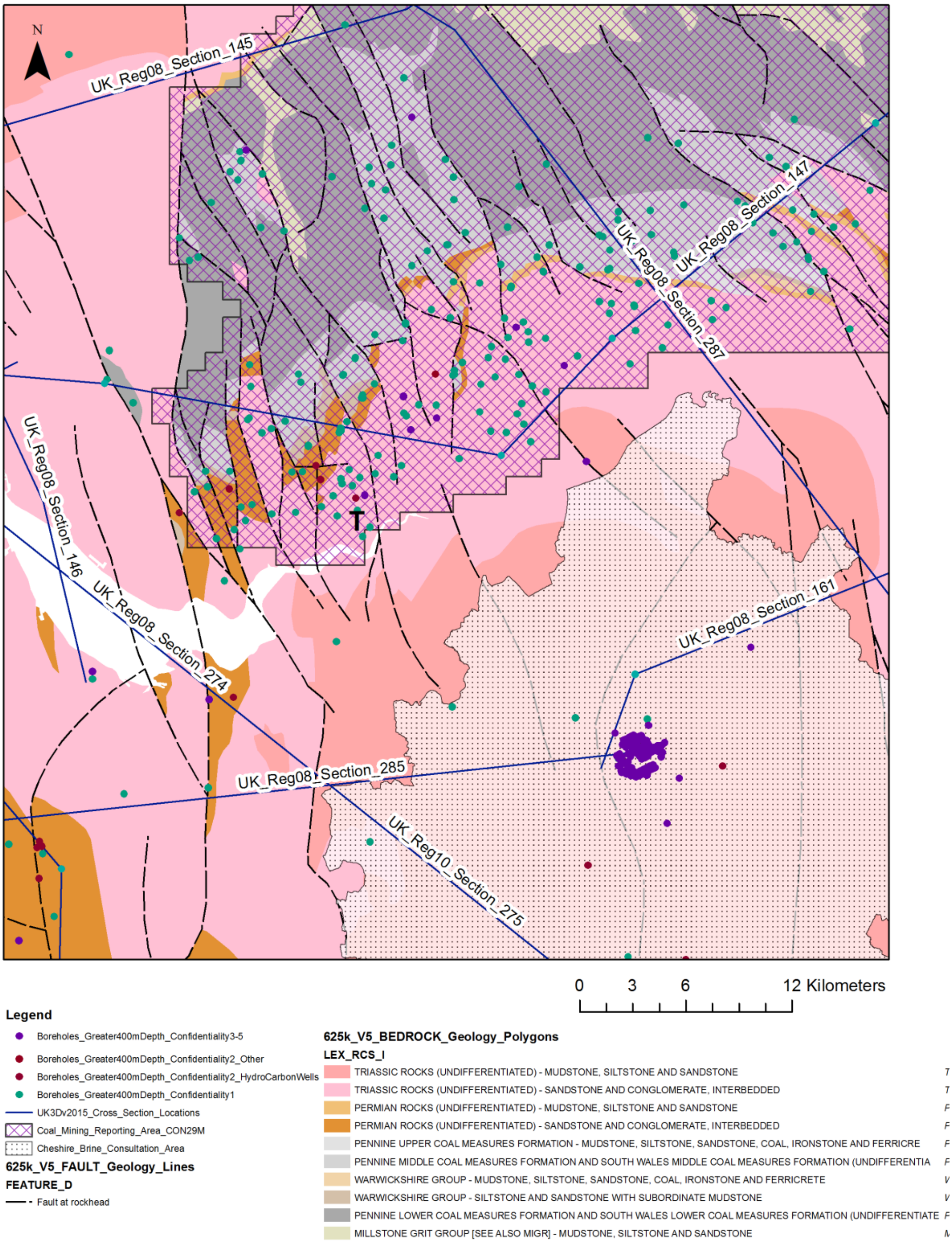

Figure A6.6 Hypothetical location of CBM extraction in the West Midlands with geology and LFV sections in the region. T indicates the approximate location for the hydrocarbon source unit.

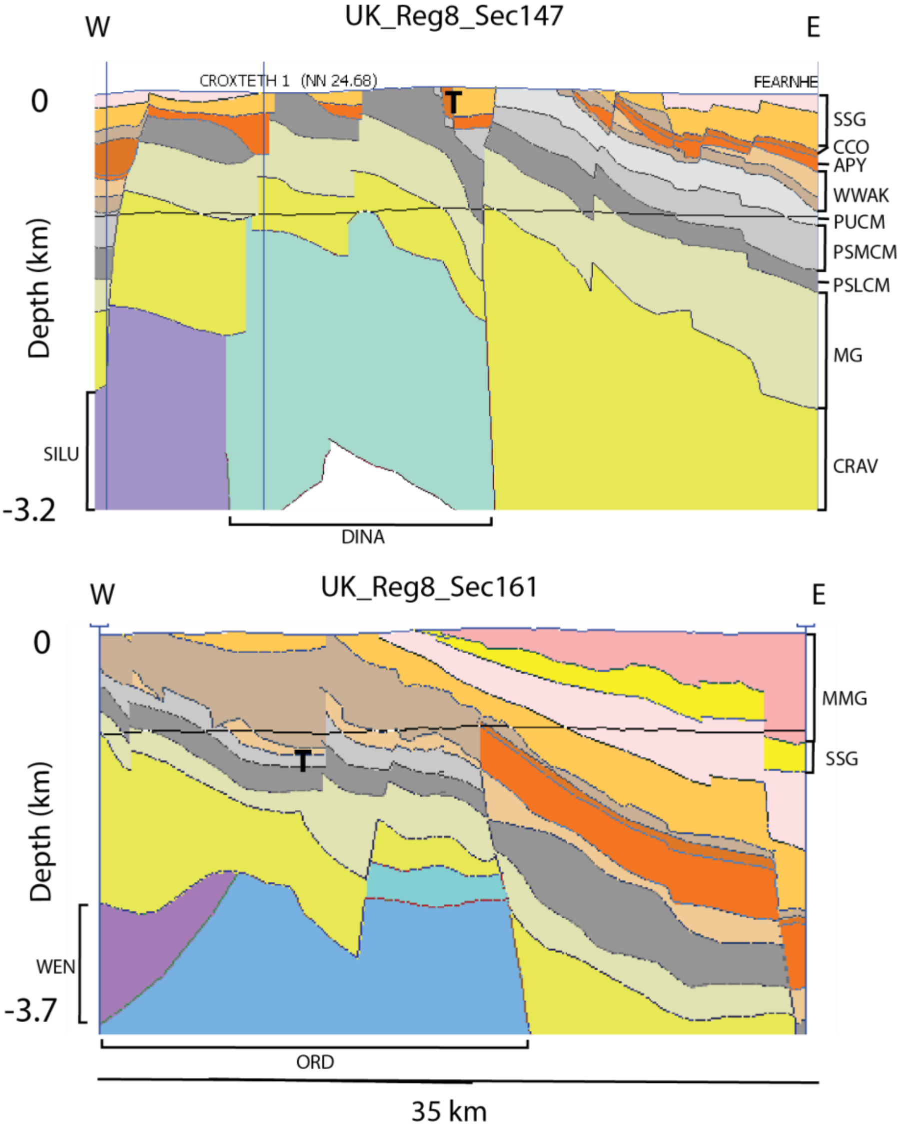

Figure A6.7 LFV sections with the case study site in the West Midlands for CBM along strike of 'T'. The hydrocarbon source unit is the Pennine Middle Coal Measures Formation (PMCM). See Table A6.1 for units described by codes, WEN is Wenlock rocks and ORD is Ordivician rocks. The near horizontal black line indicates 1000 m bgl, the shallowest level allowed for shale gas exploitation in England and Wales.

Model Unit	Age	Description
Mercia Mudstone Group (MMG)	Triassic	Mudstone and siltstone, gypsiferous
Sherwood Sandstone Group (SSG)	Triassic	Comprises the Helsby Sandstone Formation (sandstone, slightly or well cemented), Wilmslow Sandstone Formation (sandstone, slightly cemented), Chester Pebble Beds Formation (sandstone with pebbles, moderately cemented), Kinnerton Sandstone Formation (sandstone, slightly cemented)
Cumbrian Coast Group (CCO)	Permian	Comprises the Manchester Marls Formation (mudstone, gypsiferous)
Appleby Group (APY)	Permian	Comprises Collyhurst Sandstone Formation (coarse-grained sandstone)
Warwickshire Group (WWAK)	Carboniferous	Mottled mudstone with common beds of sandstone, and Etruria Marl Formation (fine-grained mudstone)
Pennine Coal Measures Group* (PUCM/ PMCM/ PLCM)	Carboniferous	Mudstone, sandstone seatearth and coal.
Millstone Grit Group (MG)	Carboniferous	Sandstone with mudstone common throughout.

Table A6.2 Rock units present in the hypothetical West Midlands AOI. Descriptions are from the sheet memoir, colours correspond with those used in the LFV sections (Figure A6.7) and the AOI conceptual model (Figure A6.8). * indicates the hydrocarbon source unit.

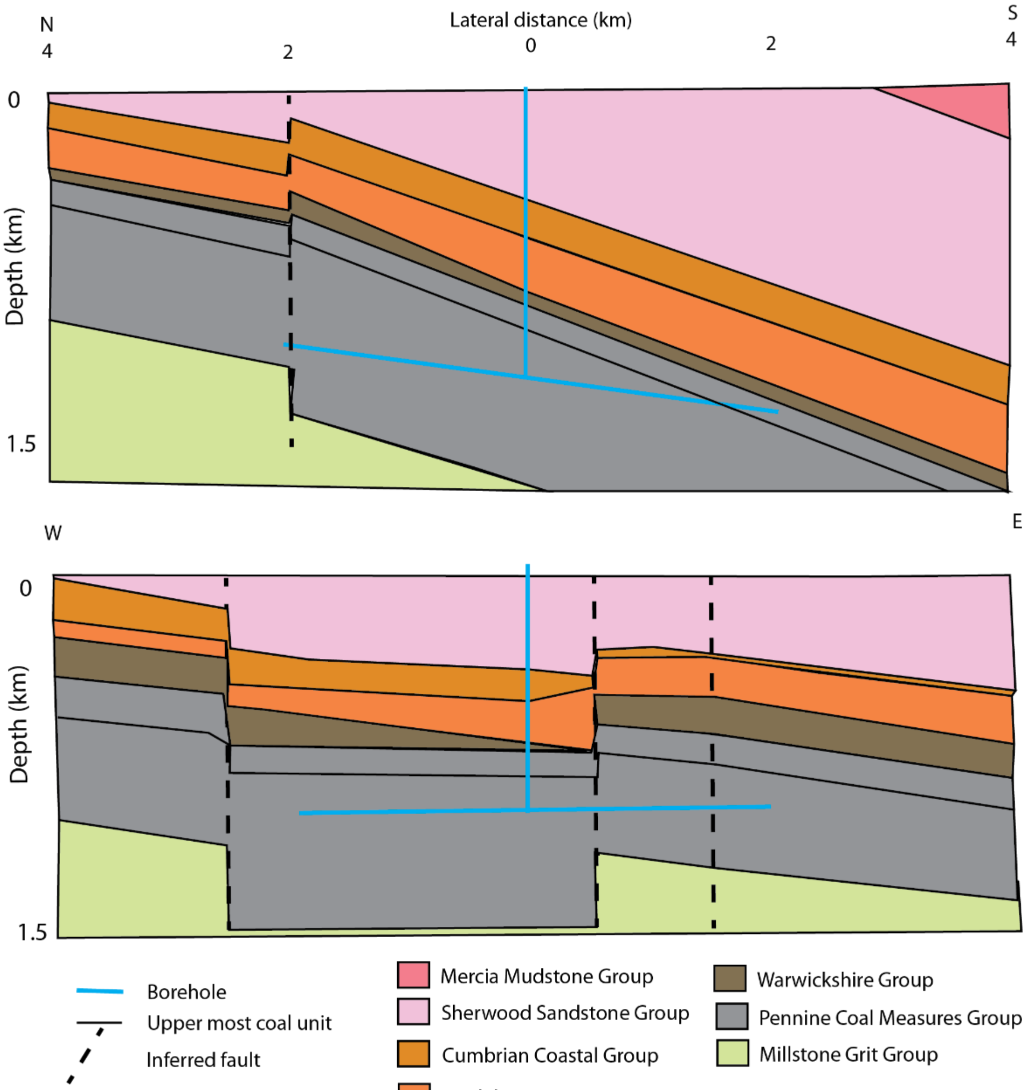

Figure A6.8 Conceptual model of the AOI for the hypothetical CBM site in the West Midlands. The hydrocarbon source unit is the Pennine Coal Measures Group.

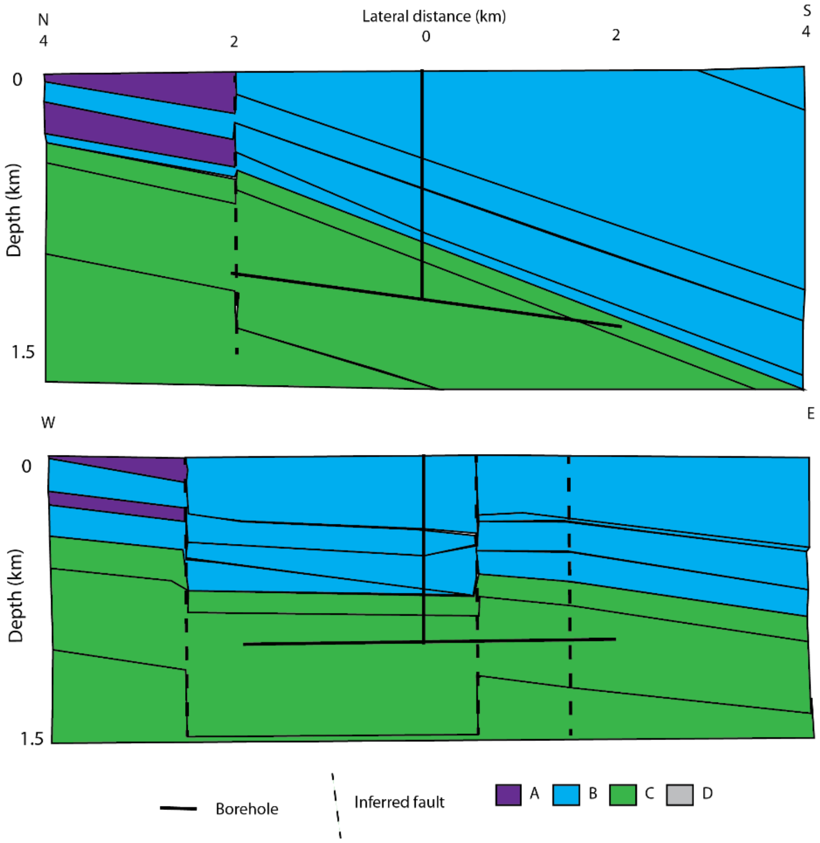

Figure A6.9 Receptor classifications for units within the conceptual model of the AOI in the West Midlands.

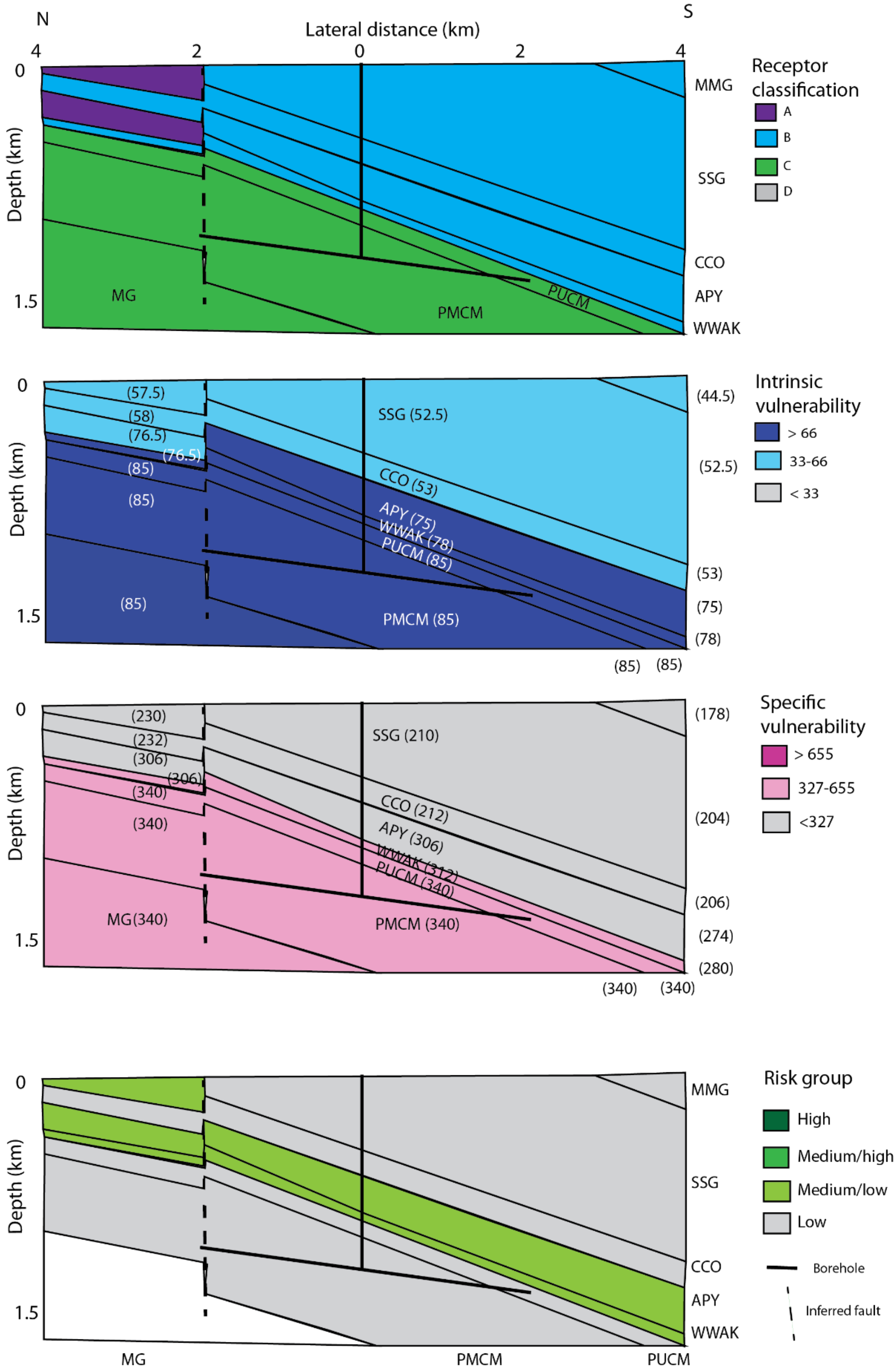

Figure A6.10 Conceptual model for the AOI in the West Midlands of England for CBM from the Pennine Coal Measures Group. Top to bottom; potential receptor classifications, intrinsic vulnerability scores, specific vulnerability scores and risk group for each potential receptor. Intrinsic vulnerability scores are provided for the north, centre and south of the AOI. The risk group is only shown for the centre. See Table A6.2 for unit code translations. The confidence for this assessment is low. Boundaries used for intrinsic and specific vulnerability and risk groups are used for preliminary purposes.

Summary for Case Study 2: Coal bed methane, West Midlands

- In the AOI the Sherwood Sandstone and the Appleby Group (Collyhurst Sandstone) have been downgraded from potential receptor class ‘A’ to ‘B’ in the south and east, based on borehole evidence of water chemistry. Evidence suggests that this would not be appropriate west of the fault. The salinity of groundwater north of the east-west trending fault is not known; therefore potential receptors have not been downgraded here either. More information is needed to be certain of these classifications. Intrinsic vulnerability scores are relatively high for all of the potential receptors, ranging from 85 to 44.5 resulting from the limited vertical separation between the Pennine Middle Coal Measures Formation and the potential receptors. The depth of the Coal Measures varies from 500 m below OD in the north to 1000 m below OD in the south, resulting in an intrinsic vulnerability score difference of up to 5 for the units furthest from the hydrocarbon source unit. However, this does not change the intrinsic vulnerability categories for the potential receptors with these preliminary boundaries.
- The specific vulnerability scores for the potential receptors are lower (178 to 340) as a result of the assumed relatively low hazard nature of CBM activities, despite an assumed head gradient from the source to the potential receptors.
- The risk group, for the potential receptors classified as ‘A’ (the Sherwood Sandstone and the Appleby Group to the north and west) is medium/low but where these units are downgraded to potential receptor class ‘B’, they are in the low risk group, indicating the importance of correct potential receptor classification.
- The difference in hydrocarbon source unit depth of 500 m does not change the risk group of the units but does change the specific vulnerability scores. The assessment would improve from a greater understanding of the head distribution and groundwater flow paths and from further identification of faults and fault behaviour in the region, in addition to understanding the geological variability. It should be noted that The National Methane Baseline Survey (Bell et al., 2015) did not observe areas of high naturally occurring methane concentrations in aquifers in the region.

CASE STUDY 3: COAL BED METHANE, EAST MIDLANDS

Hydrocarbon source and extraction method
Pennine Coal Measures Group, for CBM, Nottinghamshire with 2 km lateral wells (Figure A6.11). Here, the Pennine Coal Measures Group comprises the Pennine Lower and Middle Coal Measures Formations. The top of the hydrocarbon source unit is identified as the uppermost point in the Pennine Coal Measures in which coal seams begin to increase in prevalence within the succession.
AOI
Extending to a distance 2 km from lateral boreholes.
Geological setting
East Midlands region of the Carboniferous-aged Pennine Basin, which stretches from the Midlands to the Scottish Border (T in Figure A6.11, middle of the cross sections in Figure A6.12). The region has a history of conventional oil and gas extraction and coal mining and has been extensively explored with boreholes and seismic surveys. Carboniferous and older rocks become deeper eastwards from the Pennines where they are at the surface, towards the North Sea where they are overlain by post Carboniferous rocks which also dip to the east. Coal Measures are thicker in the west than the east (>1000 m compared with ~200 m in some places in the east). The maximum depth of the Coal Measures from east to west is quite constant (~ 700 m); however the unit deepens slightly to the northeast, reaching 900 m below OD. The AOI is located 11 km to the east of the outcrop of the Pennine Coal Measures Group (Figure A6.11). Below the Coal Measures are the Craven Group and Millstone Grit Group (both Carboniferous-age) which can reach thicknesses of 1400 m and 500 m, respectively, but are closer to 50 m in thickness in the east, above the Eakring Anticline (Figure A6.12). The Permian and younger rocks overlying the Coal Measures dip gently to the east towards the North Sea and retain relatively uniform thicknesses (Figure A6.12). The base of this sequence outcrops just east of the line of section UK_Reg8_Sec143. The lowest unit in the succession is a thin (< 5 m thick) unit of Permian Basal Breccia which overlies the Carboniferous age rocks (although it is not possible to see this in the sections due to its thinness). Over most of the area the Zechstein Group overlies this unit (< 150 m thick), although it is thinner and sometimes absent in the south. Overlying this is the Triassic Sherwood Sandstone (~150 m in thickness). This is the second most important aquifer in the UK. To the east of the AOI the Sherwood Sandstone is overlain by the largely low permeability Mercia Mudstone (~140 m thick).
Conceptual model
The conceptual geological model for the AOI across (west-east) and down dip is shown in Figure A6.13. Because the AOI is not close to any of the LFV sections (Figure A6.11), these were only used to gain an understanding of the regional geology. More detailed information was obtained from three deep boreholes within the AOI (Figure A6.11); one 4 km to the north-northwest, one 1.5 km to the southwest and one 1.5 km to the northeast. The general geological sequence and unit descriptions are shown in Table A6.3. The Pennine Middle Coal Measures Formation and the Pennine Lower Coal Measures Formation are combined in this analysis as the Pennine Coal Measures Group. The upper units of the Coal Measures only have occasional coal beds. The frequency of recorded coal beds increases between ~200 and 400 m bgl indicating the location of the hydrocarbon source unit interval. However, there is no conclusive evidence for a systematic variability in the depth of increased coal occurrence across the AOI. Therefore, while a depth of 300 m to the top of the hydrocarbon source unit interval has been used in the 'best-guess' conceptual model, scenarios in which the top is at a depth of 200 m and 400 m were also tested. The total thickness of the Coal Measures varies between 700 m in the north and west, and 300 m east of the centre of the AOI. The base of the Coal Measures is likely to have a maximum depth of ~ 900 m and a minimum depth of 500 m, being shallower in the east and south.

In the conceptual model, a thin (~ 2 m in thickness at the hypothesised borehole location) unit of Permian Basal Breccia overlies the Coal Measures (this unit is too thin to see at the scale of the conceptual diagrams and cross sections). It thickens (up to 5 m) to the west and is not present towards the east. Overlying the Permian Basal Breccia is the Zechstein Group (described as Permian Marls in the borehole logs), which has a fairly uniform thickness of about 50 m across the AOI. This unit dips to the east along with the overlying Sherwood Sandstone. The Sherwood Sandstone thickens from about 200 m in the west to 300 m in the east and it is overlain by up to 200 m of the Mercia Mudstone in the east of the AOI. Vulnerability has also been assessed for the underlying strata. Since no boreholes penetrate these units in the AOI there is a very high level of uncertainty regarding their thickness and depth. Nevertheless, they are thought to become shallower to the east over the Eakring Anticline. The Millstone Grit underlies the Coal Measures and varies from 300 m in thickness in the north to 50 m in the south, and is located at a depth of 900 m bgl to 500 m bgl. The Craven Group varies from 500 m to 200 m in thickness and 1200 m to 700 m bgl in depth. The geological map (1:50 000) shows an inferred 600 m-long fault about 500 m to the southeast of the hypothetical drilling site, although it is not clear which of the geological units it cuts. In addition, sections UK_Reg8_Sec287 and 171 show that a large fault could pass ~ 1 km to the east of the drilling site, cutting from the basement to the base of the Pennine Middle Coal Measures with an offset of up to 400 m. Another fault passes about 200 m to the west of the site and cuts from the basement to the base of the Pennine Lower Coal Measures.	
Baseline methane	
Bell et al. (2015) sampled for methane concentrations in aquifers in the East Midlands. Samples from 14 sites were collected from the area shown in Figure A6.11, from the Pennine Coal Measures Group, Zechstein Group and Sherwood Sandstone Group. One location is very close to the AOI. Bell et al. (2015) found that methane concentrations were above the detection limit in all aquifers, but none exceeded the groundwater equivalent LEL (Section 6.1) and very few exceeded 10 µg/l. In the area, methane concentrations were generally lowest in the Sherwood Sandstone. Very slightly higher methane concentrations were noted in the confined compared with the unconfined Sherwood Sandstone aquifer, although the highest concentration (465 µg/l) was from the unconfined aquifer. This is thought to be due to the reducing conditions beneath the thick glacial sediment cover which are conducive to elevated methane concentrations. There are no glacial deposits present in the AOI.	
Potential receptors	**Classification**
Where model units were classified as variable aquifers in the LFV project (Figure A6.12) (the Mercia Mudstone and Zechstein Group), the EA aquifer designation maps were used to identify the designation based on the closest outcrop to the AOI.	
Mercia Mudstone Group	B - secondary aquifer, top of the unit < 400 m bgl.
Sherwood Sandstone Group	A - principal aquifer, top of unit < 400 m bgl. Classification supported by electrical conductivity of 640 µS/cm at 60 m bgl within 10 km of the AOI.
Zechstein Group	A – principal aquifer, tops of the unit < 400 m bgl.
Permian Basal Breccia	A – principal aquifer, tops of the unit < 400 m bgl.
Pennine Middle Coal Measures Group	B – secondary aquifer, top of the unit is < 400 m bgl.
Millstone Grit Group	C - secondary aquifer, top of the unit is > 400 m bgl.
Craven Group	C – secondary aquifer, top of the unit is > 400 m bgl.
Hazard	**Score**

Release mechanism of hydrocarbon	Water table lowering and depressurisation (CBM)
Head gradient driving flow	No direct information in the AOI or region. Bullard and Niblett (1951) found an elevated heat flow in six boreholes, over the Eakring Anticline, 10 km to the northeast of the AOI. This heat flow anomaly was not present under the Kelham Hills to the south. They concluded that this is more likely to be from heat transport from groundwater which has recharged the Carboniferous Limestones in the Pennines to the west and flowed through fissures eastwards to Eakring where it is forced upwards over the anticline. They calculate that the measured heat flow could be achieved with waters flowing over thousands of years through rocks with only a 1% porosity. The relatively low TDS (3262 mg/l) of waters in the Carboniferous Limestones shown at Mansfield Number 1 borehole at 1329 m bgl, might also indicate a relatively short residence time and flow within these rocks. The Eakring Anticline is 10 km to the northeast of the AOI; however the conceptual models indicate that the Carboniferous-aged rocks become shallower towards the east and therefore there is a chance that the waters begin to rise in this area. A borehole at Popplewick, 4 km to the south of the AOI shows an elevated geothermal gradient in the Coal Measures which might indicate upwards fluid flows. Nevertheless, temperatures measured in the Blidworth Colliery indicate a low geothermal gradient (22.9°C/km), although this may be due to local flow pathway perturbations caused by the collieries. Because of the uncertainty and chance that there could be upward flow in the AOI an upwards head gradient is assumed as a worst case scenario. The confidence in this is medium.
Intrinsic vulnerability	
Vertical separation distance between source and base of receptor	Borehole logs indicate that the top of the hydrocarbon source unit interval is highly variable in the AOI so vulnerability assessments were conducted for three separation scenarios; scenario 1 was the 'best guess', with the top of the hydrocarbon source unit at 300 m bgl, scenario 2 was a worst case scenario with the top of the hydrocarbon source unit at 200 m bgl, and scenario 3 was a best case scenario with the top of the hydrocarbon source unit at 400 m bgl. The depth of potential receptor units overlying the hydrocarbon source unit are relatively well known in the area due to their limited lateral variability and the availability of records from a number of boreholes. For potential receptor units underlying the hydrocarbon source unit (Millstone Grit and Craven Group) it was assumed that the coals could be exploited to the base of the unit. Very few boreholes penetrate units below the Coal Measures and therefore the depths of these units are not well constrained. The Mercia Mudstone was included in the vulnerability assessment since this is present in the eastern part of the AOI. However the vertical separation was not calculated since is not expected to directly overlie the activity. The confidence in this factor is low due to the unknown depth to the top of the hydrocarbon source unit interval and to the depths of the units that are underlying the hydrocarbon source unit.
Lateral separation distance between source and receptor	In the AOI the lateral separation does not apply to most units. However, there is a fault which brings the Craven Group into contact with the Coal Measures below the area of proposed activity. The Mercia Mudstone occurs within 2 km of the lateral sub-surface extension of the activity and has therefore been given a lateral separation.

	The confidence for this factor is medium because there is less variability across the AOI.
Mudstones and clays in intervening units between source and receptor	The thickness of mudstones and clays in the intervening layer was calculated according to the average composition of the interval based on the borehole logs. Above the hydrocarbon source unit the Coal Measures contain a high proportion (80%) of mudstone which provides a large thickness of intervening mudstones between the hydrocarbon source unit and the potential receptors. Borehole records indicate that the Zechstein Group is also comprised predominantly of marl in this area, and so it is considered a mudstone. The borehole record from the Mansfield number 1 borehole indicates a very high proportion of the Millstone Grit is shale. The shale content has been estimated as 90% providing roughly 270 m of mudstone/clay in between the hydrocarbon source unit and the Craven Group. The confidence for this factor is medium because there are borehole logs which provide an indication of the unit's composition nearby.
Groundwater flow mechanism in intervening units between source and receptor, including the receptor	Groundwater flow is likely to be intergranular in the Sherwood Sandstone and Basal Permian Breccia. In the Zechstein Group groundwater flow through fractures is more common, but fractures are not likely to be well connected in the marls. Fractures are also known to control groundwater flow in the Coal Measures and older units. These are also likely to be poorly connected. Overall, poorly connected fractures dominate groundwater flow in this sequence upwards until it reaches the Sherwood Sandstone where intergranular flow becomes an important flow mechanism and flow changes to mixed-fracture and intergranular. The confidence for this factor is medium.
Faults cutting intervening units and receptor	An inferred 600 m-long fault runs about 500 m to the southeast of the hypothetical drilling site. It is not clear which units it cuts. In addition, sections UK_Reg8_Sec287 and 171 show that a large fault could pass ~ 1 km to the east of the drilling site, cutting from the basement to the base of the Pennine Middle Coal Measures with an offset of up to 400 m. Another fault passes about 200 m to the west of the site and cuts from the basement to the base of the Pennine Lower Coal Measures. There is no evidence to suggest that any of these faults are transmissive. The confidence for this factor is medium.
Solution features in intervening units and receptor	In some places, the Edlington Formation of the Zechstein Group, present in the AOI, can have solution features developed in anhydrite and gypsum beds. However, there is no direct evidence for anhydrites or gypsum beds in the Nottinghamshire area (Bullard et al., 1951) or in the surrounding boreholes. Other units are unlikely to have solution features; therefore all units have been classified as having no potential solution features. The confidence for this factor is medium.
Anthropogenic features-mines close to site of interest	A large proportion of the region and the AOI is part of the coal mining reporting area (Figure A6.11*)* and therefore there are likely to be coal mines in the area. The confidence for this factor is high.
Anthropogenic features-boreholes close to site of interest	There are two boreholes within the AOI (1.5 km to the northeast and 1.5 km to the southwest) which penetrate the Coal Measures and therefore are within 200 m vertically of the hydrocarbon source unit. The confidence for this factor is high.

Potential receptor	Intrinsic vulnerability score	Specific vulnerability score	Risk group	Confidence
		300 m scenario		
Mercia Mudstone Group	41.5	166	Low	Low
Sherwood Sandstone Group	61	244	Medium/low	
Zechstein Group	64.5	258	Medium/high	
Permian Basal Breccia	64.5	258	Medium/high	
Pennine Coal Measures Group	85	340	Medium/low	
Millstone Grit Group	85	170	Low	
Craven Group	71	142	Low	
		200 m scenario		
Mercia Mudstone Group	45	180	Low	Low
Sherwood Sandstone Group	66	264	Medium/high	
Zechstein Group	73	292	Medium/high	
Permian Basal Breccia	73	292	Medium/high	
Pennine Middle Coal Measures Group	85	340	Medium/low	
Millstone Grit Group	85	170	Low	
Craven Group	71	142	Low	
		400 m scenario		
Mercia Mudstone Group	41.5	166	Low	Low
Sherwood Sandstone Group	59.5	238	Medium/low	
Zechstein Group	59.5	238	Medium/low	
Permian Basal Breccia	59.5	238	Medium/low	
Pennine Middle Coal Measures Group	85	340	Medium/low	
Millstone Grit Group	85	170	Low	
Craven Group	71	142	Low	

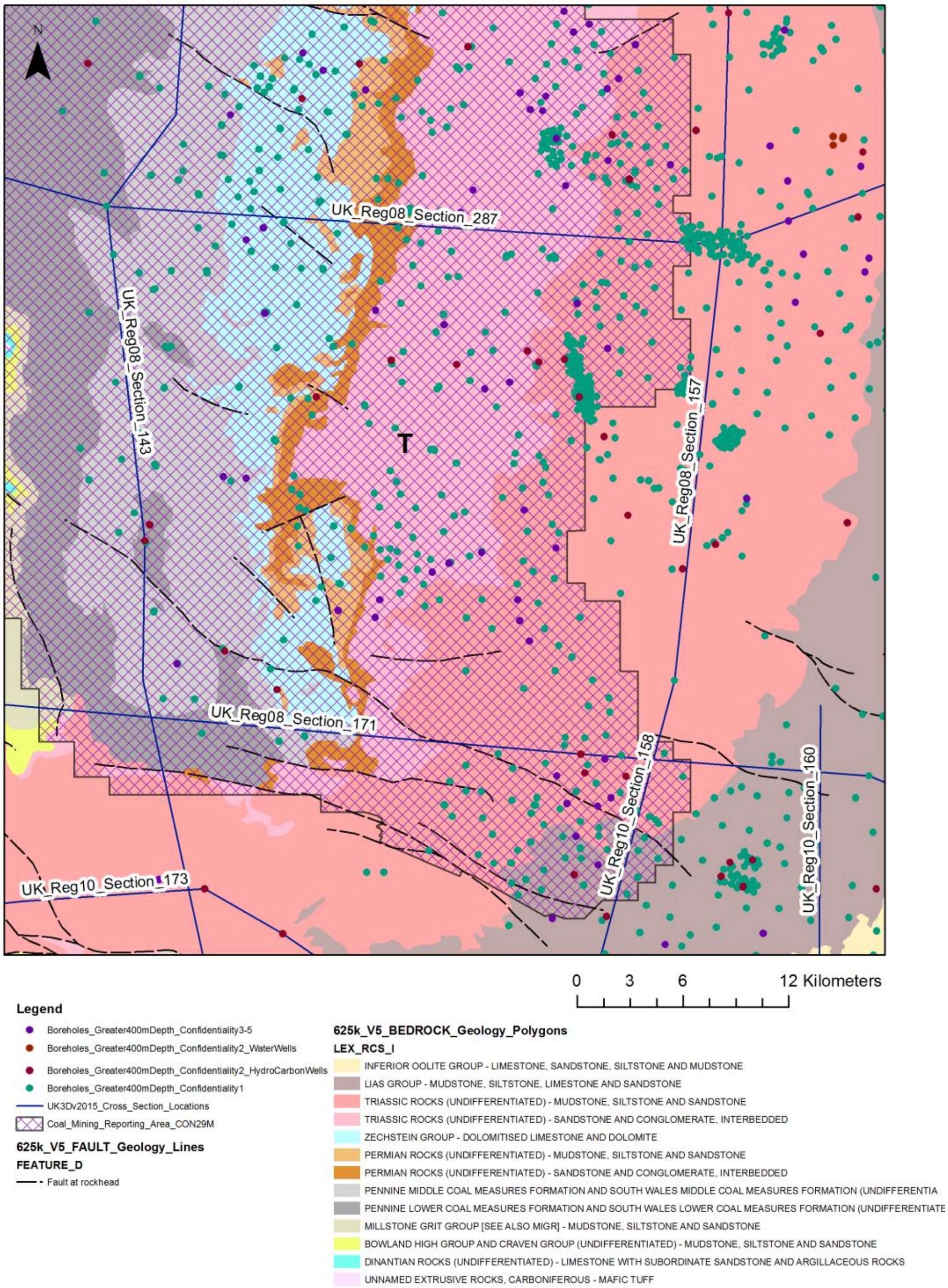

Figure A6.11 Hypothetical location of CBM in the East Midlands, T indicates rough location for the hydrocarbon source unit.

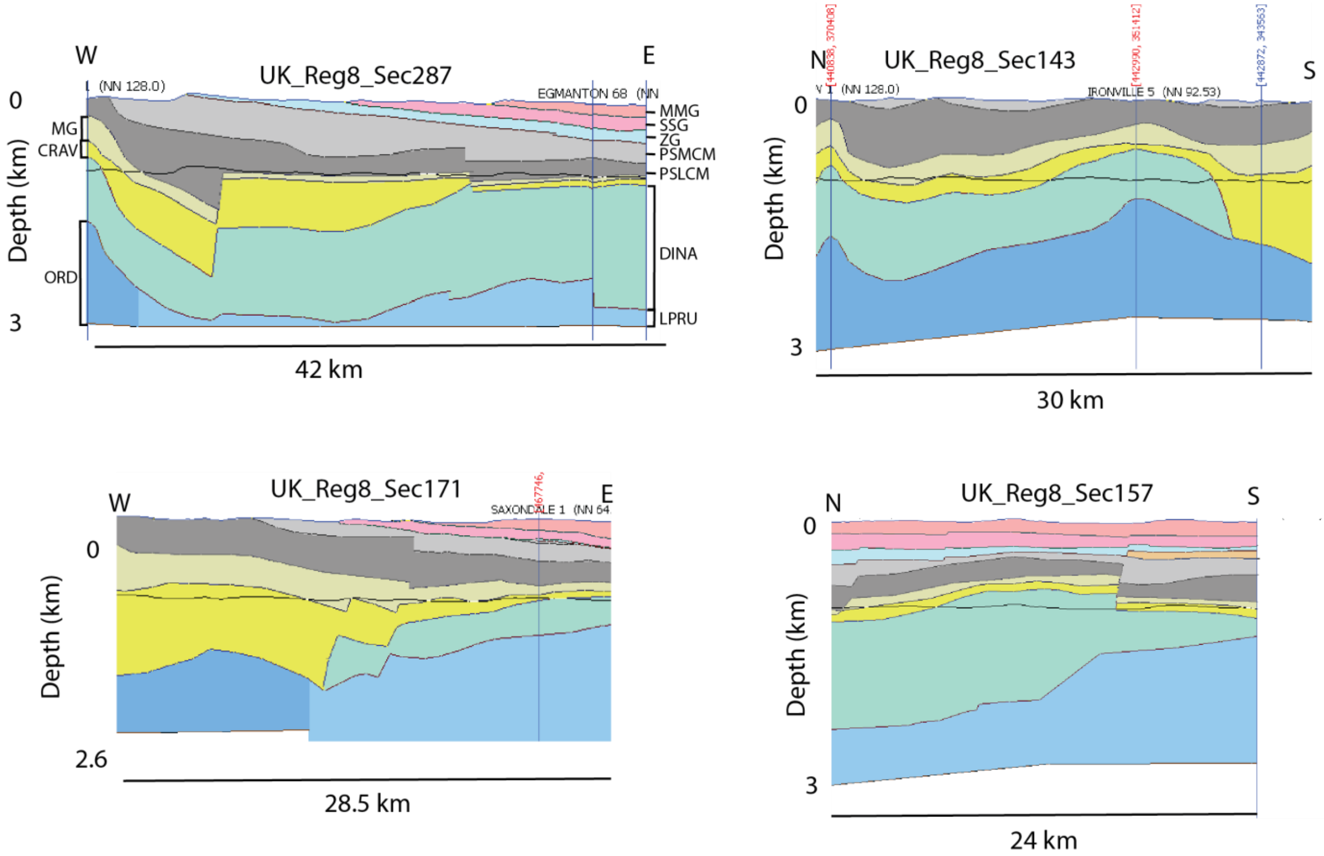

Figure A6.12 Cross sections surrounding hypothetical hydrocarbon source unit area of CBM (hydrocarbon source unit is roughly in the centre of these cross sections). Locations of the cross sections are shown in Figure A6.1. Cross sections UK_Reg8_Sec287 and UK_Reg8_Sec171 are across strike of the basin structure and UK_Reg8_143 and UK_Reg8_Sec157 along strike. Vertical lines are the locations of intersecting cross sections and the near horizontal black line indicates 1000 m bgl, the shallowest level allowed for shale gas exploitation in England and Wales. Rock codes shown on UK_Reg8_Sec287 are described in Table A6.3.

Model Unit	Age	Description
Mercia Mudstone Group (MMG)	Triassic	Mudstone and siltstone with beds of gypsum and dolomitic mudstone and siltstone.
Sherwood Sandstone Group (SSG)	Triassic	Fine to medium grained locally coarse and pebbly to conglomerate sandstone.
Zechstein Group (ZG)	Permian	Mudstone, siltstone and sandstone, with some dolostone and conglomerate.
Permian Basal Breccia (PBB)	Permian	Breccia in a dolomitic limestone matrix.
Pennine Middle Coal Measures Formation (PSMCM)*	Carboniferous	Mudstone, siltstone and sandstone with numerous coal seams and seatearths.
Pennine Lower Coal Measures Formation (PSLCM)	Carboniferous	Mudstone, siltstone and sandstone with numerous coal seams and seatearths.
Millstone Grit Group (MG)	Carboniferous	Mudstone and siltstone with thick sandstone beds.
Craven Group (CG)	Carboniferous	Mudstone and siltstone.
Dinantian (DINA)	Carboniferous	Limestone and dolostone
Ordovician (ORD) **	Ordovician	Mudstone, siltstone and sandstone
Lower Palaeozoic Rocks (LPRU) **	Lower Palaeozoic	Undefined

Table A6.3 Rock units present in the hypothetical East Midlands CBM AOI. Colours correspond with those used in the LFV sections (Figure A6.21) and conceptual model (Figure A6.13). * indicates the hydrocarbon source unit which belongs to the Pennine Coal Measures Group. ** indicates description from BGS Lexicon, otherwise descriptions are from the BGS sheet memoir (Howard et al., 2009).

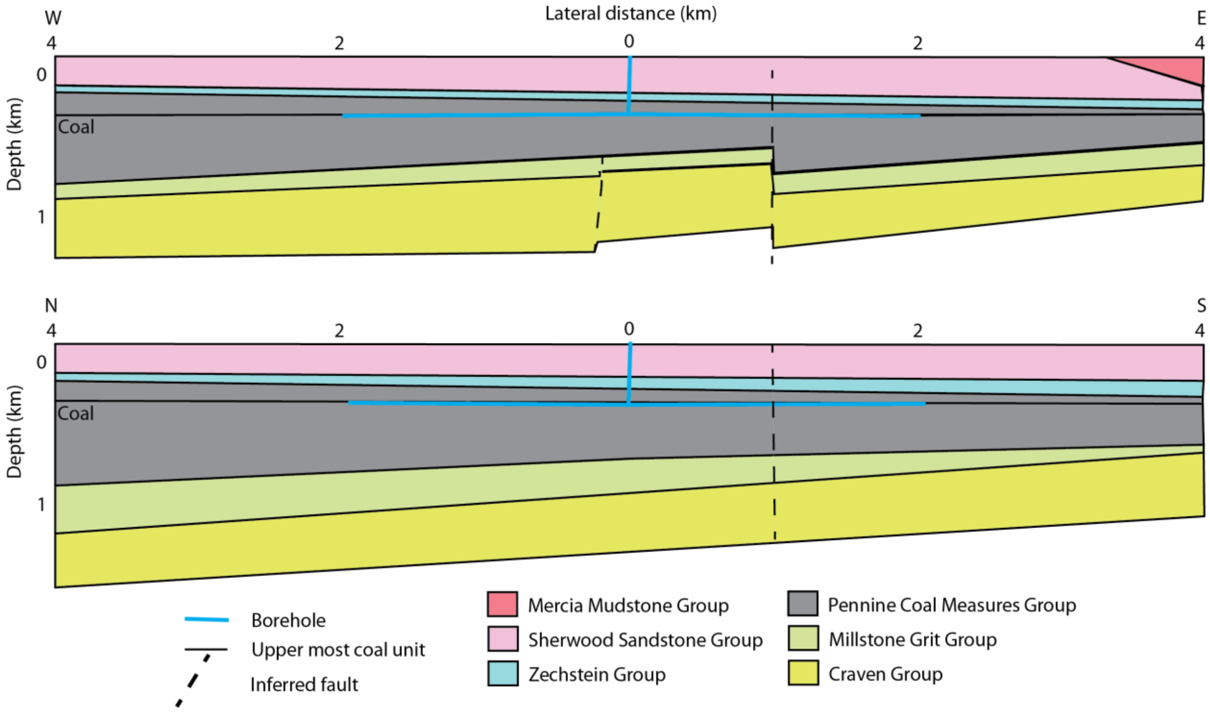

Figure A6.13 Conceptual model of the AOI for the hypothetical CBM site in the East Midlands. The hydrocarbon source unit is the Pennine Coal Measures Group (combined unit).

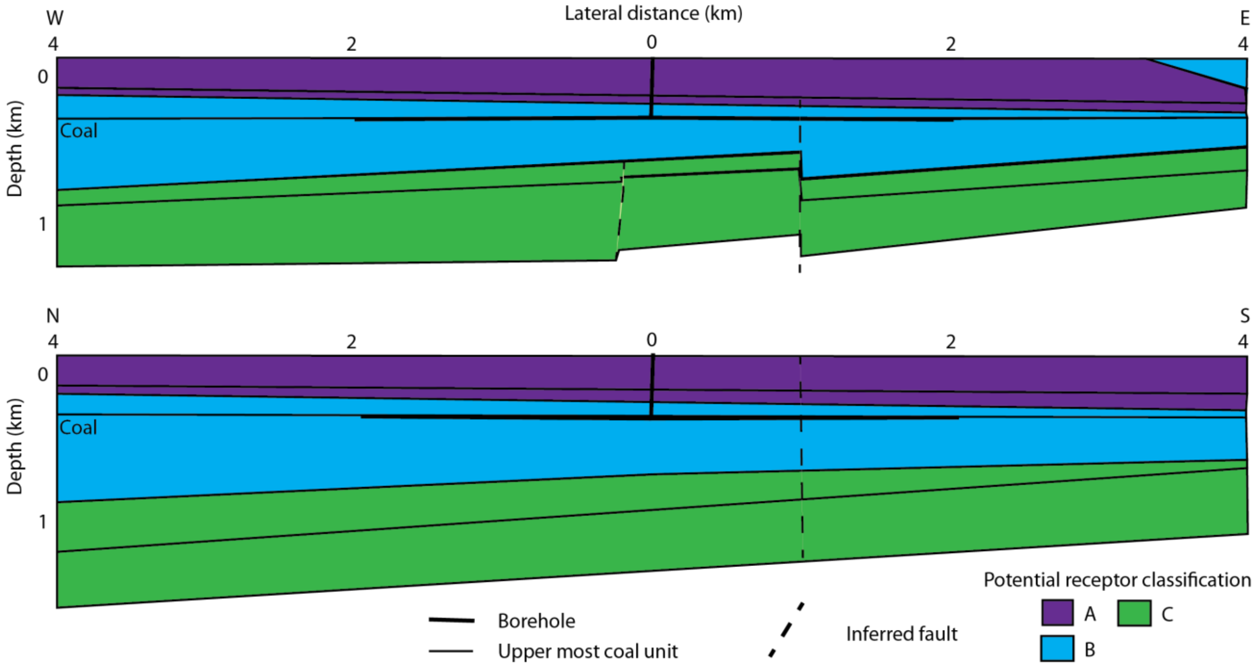

Figure A6.14 Potential receptor classifications for units within the conceptual model of the AOI for CBM in the East Midlands.

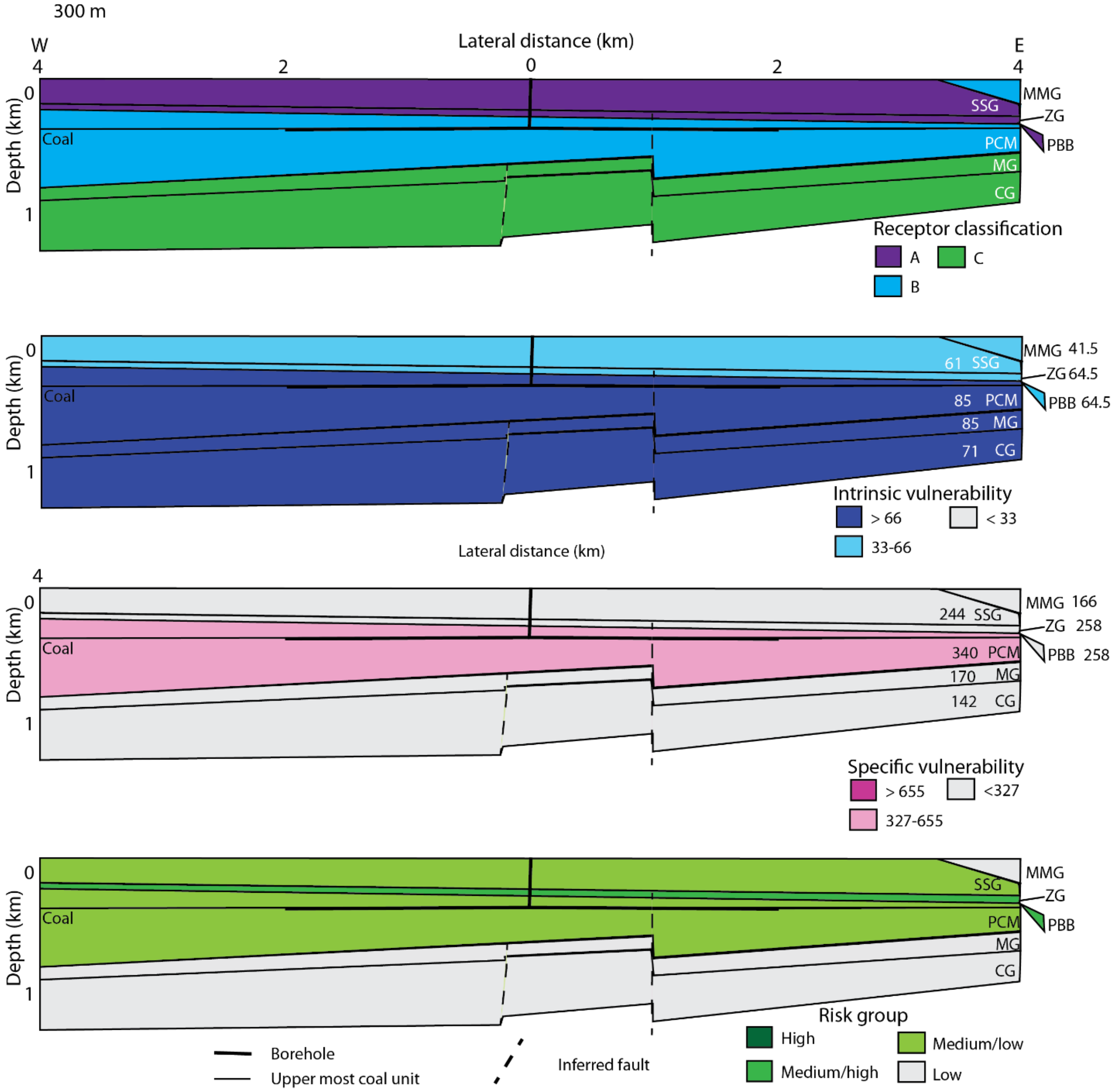

Figure A6.15 Conceptual model for the AOI for potential CBM in the Pennine Coal Measures Group with upper limit of coal exploitation at 300 m bgl with units identified as potential receptors, intrinsic and specific vulnerability scores, and risk group for each potential receptor. See Table A6.3 for code translations. The confidence for this assessment is low. Boundaries used for intrinsic and specific vulnerability scores and risk groups are used for preliminary purposes.

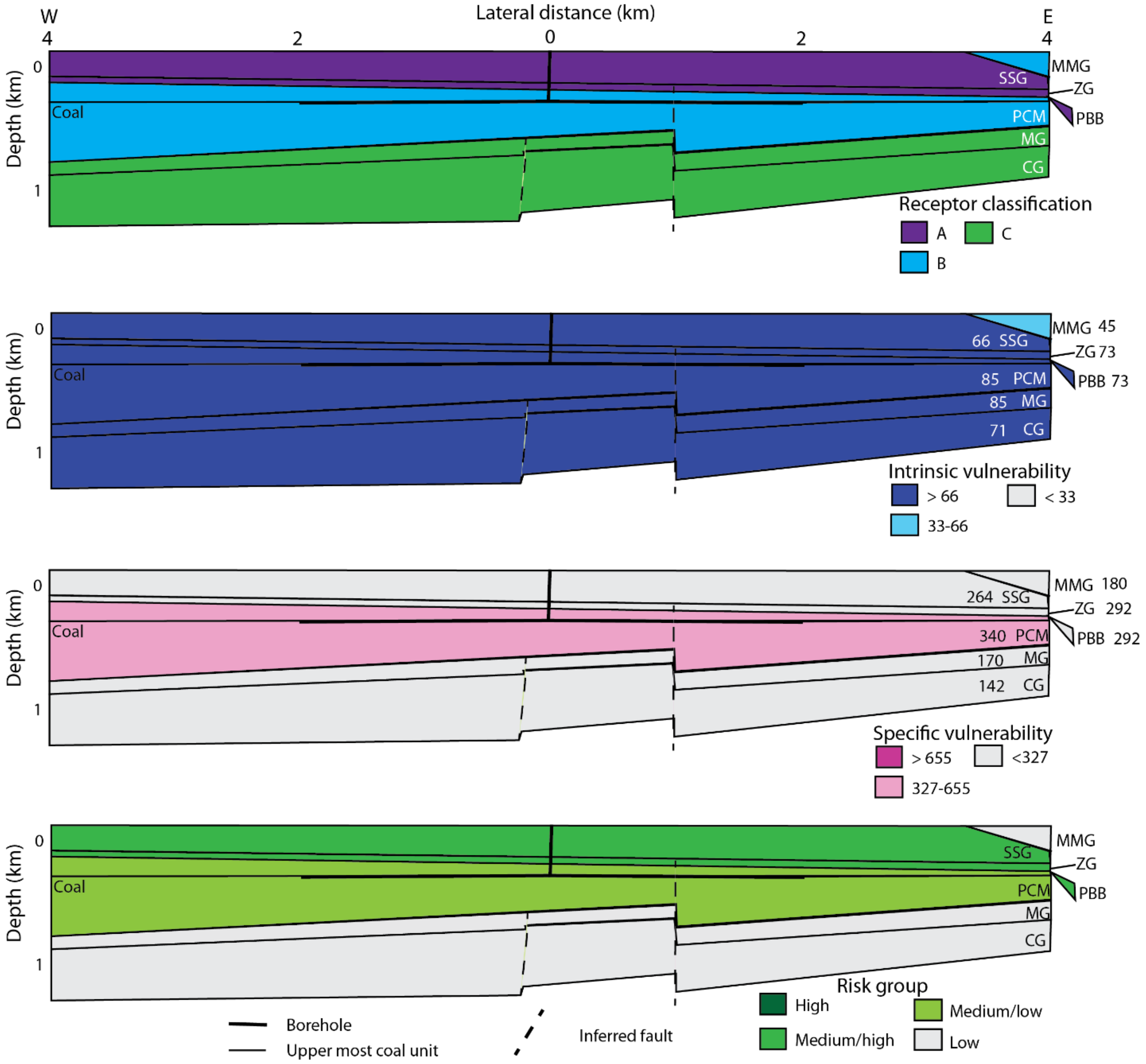

Figure A6.16 Conceptual model for the AOI for potential CBM in the Pennine Coal Measures Group with upper limit of coal exploitation at 200 m bgl with intrinsic and specific vulnerability scores, and risk group for each potential receptor. See Table A6.3 for code translations. The confidence for this assessment is low. Boundaries are used for intrinsic and specific vulnerability scores and risk group are used for preliminary purposes.

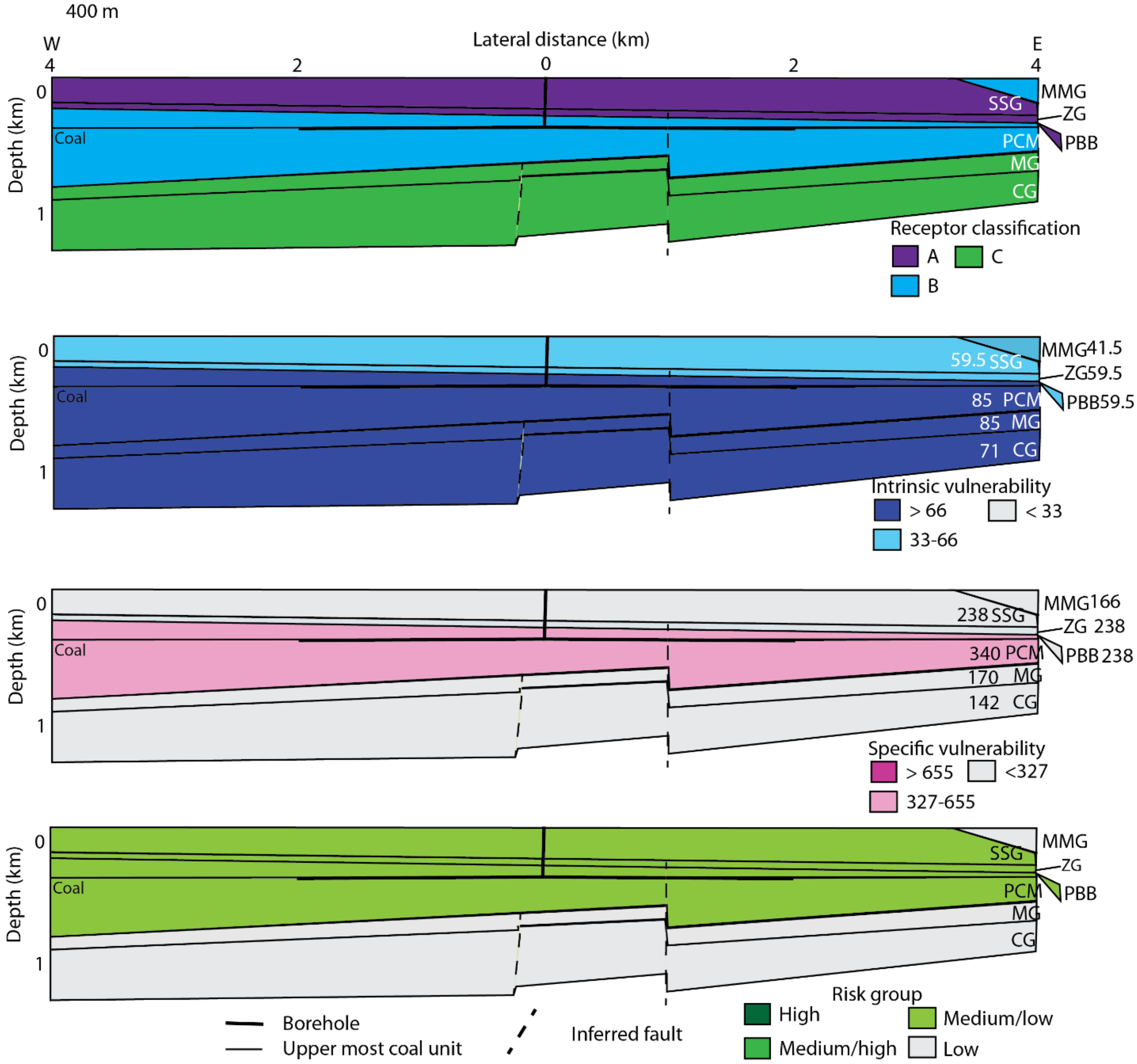

Figure A6.17 Conceptual model for the AOI for potential CBM in the Pennine Coal Measures Group with upper limit of coal exploitation at 400 m bgl with units identified as potential receptors, intrinsic and specific vulnerability scores, and risk groups for each potential receptor. See Table A6.3 for code translations. The confidence for this assessment is low. Boundaries used for intrinsic and specific vulnerability scores and risk group are used for preliminary purposes.

Summary for Case Study 3: Coal bed methane, East Midlands

- In this AOI there is a general decrease in potential receptor rank with depth, with the exception of the Mercia Mudstone which is classified as ‘B’, because it is a secondary aquifer. The Zechstein Group is classified as potential receptor ‘A’ but it is clear from local borehole logs that it primarily comprises Permian Marls which may not supply significant quantities of groundwater and therefore a review of this classification would be necessary.
- Intrinsic vulnerability scores for the potential receptors in the ‘best-guess’ (hydrocarbon source unit at 300 m depth) scenario are quite varied (41 to 85) and relatively high compared with the other case studies. Intrinsic vulnerability scores are highest for units closer to the hydrocarbon source rock and with the smallest mudstone thickness in the intervening units. Potential pathways for all of the units include the faults within the AOI, one of which is thought to cut

all of the units, the presence of mining in the area and also boreholes which could connect the hydrocarbon source unit and potential receptors.

- The intrinsic vulnerability scores for potential receptors overlying the coal units were sensitive to the depth of the coal unit demonstrating the sensitivity of the assessment to proximity of potential receptors and the hydrocarbon source unit and thus the importance of reducing uncertainty regarding the geometry. However, this is not a linear relationship; the closer the potential receptor to the hydrocarbon source unit the larger the potential differences in intrinsic vulnerability score with the same difference in separation distance.
- Specific vulnerability scores are all relatively low (77 to 340) as a result of the assumed relatively low hazard nature of CBM compared to some other technologies. Specific vulnerability scores are higher in the potential receptors overlying the hydrocarbon source unit (than those underlying it) reflecting the probability that the head gradient could be upwards. Apart from this, the potential receptors with the highest intrinsic vulnerability scores also have the highest specific vulnerability scores.
- The overall confidence in the intrinsic and specific vulnerability scores is low because of the uncertainty associated with the minimum depth at which coal units could be exploited. The confidence in all other factors is medium.
- The scenario influenced the risk group of some potential receptors; the Zechstein Group and Permian Basal Breccia are in the medium/high risk group in the 300 and 200 m scenario, but the medium/low risk group in the 400 m scenario. The Sherwood Sandstone is in the medium/low risk group for the 300 m and 400 m scenario but medium/high for the 200 m scenario. The Pennine Middle Coal Measures are in the medium/low risk group for all scenarios. The scenario has not impacted the risk group for the other potential receptors.
- The proximity of the potential receptor to the hydrocarbon source unit is a major uncertainty that will impact the intrinsic vulnerability score, specific vulnerability score and risk group of potential receptors. This should be addressed through further investigations. The assessment would improve from a greater understanding of the head distribution and groundwater flow paths and further identification of faults and fault behaviour in the region. The quality of the groundwater, groundwater flow system, abstractions and outflows from the potential receptors should be assessed in greater detail, in particular in those potential receptors in the medium/low to high risk groups.

CASE STUDY 4: SHALE GAS, NORTHWEST

Hydrocarbon source and extraction method
Bowland Shale Formation, part of the Craven Group, Lancashire with 2 km lateral wells (Figure A6.18).
AOI
Extending to 2 km from lateral borehole of 2 km
Geological setting
The Carboniferous-aged Bowland shale lies within the Fylde of the West Lancashire Basin. This is a low lying area west of the Pennines. These rocks outcrop to the east, at an elevation of ~130 m OD, but dip below younger Carboniferous and Permo-Triassic aged rocks in the Lancashire Basin. The Mercia Mudstone and the Sherwood Sandstone outcrop across the west and east of the region, respectively. At the coast there is up to 1200 m of Triassic-aged sediments. The Fylde is structurally complex with a variety of faults of different ages cutting and trending north-northeast–south-southwest, and a large variability in unit thicknesses (see Figure A6.19). Towards the coast and under the AOI, the top of the hydrocarbon source unit can be more than 2000 m below OD. There is a southwest trending synclinal fold in the centre of the Fylde area (Sage and Lloyd, 1978).
Conceptual model
The conceptual geological model for the AOI across (west-east) and along (north-south) strike is shown in Figure A6.20. The conceptual model is based on three boreholes in the centre and west of the AOI. The boreholes were located in the centre, 6 km to the west and 7 km to the northwest of the AOI. LFV sections (Figure A6.19) were used to provide an understanding of the regional geology and the possible variability in the area. The general geological sequence and unit descriptions are as shown in Table A6.4. There is little information regarding the depth and thickness of units in the AOI and a high degree of variability. In particular, little is known about the south and east of the area, or about the nature of the faults. Nevertheless, the Woodsford Fault in the east of the AOI is expected to be significant since this forms the boundary between the outcropping Mercia Mudstone to the west and the Sherwood Sandstone to the east. LFV sections show that the Appleby Group and the Millstone Grit are not present to the east of this fault. The Craven Group (hydrocarbon source unit) is expected to be much shallower in the footwall of the fault, only 300 m below OD compared with 1800 m below OD west of the fault. The Mercia Mudstone, Sherwood Sandstone and Cumbrian Coast Group become deeper to the west of the AOI. Boreholes indicate that the Appleby Group is thinner to the west and north of the AOI (ranging from 1000 m in thickness in the hanging wall of the Woodsford Fault to 200 m thickness in the northwest). To the north, this decrease in thickness corresponds with an increase in thickness of the Cumbrian Coast Group (from 200 to 600 m). The Millstone Grit has a fairly uniform thickness and depth across the AOI (350 m at ~ 1400 m depth). The borehole to the northwest also recorded about 50 m of Coal Measures. The faults shown on the conceptual model are from the 1:50 000 geological map. They strike north-northeast–south-southwest. The fault shown in the north-south cross section is the most central fault in the west-east section. The easterly fault is expected to be large, and an approximate throw has been obtained from the LFV sections. The throw on the other faults is not known, but they do not offset geological units at the surface.

In the assessment for the area east of the Woodsford Fault the Craven Group overlying the target depth (1800 m) has been included as an intervening unit.	
Baseline methane	
Five sites were sampled by Bell et al. (2015) within the area shown in Figure A6.18, one west of the AOI from superficial deposits to the west and four from the Sherwood Sandstone 10 to 12 km to the east, where the aquifer is unconfined. No samples were from the AOI. Bell et al. (2015) found that methane concentrations were above the detection limit, but none exceeded the groundwater equivalent LEL (Lower Explosive Limit). Methane concentrations were typically lower in the Sherwood Sandstone than in the superficial deposits.	
Potential receptors	**Classification**
Receptor classification was initially based on aquifer designations obtained from the LFV sections (Figure A6.19). Where units were classified as variable aquifers in the LFV (Figure A6.19) (Mercia Mudstone and Cumbrian Coast Group), the EA aquifer designation maps were used to identify the designation in this particular region. All these units are secondary aquifers in this region.	
Mercia Mudstone Group	B – secondary aquifer, top of unit < 400 m bgl and 8 km west of the AOI, at the Gas Works in Blackpool, a salinity of ~955 mg/l was recorded at 57 m bgl.
Sherwood Sandstone Group	A and D – principal aquifer, top of unit < 400 m bgl but groundwater beneath the Mercia Mudstone at Kirkham (to the west of the Woodsford Fault), at a depth of ~ 370 m bgl, has TDS of >100,000. Therefore, west of the fault the Sherwood Sandstone has been downgraded to potential receptor class 'D'. Where not confined by the Mercia Mudstone, borehole evidence at Salwick, 3 km east of the fault, suggests a much lower TDS (350 mg/l), consistent with the potential receptor class 'A'. 5 km southeast of the AOI saline water was encountered in the Clifton Marsh Landfill borehole at a depth of 61 m in the Sherwood Sandstone group but no concentration is recorded and this borehole is close to the Ribble estuary. The difference in salinity over such a short distance points to the barrier-like behaviour of the fault within the Sherwood Sandstone and therefore the assessments will also be conducted both west and east of the fault with the Sherwood Sandstone as a potential receptor class D and A, respectively.
Cumbrian Coast Group	C – secondary aquifer, top of unit > 400 m bgl
Appleby Group	B –principal aquifer, top of unit > 400 m bgl
Millstone Grit Group	C –secondary aquifer, top of unit > 400 m bgl
Craven Group	C – secondary aquifer, top of unit > 400 m bgl
Hazard	**Score**
Release mechanism of hydrocarbon	Shale gas and high volume hydraulic fracturing.
Head gradient driving flow	No information on groundwater head gradients from boreholes within the AOI or surrounding area. Sage and Lloyd (1978) suggest from a general piezometric map of the Fylde that some groundwater flow enters the Permo-Triassic sandstones from the Carboniferous sequence at a rate

	of ~ 30000 m^3/day along a front of about 15 km (Downing et al., 1987). The sandstones are thought to form one of the main outlets for groundwater, although direct evidence for flow from Upper Palaeozoic rocks into the sandstones is limited (Downing et al., 1987). In the south, however, the presence of Permian marls (Manchester Marls/Cumbrian Coast Group) prevents a uniform groundwater flow from the east into the sandstones (Sage and Lloyd, 1978). Downing et al. (1987) also suggest that the available evidence, including salinity >1000 mg/l in Triassic sandstones confined by the Mercia Mudstone (Sage and Lloyd, 1978), appears to preclude significant flow to the west below the Mercia Mudstone. Downing et al. (1987) suggest that the occurrence of oil at Formby implies that, near the coast, there is, or has been, a groundwater discharge zone originating in the Carboniferous, but apart from the possibly anomalous heat-flow values at Kirkham, heat flow in the Fylde is not above average – although the data are sparse. While the above evidence is not conclusive, an upward hydraulic gradient in this area is conceivable and therefore a score of two is appropriate in this case for all units.
Intrinsic vulnerability	
Vertical separation distance between source and base of receptor	The depth of potential receptor units and hydrocarbon source unit are not particularly well known in the area due to their lateral variability and limited availability of borehole records. Therefore, the confidence in this factor is low.
Lateral separation distance between source and receptor	In the current conceptual model of the AOI no units (with the exception of the directly overlying Millstone Grit) would be brought into lateral contact with the exploitation activity within 2 km. The confidence for this factor is, again, low because the geometry of the units around this fault is uncertain.
Mudstones and clays in intervening units between source and receptor	The thickness of mudstones and clays in the intervening layer between the top of the hydrocarbon source unit and the base of the potential receptor was based on the average composition of the interval recorded in a borehole log 1 km to the northwest of the AOI. Above the hydrocarbon source unit, the Millstone Grit is 51% mudstone (the remainder sandstone), providing 150 m of mudstone thickness to the overlying units. The borehole log shows the Appleby Group as a 50% mudstone, providing a cumulative mudstone thickness in the intervening units of 375 m for the overlying units. The Cumbrian Coast Group and Mercia Mudstone are all mudstone, and the Sherwood Sandstone is sandstone only. The confidence level for this factor is medium because the information was obtained from nearby borehole logs. However, there remains some uncertainty in the thickness of the units.
Groundwater flow mechanism in intervening units between	In the first unit above the source, the Millstone Grit, groundwater flow is expected to be predominantly through poorly connected fracture flow. The overlying Appleby Group is expected to be dominated by intergranular flow, thus changing the cumulative groundwater flow to >

source and receptor, including the receptor	50% intergranular flow. While groundwater flow in the Cumbrian Coast Group is likely to be through poorly connected fractures, the limited thickness, in comparison to the thickness of the underlying Appleby Group, means that the unit does not change the flow type category. Groundwater flow in the Sherwood Sandstone is also likely to be intergranular. This remains the dominant groundwater flow type in the sequence, despite the Mercia Mudstone likely be dominated by fracture flow. For the assessment to the east of the fault the sequence is assumed to be dominated by fracture flow from the Craven Group.
Faults cutting intervening units and receptor	A fault cuts all units to the east of the AOI. There are also a number of north-northeast–south-southwest oriented faults in the western part of the AOI. The closest fault is within the hypothetical footprint of the hydrocarbon activity. The hydrogeological impact of these faults is not known. The confidence in this factor is medium.
Solution features in intervening units and receptor	Gypsum and anhydrite have been recorded in boreholes penetrating the Mercia Mudstone and Sherwood Sandstone in the AOI. In addition, one borehole log specifies 'a few small voids' which might have resulted from the dissolution and removal of halite in these units. The confidence level for this factor is medium.
Anthropogenic features-mines close to site of interest	There are no recorded mines in the AOI. The confidence level for this factor is high.
Anthropogenic features-boreholes close to site of interest	There are two boreholes with depths of ~450 m within 0.5 to 2 km laterally from the vertical drill location, therefore a value of 1 has been attributed to all units. The confidence level for this factor is high.

Potential receptor	Intrinsic vulnerability score	Specific vulnerability score	Risk group	Confidence
		West of fault		
Mercia Mudstone Group	30	240	Low	Low
Sherwood Sandstone Group	32	256	Low	
Cumbrian Coast Group	28	224	Low	
Appleby Group	39.5	316	Medium/low	
Millstone Grit Group	72	576	Medium/low	
Craven Group	72	576	Medium/low	
		East of fault		
Sherwood Sandstone Group	33	264	Medium/high	Low
Cumbrian Coast Group	29	232	Low	
Craven Group	72	576	Medium/low	
Craven group (target)	23.5	188	Medium/low	

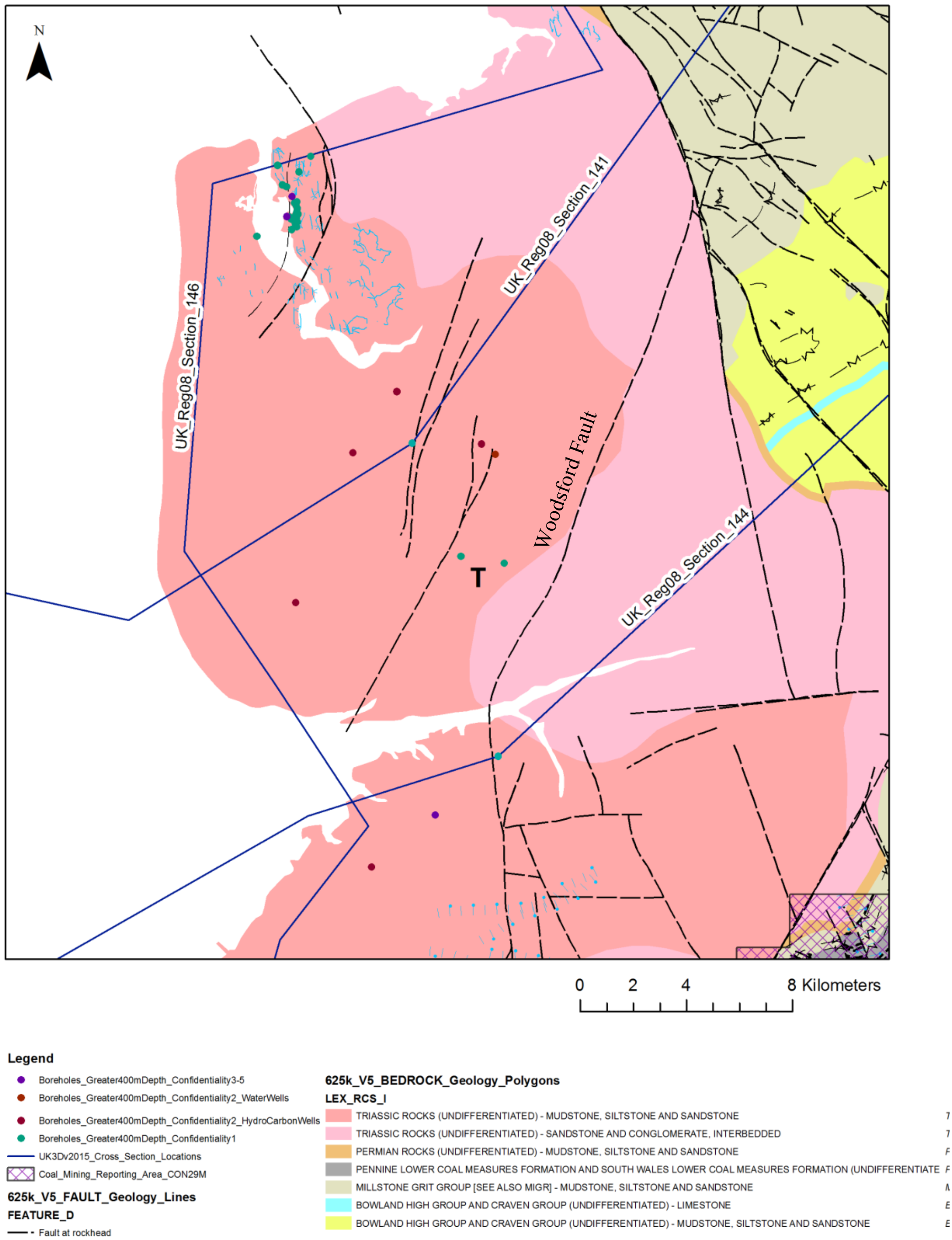

Figure A6.18 Hypothetical location of shale gas, T indicates rough location for the hydrocarbon source unit.

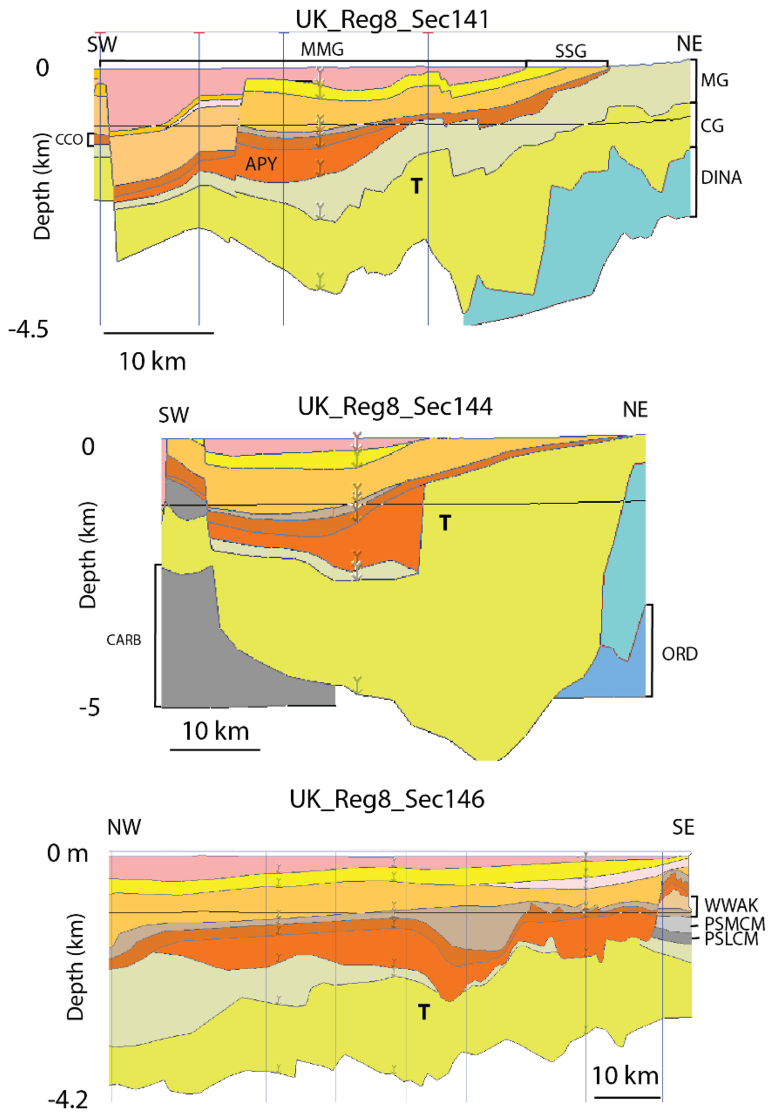

Figure A6.19 Cross sections surrounding hypothetical hydrocarbon source unit area of shale gas (hydrocarbon source unit is roughly in the centre of these cross sections). Locations of the cross sections are shown in Figure A6.18. The hydrocarbon source unit is the Bowland Shale, within the Craven Group (CG), shown by 'T'. UK_Reg8_Sec141 and UK_Reg8_Sec144 are across strike, to the north and south respectively. UK_Reg8_Sec146 is along strike, to the east. See Table A6.4 for unit codes. Vertical lines are the locations of intersecting cross sections and the horizontal black line indicates 1000 m bgl, the shallowest level allowed for shale gas exploitation in England and Wales.

Model Unit	Age	Description
Mercia Mudstone Group (MMG)	Triassic	Mudstone and siltstone with gypsum and some breccias
Sherwood Sandstone Group (SSG)	Triassic	Medium-grained sandstone with thin, impersistent mudstone
Cumbrian Coast Group (CCO)	Permian	Comprises the Manchester Marls Formation (mudstone, locally with thin, interbedded gypsum or anhydrite, and dolostone)
Appleby Group (APY)	Permian	Comprises Collyhurst Sandstone Formation (coarse-grained sandstone)
Coal Measures (CM)	Carboniferous	Mudstone (from borehole log)
Millstone Grit Group (MG)	Carboniferous	Mudstone, siltstone and sandstone (~25%)
Craven Group* (CG)	Carboniferous	Calcareous mudstone, limestone and mudstone

Table A6.4 Rock units present in the hypothetical Northwest AOI. Descriptions are from the sheet memoir, colours correspond with those used in the LithoFrame Viewer sections (Figure A6.19) and the AOI conceptual model (Figure A6.20). * indicates the hydrocarbon source unit. Units below the hydrocarbon source unit horizon are not described.

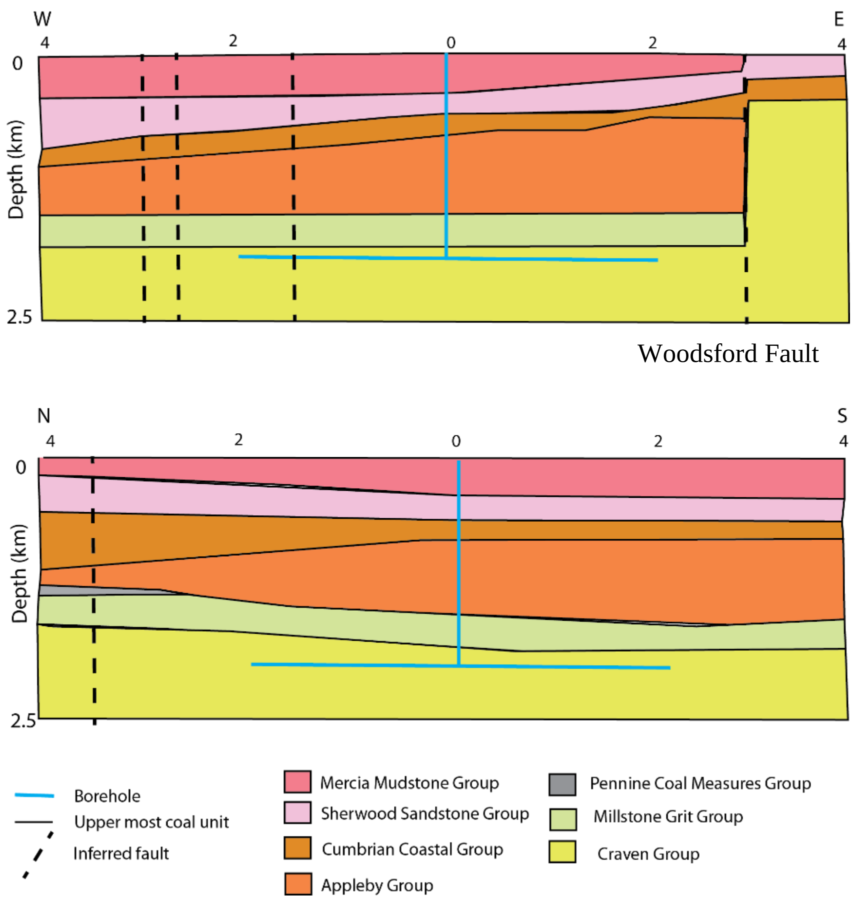

Figure A6.20 Conceptual model of the AOI for the hypothetical shale gas site in the Northwest. The hydrocarbon source unit is the Craven Group (Bowland Shale).

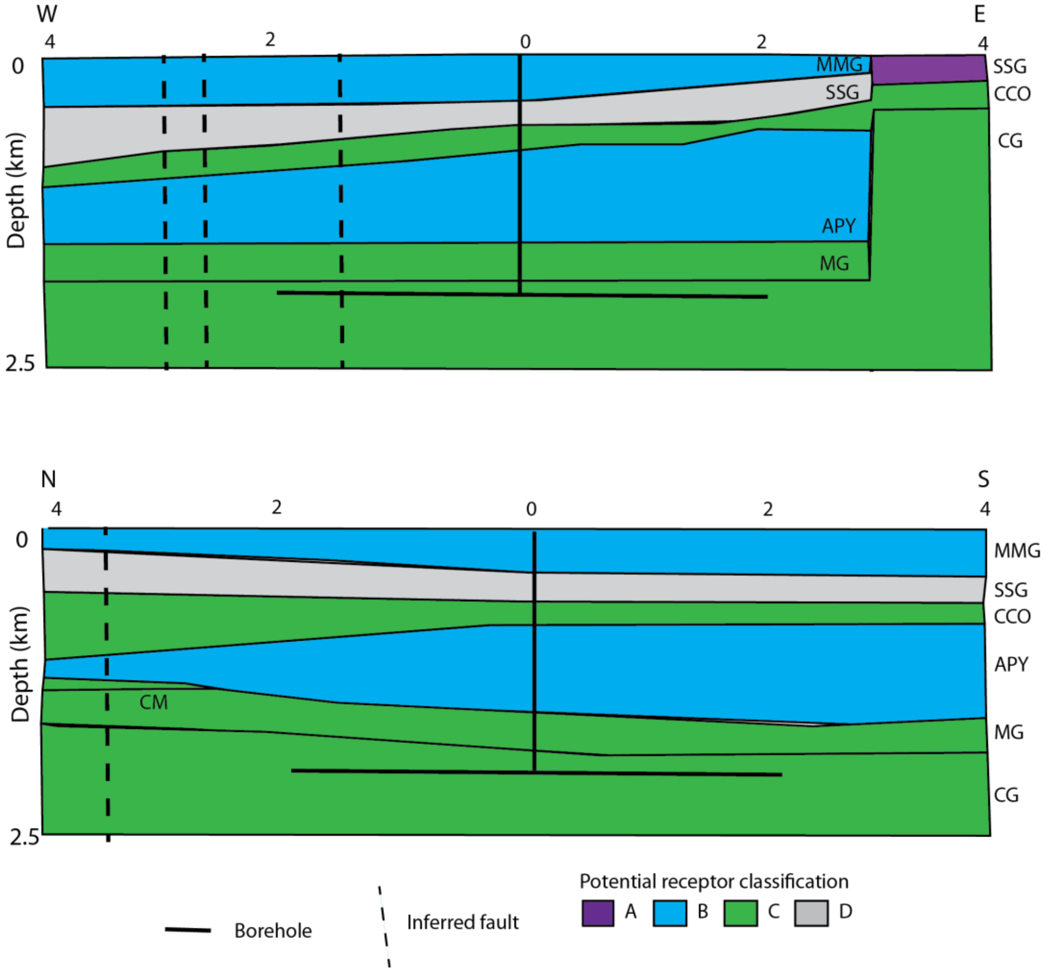

Figure A6.21 Receptor classifications for units within the conceptual model of the AOI for shale gas in the Northwest.

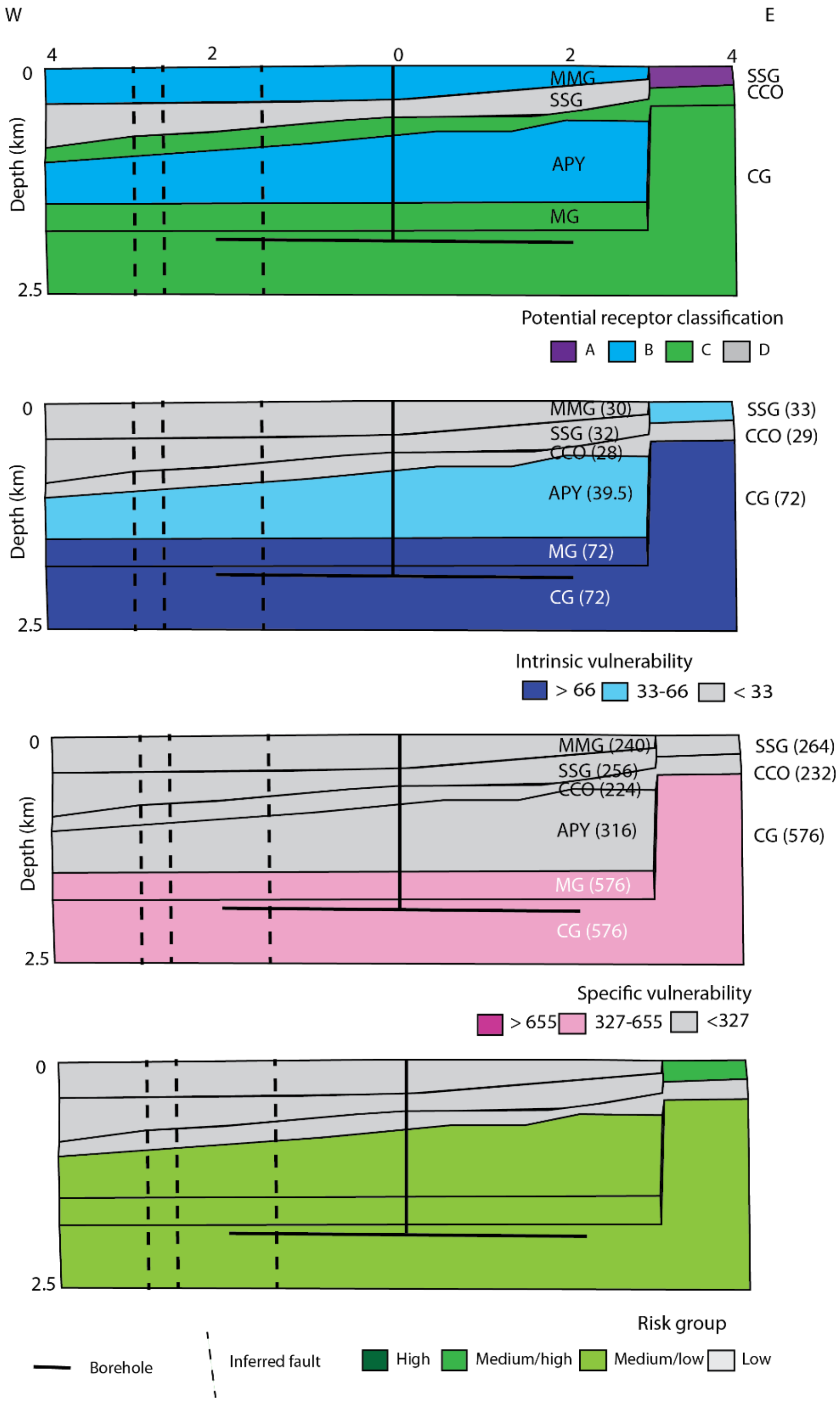

Figure A6.22 Conceptual model for the AOI for potential shale gas exploitation activities in Northwest England with units identified as potential receptors, intrinsic vulnerability scores, specific vulnerability scores and risk groups for each potential receptor for west and east of the fault. See Table A6.4 for code translations. The confidence for this assessment is low. Boundaries used for intrinsic and specific vulnerability and risk groups are used for preliminary purposes.

Summary of Case Study 4: Shale gas, Northwest

- Intrinsic vulnerability scores for the potential receptors (28 to 72) are quite varied compared with some case studies. The potential receptors with the highest intrinsic vulnerability scores are the Craven Group and Millstone Grit due to their proximity to the hydrocarbon source unit. The potential receptor with the next highest intrinsic vulnerability score is the Appleby Group (Collyhurst Sandstone) (39.5) reflecting the 300 m vertical separation from the hydrocarbon source unit and 150 m mudstone in the intervening interval. The intrinsic vulnerability scores of the remaining units are all below 33 and are comparatively low due to the relatively large vertical separations, but in particular, the thick mudstone within the intervening units.
- The intrinsic vulnerability score for the Sherwood Sandstone and Cumbrian Coast Group are slightly higher in the east rather than the west of the fault due to the > 50% fracture flow groundwater mechanism in the Craven Group.
- Potential contamination pathways exist for all of the units from a number of faults and deep boreholes which could connect the hydrocarbon source unit and potential receptors. In addition, there are known solution features in the upper two units.
- The specific vulnerability scores for the potential receptors are relatively higher, between 224 and 576, as a result of the assumed relatively higher hazard nature of shale gas (in particular high volume hydraulic fracturing) compared to other technologies.
- The confidence levels in the intrinsic and specific vulnerability scores are low because of the uncertainty associated with the depth and thickness of the units, particularly in the south and east of the AOI where there are no boreholes, and also the head gradients for the latter score. Geophysical and additional borehole information should be used to constrain the subsurface geometry of the AOI, including the size of the faults. The confidence in all other factors is medium.
- The risk group is medium/high for the Sherwood Sandstone to the east of the fault due to its potential receptor classification (‘A’) and specific vulnerability score. This is despite a vertical separation of 1600 m, and reflects the groundwater flow mechanism and potential for solution features within the unit particularly. However, west of the fault, it is in the low risk group. The Appleby Group (potential receptor class ‘B’) has a medium/low risk, Millstone Grit and Craven Group are in the medium/low risk group predominantly due to their high specific vulnerability scores despite the fact that they are unlikely to be used as aquifers at these depths (> 1.5 km).
- The large difference in risk grouping east and west of the fault for the Sherwood Sandstone, and the medium/low risk grouping for the Millstone Grit and Craven Group highlights the importance of correctly classifying these units. Further information about the groundwater quality in this area, particularly on the east side of the fault should be obtained.

CASE STUDY 5: SHALE GAS AND CONVENTIONAL HYDROCARBONS, NORTHEAST ENGLAND

Hydrocarbon source and extraction method
1: Shale gas from the Bowland Shale Formation, part of the Craven Group, in the Vale of Pickering, Yorkshire (Figure A6.23). Lateral well extending to 2 km. 2: Natural gas from the Zechstein Group, in the Vale of Pickering, Yorkshire (Figure A6.23). The well is assumed to be vertical.
AOI
1: Extending to 2 km from lateral borehole 2: Extending to 2 km from vertical borehole
Geological setting
The Vale of Pickering is a low-lying (15-35 m above OD) east-west trending basin, approximately lying between Scarborough in the east and Helmsley in the west (Figure A6.23). It is bound by the North York Moors to the north, the Howardian Hills to the southwest and to the south the chalk downlands of the Yorkshire Wolds (Newell et al., *2018*), formed by the Market Weighton High (Brenchley and Rawson, 2006). The western margin is marked by the southern North Sea Basin. The bedrock outcrop across most of the Vale of Pickering is the Jurassic-aged Ampthill/Kimmeridge Clay. Underlying this are Triassic sediments (Newell et al., *2018*). Numerous cross-cutting faults trend broadly east-west across the Vale of Pickering with average throws in the order of 50 to 100 m, and a maximum of 300 m (A Newell, *pers comm.)*. A number of rock units in the Vale of Pickering have been exploited for conventional oil and gas. Structural interpretation of the Vale of Pickering was undertaken in 1987 by Kirby et al. using seismic reflection data of varying age and quality and tied to wells. There is thus a reasonable amount of geological information about the area. The structural analysis was used to produce the recent geological model of the Vale of Pickering from the post-Permian upwards by Newell et al. (*2018*). At present the model extends to the top of the Permian Zechstein but the authors state that further work should be undertaken to model the lateral thickness and facies variations within the Zechstein in order to understand the sealing capacity of the salt. Modelling of the underlying Carboniferous would also be desirable to understand the relative position of hydrocarbon source rocks.
Conceptual model
The approximate location of the AOI is shown by the letter 'T' in Figure A6.23 and Figure A6.24. The AOI lies towards the south of the Vale of Pickering, in the flat-lying land north of the River Derwent. The southern boundary of the AOI is marked by the south-dipping Gilling Fault, which forms the east-west trending graben-like structure of the Gilling-Gap, with the opposing Kilburn Fault (Newell et al., *2018*), with approximately 50 m and 150 m offset, respectively. In the area, the shale gas hydrocarbon source unit, the Carboniferous-aged Craven Group rocks containing the Bowland Shale, lies at depths of 1500 m or more. A number of boreholes penetrate to the top of this unit, but not to the base. Overlying the Craven Group are rocks of the Millstone Grit Group which are around 400 m in thickness. The overlying Permian Zechstein Group rocks are about 350 m in thickness and contain a high proportion of anhydrite and dolomite. The Sherwood Sandstone and Mercia Mudstone overlie this, and are about 200 m in thickness. The overlying Lias can be up to 450 m in thickness, the Ravenscar Group 250 m, the Oxford Clay Formation 50 m and the Corallian Group 100 m in thickness, towards the centre of the basin. These units thin to the south as the sequence becomes thinner over the Yorkshire Wolds/Market Weighton High where they are truncated by the Chalk. The Kimmeridge and Ampthill clay, which is at the top of the sequence and outcrops across most of the region, is between 100 and 250 m in thickness and also thicker in the north. The conceptual geological model for the AOIs for both hydrocarbon source units, across (north-south) and along (west-east) strike, are shown in Figure A6.25. The AOI was developed for hydrocarbon source unit 1 and a smaller volume used for hydrocarbon source unit 2. There are a number of deep (> 400 m) boreholes in the AOI; in the centre, to the northeast, southeast and southwest (Figure A6.23). The boreholes terminate in Carboniferous-aged (Namurian) units, thus providing evidence for

the depth and thickness of all of the younger units, across much of the AOI. The records of four of these boreholes were used to produce the conceptual model. In the conceptual model of the AOI the geological sequence becomes shallower to the south due to stepping across north-dipping normal faults. There is little east-west variability in the depth and thickness of units. There is a slight dip from west to east along-strike, with a difference in depth of units of about 100 m. Hydrocarbon source unit 1 (Craven Group) in the AOI lies between 2200 m in the north and 1700 m in the south although the depth is not well constrained as only the borehole in the centre of the AOI differentiates this and the overlying Millstone Grit. None of the boreholes penetrate to the base of hydrocarbon source unit 1 and therefore the thickness is not known. However, this is not important for the risk assessment since calculations use the top of the unit. In the central borehole the Millstone Grit is over 350 m in thickness, and contains approximately 50% mudstone. Since there is no more information this thickness is applied across the AOI. The depth of the Millstone Grit varies from 1800 m below OD in the north to 1400 m in the south. The overlying Zechstein Group comprises between 350 and 500 m of anhydrite (up to 60% in the north of the AOI), dolomite (~ 35 %) and a small amount of claystone. The Sherwood Sandstone overlies this. This unit decreases in depth to the south but increases in thickness, from just over 100 m thickness in the north at a depth of ~ 1200 m below OD to ~400 m in thickness in the south, at a depth of ~ 600 m below OD. Borehole records indicate that this unit is predominantly sandstone, with some anhydrite. The Mercia Mudstone overlies this and, similarly, is thicker but shallower in the south; from ~200 m thick at a depth of ~ 1000 m below OD in the north to ~ 500 m thick at a depth of 300 m below OD in the southwest. Borehole records indicate that this unit is shale with some gypsum and anhydrite, and some sandstone and siltstone. The Lias, Ravenscar Group and Oxford Clay and Kellaways formations and the Corallian Group lie between the Mercia Mudstone and the outcropping Kimmeridge Clay. The Lias is thicker and deeper to the north (400 m thick at 600 m below OD) than the south (150 m thick at 150 m below OD). The thickness of the Ravenscar Group, Oxford Clay and Kellaways Formations and the Corallian are relatively constant across the AOI, but the units are approximately 300 m shallower in the south. The Kimmeridge Clay is approximately 200 m thicker in the north of the AOI. The Cromer Knoll Group (Speeton Clay Formation) is present to the east of the AOI, but not within it. There is slightly less variability in the unit depths and thicknesses in the AOI for hydrocarbon source unit 2 as there are no lateral boreholes and hence the AOI is smaller. The hydrocarbon source unit (Zechstein Group) varies from a depth of 1400 m below OD in the north to 1000 m below OD in the south (Figure A6.25). The overlying units are also deeper in the north than in the south, with the greatest difference in depth for the top of the Mercia Mudstone which is 900 m below OD in the north and 400 m below OD in the south. The Lias is thicker in the north than in the south (~400 m and ~150 m respectively). There is little difference in thickness and depth along-strike. A number of large-scale faults (marked on the 1:625 000 geological map and included in Newell et al., *2018*) strike roughly west-east in the AOI. Newell et al. *(2018)* indicate that these faults offset the post-Permian bedrock units but it is not known whether or not these faults are hard-linked to the Carboniferous-aged units or are listric with a base in the more-ductile anhydrite units of the Zechstein Group. In this conceptual model the faults have been assumed to continue to depth and cut the pre-Permian units, as a worst-case scenario. The Gilling Fault forms the southern boundary of the AOI. Other large faults lie ~1 km south of the centre of the AOI and a northwest-southeast striking fault lies ~2 km north of the centre of the AOI. Two additional faults are marked on the 1:50 000 geological map, immediately north of the centre. These faults are currently modelled as relatively simple planes but may, in reality, be more complex (Newell et al., *2018).* Newell et al., *pers comm* states that most of the faults are believed to have throws of 50 to 100 m.
Baseline methane
Bell et al. (2015) sampled for methane concentrations in aquifers in the northeast as part of the Methane Baseline Survey of Great Britain. Five sites were sampled within the area shown in Figure A6.23; three from the Corallian Group and two from the West Walton Formation (below the Corallian

Group), all where the aquifers outcrop at rockhead. Sample locations for the Corallian Group aquifer are about 7 km to the south, 8 km to the west and 30 km to the east of the hydrocarbon source unit 1 AOI. Sample locations in the West Walton Formation are about 2 km to the north and 32 km to the east of the hydrocarbon source unit 1 AOI. It was found that methane concentrations were above the detection limit in the region but no samples exceeded the groundwater equivalent LEL (Section 6.1) Smedley et al. (2017) investigated the baseline chemistry of groundwater from a shallow Quaternary/Kimmeridge Clay aquifer and the Corallian aquifer. High concentrations of dissolved methane were observed in the superficial aquifer groundwaters (up to 37 mg/l). These waters were also confined and highly reducing. While the methane appears to be of mixed biogenic-thermogenic origin, further work is needed to determine whether the source includes a deeper hydrocarbon reservoir contributing via fractures, or a shallower source in the Quaternary or Kimmeridge sediments (Smedley et al. 2017).	
Potential receptors	**Classification**
Receptor classification was initially based on aquifer designations obtained from the LFV sections, according to EA aquifer designations (Figure A6.26). Where model units were classified as variable aquifers (Corallian Group, Lias, Mercia Mudstone and Zechstein Group) the EA aquifer designation maps were used to identify the designation based on outcrops with similar lithologies. For the Corallian Group this was 2 km to the west of the hydrocarbon source unit 1 AOI, the Lias 9 km to the north, over the north York Moors and also 8 km to the southwest over the Market Weighton High, and the Mercia Mudstone 12 km to the southwest. The furthest located outcrop was for the Zechstein Group, 40 km to the west, at the foot of the Pennines.	
Kimmeridge and Ampthill Clay Formations	B – designated as unproductive. A 47 m deep borehole to the eastern side of the AOI, had a TDS of 1140 mg/l although a smell of H_2S was recorded and it was highly corrosive. Another borehole also within the AOI suggests that the water quality in this unit is 'fairly good'. A borehole 5.6 km to the west of centre, 91 m deep had an EC of 513 µS/cm (TDS ~ 266 mg/l). There are a number of boreholes which abstract water from this unit, with one yielding ~ 5 l/s and potable water quality.
Corallian Group	A – principal aquifer, < 400 m bgl; a 61 m deep borehole 1 km to the north of the AOI 1 indicates a TDS of 310 mg/l
Kellaways and Oxford Clay Formations	D – unproductive strata
Ravenscar Group	B – secondary aquifer, < 400 m bgl.
Lias	C – secondary aquifer, > 400 m bgl.
Mercia Mudstone Group	C – secondary aquifer, > 400 m bgl.
Sherwood Sandstone Group	B – principal aquifer, > 400 m bgl.
Zechstein Group	D - principal aquifer, > 400 m bgl, but ~16 km to the northeast of the hydrocarbon source unit 1 AOI at depths of 1647 to 1702 m bgl, TDS ranges from 67,100 to 306,200 mg/l. Records from a borehole in the centre of the AOI indicate 'saline' water in this unit, and another in the southwest of the AOI records that the water is 'black and sulphurous'.
Millstone Grit Group	C – secondary aquifer, > 400 m bgl
Craven Group	C – secondary aquifer, top of unit > 400 m bgl
Hazard	**Score**

Release mechanism of hydrocarbon	1: Shale gas and high volume hydraulic fracturing. 2: Conventional hydrocarbons
Head gradient driving flow	There is little information on groundwater head distributions at depth in the AOI, or region. Groundwater was found to be artesian in a borehole drilled into the Corallian Group aquifer 1 km to the north of the AOI for hydrocarbon source unit 1, with head 2 m above ground level. Artesian conditions were also found in the Corallian Group 4 km to the southwest of the AOI for hydrocarbon source unit 1. There are no records of hydraulic head in other formations in the AOI. The East Yorkshire Hydrogeological map (IGS, 1980) does not have groundwater head information on these units. Downing et al. (1987) suggest that, north of the Vale of York, the Triassic sandstones are the main outlet for groundwater. Groundwater is thought to flow south along the Vale of York, along the line of the Yorkshire Ouse (west and south of the AOI). They suggest that there may be some deep regional flow to the east within the Triassic sandstones, 'particularly along the line of the Vale of Pickering', draining the groundwater from deep Upper Palaeozoic rocks and therefore an upwards gradient. While there is some evidence of upwards head gradients at shallow depths in the AOI, there is no information regarding groundwater head at greater depths, for example, from the hydrocarbon source unit depths. Nevertheless, it is not possible to rule this out and therefore the worst case scenario remains that the head gradient might be from the source to the potential receptor for all units. This is given a medium confidence level for the upper two units and a low confidence level for the underlying units.
Intrinsic vulnerability	
Vertical separation distance between source and base of receptor	There are a number of deep boreholes in and around the AOI so there is reasonable information about the depth and thickness of the units. For hydrocarbon source unit 1, there is a difference of about 550 m depth for the top surface for the Craven Group between the north and south of the conceptual model. Consequently, three vulnerability scenarios were tested; centre of the AOI, minimum separation (south) and maximum separation (north). It was found that the vertical separation to the base of the potential receptors does not change systematically for all of the units due to the variation in thickness of the intervening units. The vertical separation to the base of the potential receptors is greatest in the south, then the north and then the centre of the AOI. The biggest difference in vertical separation is for the Lias, in which the vertical separation with the hydrocarbon source unit is 430 m greater in the south and 80 m greater in the north, than in the centre of the AOI. For the Ravenscar Group the vertical separation is 370 m greater in the south and 295 m greater in the north. The vertical separation difference is greater for units overlying the Ravenscar Group than underlying it. Only one scenario was tested for hydrocarbon source unit 2 due to the small differences in results for hydrocarbon source unit 1. The confidence in the vertical separation distance is medium due to the presence of deep boreholes in the AOI.
Lateral separation distance between source and receptor	In the AOI the lateral separation distance factor does not apply since no units are brought into horizontal contact with the hydrocarbon source unit. The exceptions are the Millstone Grit and the Sherwood Sandstone which directly overlie the hydrocarbon source units. Other units are not brought to the same horizontal level in the AOIs due to the relative thickness of the overlying

	Millstone Grit and Zechstein Group and the comparatively limited throw of the faults. The confidence in the horizontal separation distance is medium because there is little variability in depth and thickness of units across the AOI. However, the actual throws on the faults are not known.
Mudstones and clays in intervening units between source and receptor	The composition of all units was assessed from borehole records. The Millstone Grit is estimated to be 50% mudstone. The Zechstein Group is predominantly anhydrite and dolomite with little mudstone,. The Lias is predominantly mudstone. The Ravenscar Group is predominantly sandstone (with some mudstone). The Oxford Clay is predominantly mudstone. The Corallian Group limestone. The Ampthill and Kimmeridge clays are mudstone. The cumulative mudstone thickness increases up the sequence with distance from the hydrocarbon source units. For hydrocarbon source unit 1, the large thickness of the Millstone Grit, and the fact that 50% of this is mudstone, results in all of the overlying potential receptors having a mudstone thickness of 184 m in the intervening interval between them and the hydrocarbon source unit. Receptors overlying the Mercia Mudstone have more than 350 m of mudstone thickness in the intervening interval. The only class 'A' potential receptor (Corallian Group) is separated from the hydrocarbon source unit formation by a thickness of more than 700 m mudstone in the intervening units. For hydrocarbon source unit 2, there are no mudstones in the intervening interval for the Sherwood Sandstone or the Mercia Mudstone, but there are thicknesses of over 200 m and 400 m for the Lias and Ravenscar Groups, respectively. This separation increases further up the geological sequence. The confidence level for this factor is medium since there are borehole records for all of the units in the AOI.
Groundwater flow mechanism in intervening units between source and receptor, including the receptor	Permeability in the Millstone Grit is likely to be predominantly through fracture flow due to its age, but fractures are likely to be poorly connected. There is likely to be limited permeability in the Zechstein Group anhydrite which has a tendency to re-seal fractures; however the dolomite is brittle and could be fractured. The Sherwood Sandstone is probably dominated by intergranular flow. The Mercia Mudstone and Lias are also likely to be fractured but not well connected and the Ravenscar Group is dominated by intergranular flow. While the Corallian is likely to be fractured, well-connected (e.g. Reeves et al., 1978), this unit is only 15 to 100 m thick and therefore will not have a particularly large influence on the cumulative flow type. The cumulative flow type is therefore likely to be > 50% potential receptor class 'A' to 'C' fractured, poorly connected or mixed fracture and intergranular flow, for both hydrocarbon source units. The confidence level for this factor is medium because borehole records do not provide this information for most of the units.
Faults cutting intervening units and receptor	A number of large-scale faults (marked on the 1:625 000 geological map and included in Newell et al., *2018*) strike roughly west-east in the AOI. Newell et al. *(2018)* indicate that these faults offset the post-Permian bedrock units. They state that it is not known whether or not these faults are hard-linked to the Carboniferous-aged units or are listric with a base in the more-ductile anhydrite units of the Zechstein Group. In this conceptual model the faults have been assumed to cut the pre-Permian units as well as those above as a worst-case scenario. The Gilling Fault forms the southern boundary of the AOI. Other large faults lie ~1 km south of the centre of the AOI and a northwest-southeast striking fault

	lies ~2 km north of the AOI. Two additional faults are marked on the 1:50 000 map, immediately north of the AOI. These faults are currently modelled as relatively simple planes but may, in reality, be more complex (Newell et al., *2018).* Newell et al., *pers comm* states that most of the faults are believed to have throws of 50 to 100 m. Reeves et al. (1978) state that the bulk of groundwater discharge from the Corallian aquifer in the Vale of Pickering takes place from a series of large springs whose positions are governed by faulting, where the aquifer passes beneath the impermeable clay cover of the centre of the Vale. Sometimes these break through the line of the fault. However, the documented springs are to the north and west of the AOI. Reeves et al. (1978) also state that faulting has completely or partially reduced hydraulic continuity between the confined aquifer and the outcrop. It thus appears that faults can behave as conduit-barriers in the region. Since there is no other evidence to suggest whether the faults are transmissive the category has not been changed based on this evidence. The confidence level for this factor is medium because the maps point to some evidence for faults, but there is no information regarding their hydraulic properties. In addition, the depth to which they penetrate is not known. The confidence is slightly higher for hydrocarbon source unit 2 since it is known that the faults do penetrate to this level			
Solution features in intervening units and receptor	A number of the potential receptors have potential for developing solution or karst features (Farrant, 2008) in the AOI. These include the Zechstein Group – due to the presence of anhydrite and dolomite, as well as Sherwood Sandstone and Mercia Mudstone where anhydrite has been documented in boreholes in the AOI, and gypsum in the latter to the southwest. The Corallian also has potential for solution features with swallow holes common at outcrop where it acts as a karstic aquifer. Mud losses were documented in this formation during drilling of the borehole in the northeast of the AOI. Because there is little evidence to support this factor for most of the units the confidence is medium.			
Anthropogenic features-mines close to site of interest	There are no recorded mines in the AOI. The confidence level for this factor is high.			
Anthropogenic features-boreholes close to site of interest	There are about ten boreholes drilled to the hydrocarbon source unit in the AOI with a number within 200 m vertically of both hydrocarbon source units. The confidence level in this factor is high.			
Potential receptor	Intrinsic vulnerability score	Specific vulnerability score	Risk group	Confidence
Shale gas				
Kimmeridge and Ampthill Clay Formation	36.5	292	Medium/low	Low
Corallian Group	36.5	292	Medium/High	
Kellaways and Oxford Clay Formations	34.5	276	Low	
Ravenscar Group	34.5	276	Medium/Low	
Lias	36	288	Low	
Mercia Mudstone Group	39.5	316	Low	
Sherwood Sandstone Group	41	328	Medium/Low	

Zechstein Group	44	352	Low	
Millstone Grit Group	71	568	Medium/Low	
Craven Group	71	568	Medium/Low	
Conventional oil and gas				
Kimmeridge and Ampthill Clay Formation	38	76	Low	Low
Corallian Group	38	76	Medium/low	
Kellaways and Oxford Clay Formations	37.5	75	Low	
Ravenscar Group	37.5	75	Low	
Lias	44	88	Low	
Mercia Mudstone Group	57.5	115	Low	
Sherwood Sandstone Group	71	142	Low	
Zechstein Group	71	142	Low	

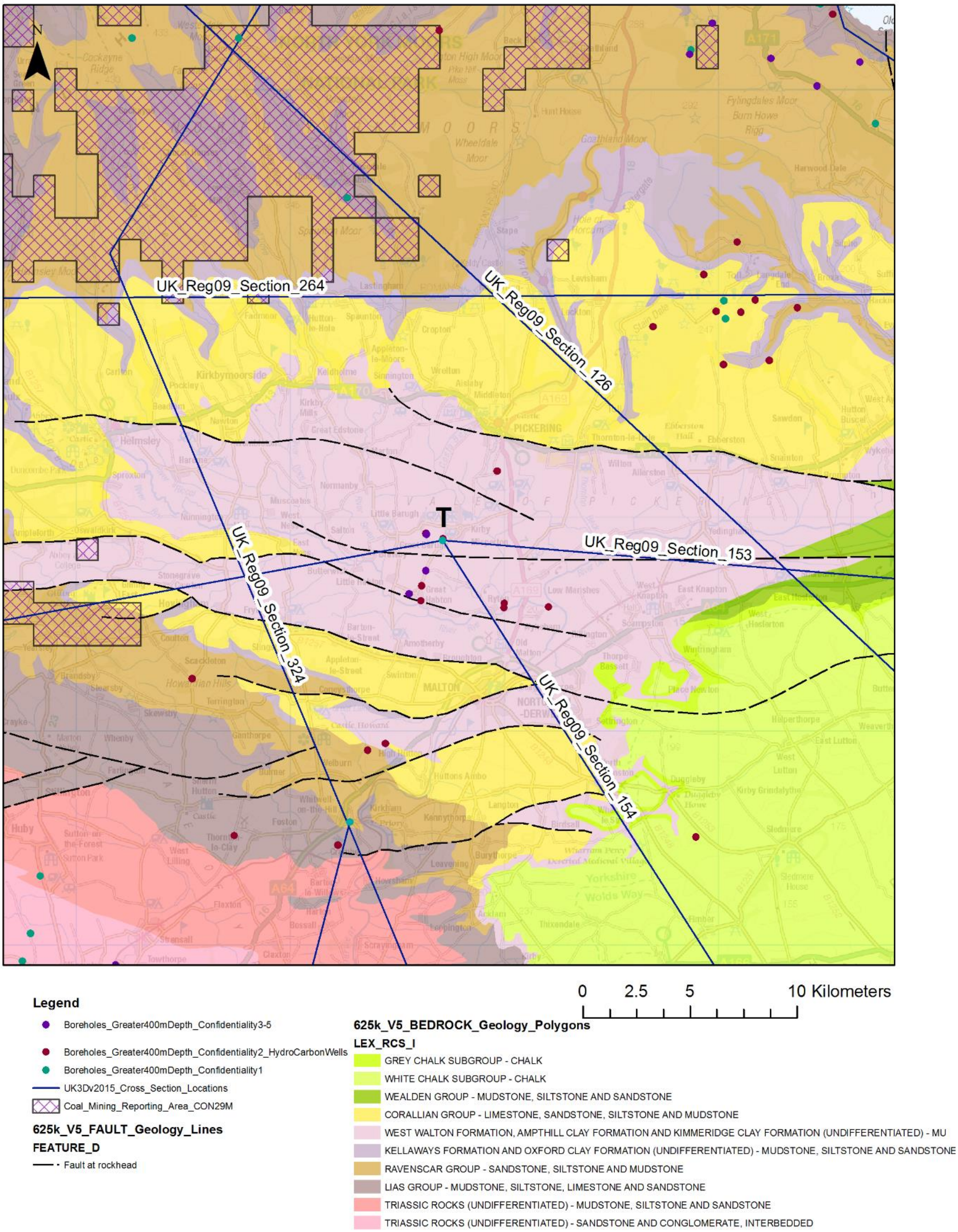

Figure A6.23 Hypothetical location of shale gas and natural gas extraction in the Vale of Pickering, Northeast England with outcrop bedrock geology, LFV sections, deep (> 400 m) boreholes and mines in the region. T indicates the approximate location for the hydrocarbon source units.

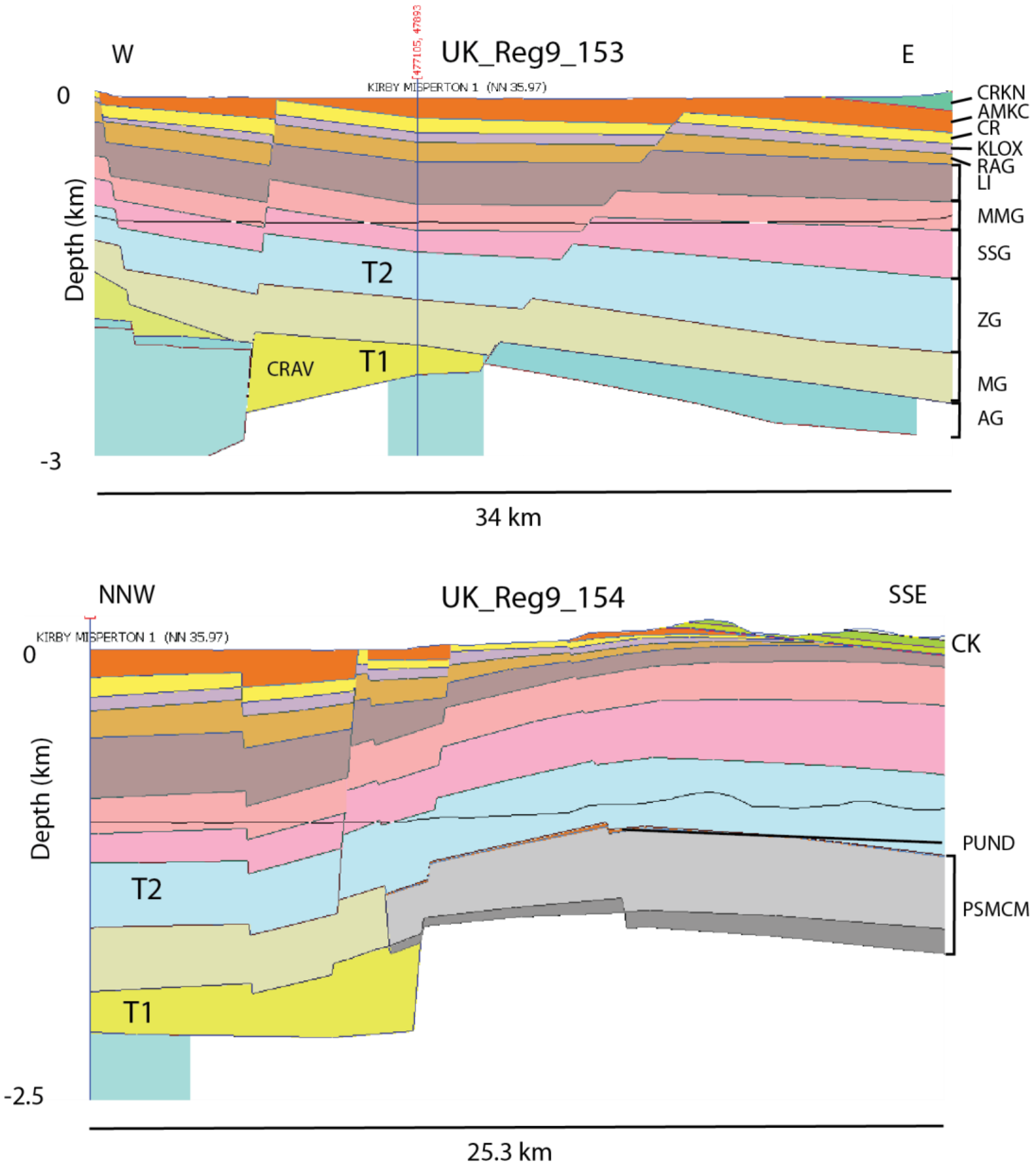

Figure A6.24 Cross sections from LFV with the approximate location of the hypothetical hydrocarbon source units, T1 is hydrocarbon source unit 1 – Craven Group and T2 is hydrocarbon source unit 2 – Zechstein Group. Cross section locations are shown in Figure A6.1. UK_Reg9_154 is approximately across the strike of the basin and UK_Reg9_153 is approximately along strike. The near horizontal black line indicates 1000 m bgl – the shallowest level allowed for shale gas exploitation in England and Wales. Rock codes are described in Table A6.5.

Model Unit	Age	Description
Cromer Knoll Group (Speeton Formation)**	Cretaceous	Clay and mudstone with subsidiary argillaceous, muddy limestone/cementstone/calcilutite and calcareous mudstone.
Kimmeridge and Ampthill Clay Formation (AMKC)	Jurassic	Comprises the Kimmeridge Clay Formation in this region; mudstone with carbonate concretions in lower part.
Corallian Group (CR)	Jurassic	Limestone (sometimes oolitic), sand and sandstone, and siltstone.
Kellaways and Oxford Clay Formations (KLOX)	Jurassic	Siltstone and silty mudstone.
Ravenscar Group (RAG)	Jurassic	Sandstone, mudstone and siltstone.
Lias (Li)	Jurassic	Mudstone and silty mudstone.
Mercia Mudstone Group (MMG)	Triassic	Mudstone, silty mudstone with siltstone and thin sandstone with beds of gypsum.
Sherwood Sandstone Group (SSG)	Triassic	Sandstone with beds of siltstone.
Zechstein Group (ZG)*2	Permian	Dolomite, limestone, evaporites, mudstone and siltstone.
Millstone Grit Group (MG)	Carboniferous	Mudstone, siltstone and sandstone.
Craven Group (CG)*1	Carboniferous	Calcareous mudstone, limestone and mudstone.

Table A6.5 Rock units present in the hypothetical southeast AOI. Descriptions are from the sheet memoir (Powell et al., 1992) and the BGS Lexicon. Colours correspond with those used in the LithoFrame Viewer section (Figure A6.24) and the AOI conceptual model (Figure A6.25). *1 indicates the hydrocarbon source unit 1 and *2 indicates hydrocarbon source unit unit 2. ** indicates unit not in AOI.

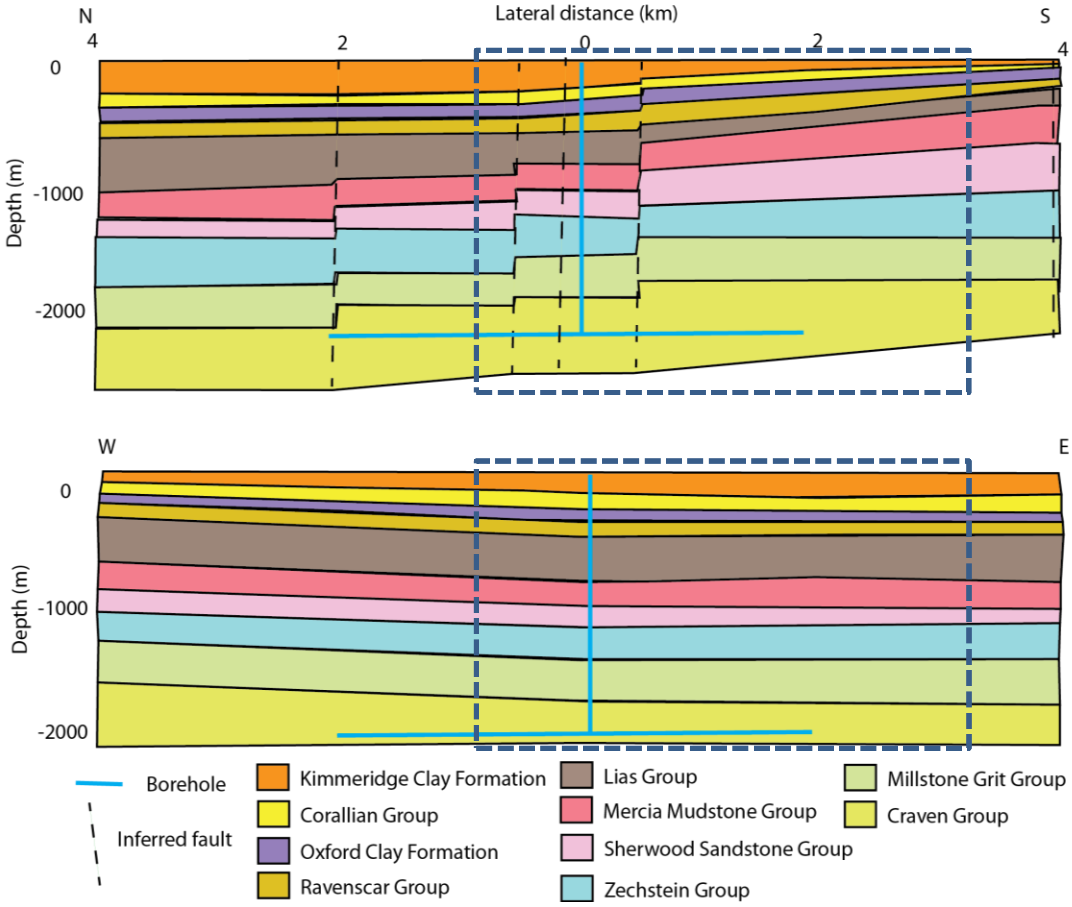

Figure A6.25 Conceptual model of the AOI for the hypothetical shale gas site in the Vale of Pickering, Northeast England. The AOI for hydrocarbon source unit 1 (Bowland Shale Formation, part of the Craven Group) is the whole conceptual model, the AOI for hydrocarbon source unit 2 (Zechstein Group) is within the box with the dotted lines.

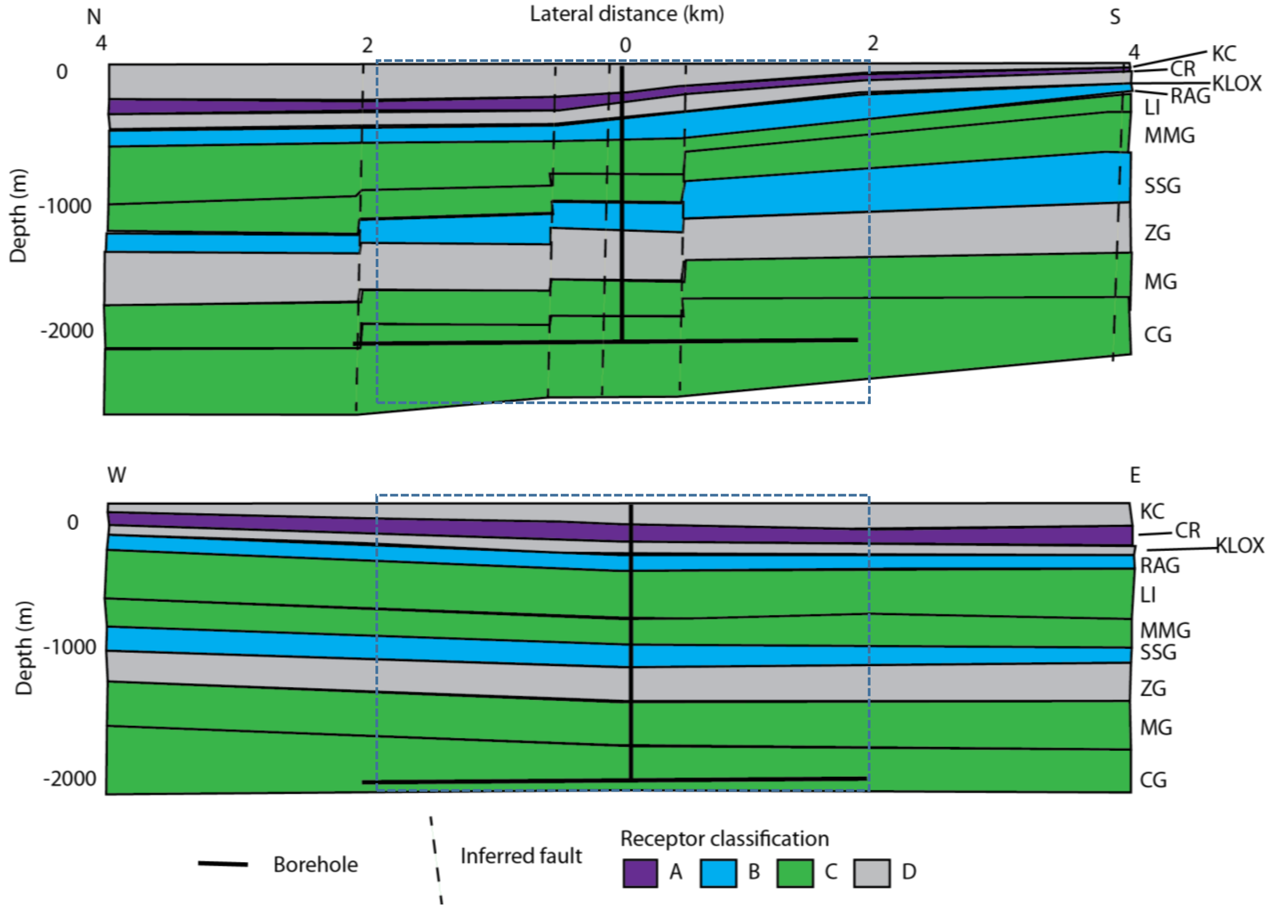

Figure A6.26 Receptor classifications for units within the conceptual model of the AOI. Whole model is AOI for hydrocarbon source unit 1 (Bowland Shale, Craven Group) and blue dotted box indicates AOI for hydrocarbon source unit 2 (Zechstein Group)

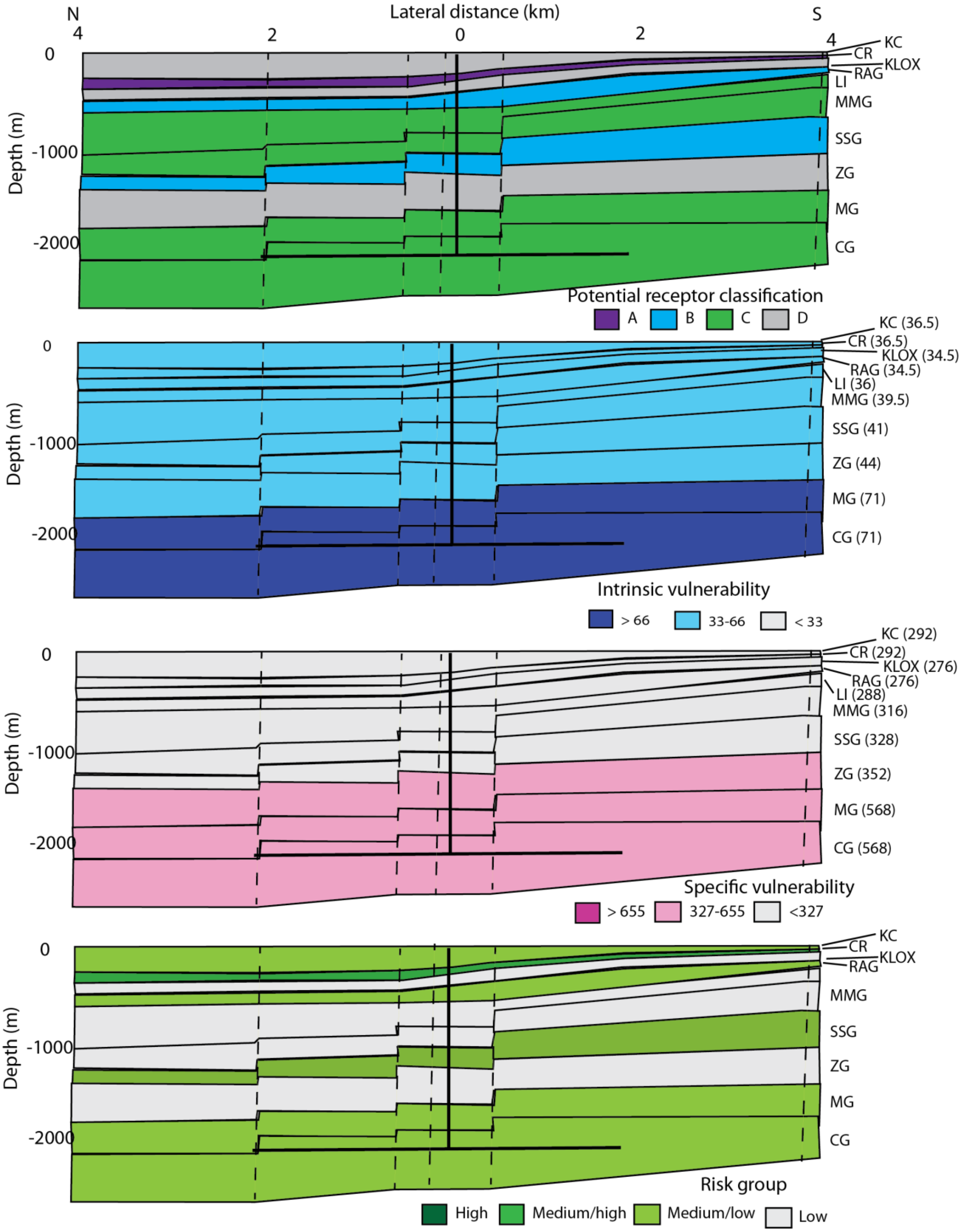

Figure A6.27 Conceptual model for the AOI in the northeast of England for potential shale gas extraction from hydrocarbon source unit 1, the Craven Group (Bowland Shale Formation). Top to bottom; potential receptor classifications, intrinsic and specific vulnerability scores risk group, for each potential receptor. See Table A6.5 for code translations. The confidence for this assessment is low. Boundaries used for intrinsic and specific vulnerability and risk groups are used for preliminary purposes.

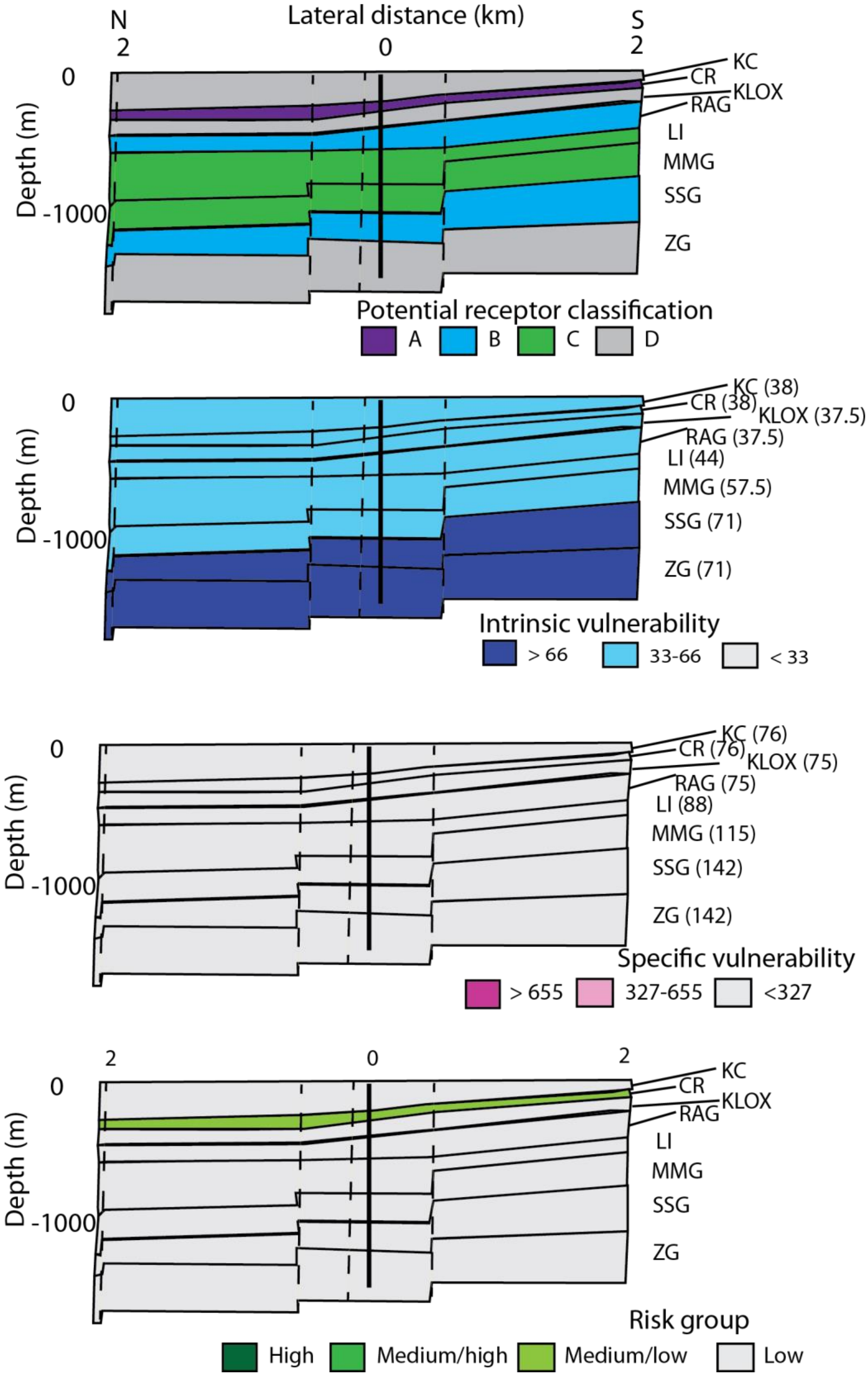

Figure A6.28 Conceptual model for the AOI in the northeast of England for conventional hydrocarbon extraction from hydrocarbon source unit 2, the Zechstein Group. Top to bottom; potential receptor classifications, intrinsic and specific vulnerability and risk groups, for each potential receptor. See Table A6.5 for code translations. The confidence for this assessment is low. Boundaries used for intrinsic and specific vulnerability and risk groups are used for preliminary purposes.

Summary of Case Study 5: Shale gas and conventional hydrocarbons, Northeast England

- For hydrocarbon source unit 1, intrinsic vulnerability scores for the potential receptors are quite varied, ranging from 34.5 to 71 (Figure A6.27).
- There was very little difference in the intrinsic vulnerability score (maximum score difference of 2) for the assessments completed for the north and south of the AOI, and this does not impact on the risk group.
- The minimum intrinsic vulnerability scores for hydrocarbon source unit 2 were slightly higher, ranging from 37.5 to 71, due to the closer proximity of the hydrocarbon source unit (Figure A6.28).
- The intrinsic vulnerability scores generally decrease with vertical separation from the hydrocarbon source unit. The slightly higher intrinsic vulnerability in the Corallian Group and Kimmeridge Clay results from the known solution features in the Corallian Group.
- It has been assumed that multiple faults could provide potential pathways for all of the units within both AOIs. However it is possible that these might not penetrate the Zechstein Group anhydrites (Newell et al., *2018*). There is some evidence for transmissive faults in the region (Reeves et al., 1978).
- The specific vulnerability scores for the potential receptors for hydrocarbon source unit 1 (Bowland Shale) are higher than other case studies (276 to 568) as a result of the assumed higher hazard nature of shale gas extraction activities compared to other technologies.
- For hydrocarbon source unit 2, the specific vulnerability scores are relatively low (75 to 142) as a result of the assumed lower hazard nature of conventional hydrocarbon extraction.
- The confidence level of the intrinsic vulnerability scores is medium because there are a number of deep boreholes in the AOI which record the depths and thicknesses of all the units. The confidence for the specific vulnerability score remains low due to the uncertainties associated with the direction of the head gradients.
- The risk group, is medium/high for the Corallian Group for hydrocarbon source unit 1 and medium/low for hydrocarbon source unit 2.
- The Kimmeridge Clay, Ravenscar Group, Sherwood Sandstone, Millstone Grit and Craven Groups are also in the medium/low risk group in relation to hydrocarbon source unit 1.
- All of the potential receptors, with the exception of the Corallian Group, are in the low risk group in relation to hydrocarbon source unit 2.
- Downgrading of the potential receptor class of units at depth (such as the Sherwood Sandstone, Millstone Grit and the Craven Group) would lower the risk group for the hydrocarbon source unit 1 to low, which is potentially more realistic at these depths. The quality of groundwater and hence potential receptor type is a major uncertainty in assessing the risk group for the aquifers.
- The assessment would benefit from a greater understanding of the head distribution and groundwater flow paths. If it could be shown that faults do not cut the Zechstein Group rocks then the risk group could be reduced for overlying units. An improved understanding of the fault behaviour in the region would also be useful.
- Smedley et al. (2017) found high concentrations of dissolved methane in the Quaternary/Kimmeridge Clay aquifer of the Vale of Pickering. It is currently unclear as to the source of this methane (biogenic or thermogenic) and requires further work to investigate the origins since the latter might indicate that permeable pathways could pre-exist in the region, or AOI.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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