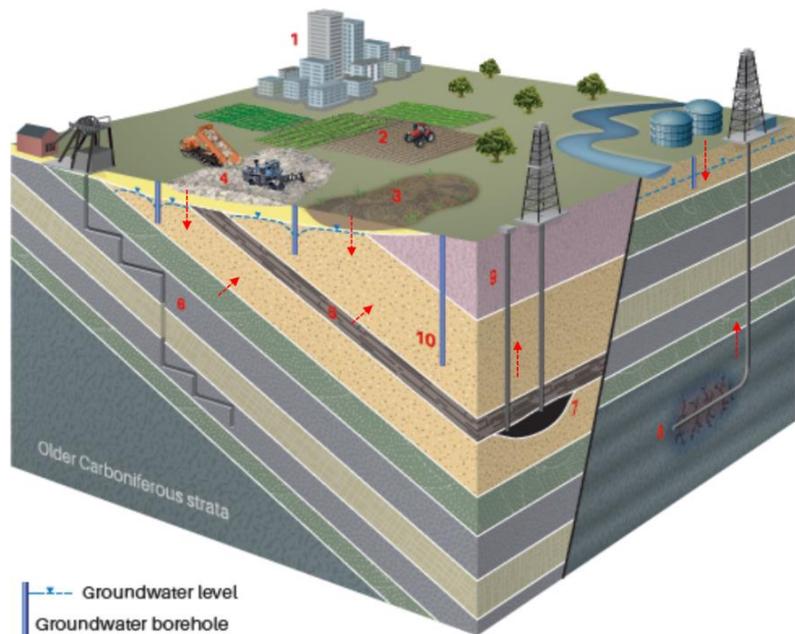




British
Geological
Survey

Baseline studies for assessing risks to groundwater from onshore oil and gas and other deep subsurface activities: synthesis report

Environmental Change and Resilience Programme
Open Report OR/21/042



BRITISH GEOLOGICAL SURVEY

ENVIRONMENTAL CHANGE AND RESILIENCE PROGRAMME

OPEN REPORT OR/21/042

The National Grid and other
Ordnance Survey data
© Crown Copyright and
database rights 2021.
Ordnance Survey Licence
No. 100021290 EUL.

Keywords

Groundwater, baseline, oil
and gas.

Bibliographical reference

R A BELL, D MALLIN MARTIN, P
L SMEDLEY. 2021.

Baseline studies for assessing
risks to groundwater from
onshore oil and gas and other
deep subsurface activities:
synthesis report. *British
Geological Survey Open
Report*, OR/21/042. 49pp.

Copyright in materials derived
from the British Geological
Survey's work is owned by
UK Research and Innovation
(UKRI) and/or the authority
that commissioned the work.
You may not copy or adapt
this publication without first
obtaining permission. Contact
the BGS Intellectual Property
Rights Section, British
Geological Survey, Keyworth,
e-mail ipr@bgs.ac.uk. You
may quote extracts of a
reasonable length without
prior permission, provided a
full acknowledgement is given
of the source of the extract.

Maps and diagrams in this
book use topography based
on Ordnance Survey
mapping.

Baseline studies for assessing risks to groundwater from onshore oil and gas and other deep subsurface activities: synthesis report

R A Bell, D Mallin Martin, P L Smedley

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of UK Research and Innovation.

British Geological Survey offices

**Nicker Hill, Keyworth,
Nottingham NG12 5GG**

Tel 0115 936 3100

BGS Central Enquiries Desk

Tel 0115 936 3143

email enquiries@bgs.ac.uk

BGS Sales

Tel 0115 936 3241

email sales@bgs.ac.uk

**The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP**

Tel 0131 667 1000

email scotsales@bgs.ac.uk

**Natural History Museum, Cromwell Road,
London SW7 5BD**

Tel 020 7589 4090

Tel 020 7942 5344/45

email bgs_london@bgs.ac.uk

**Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT**

Tel 029 2167 4280

**Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB**

Tel 01491 838800

**Geological Survey of Northern Ireland, Department of
Enterprise, Trade & Investment, Dundonald House, Upper
Newtownards Road, Ballymiscaw,
Belfast, BT4 3SB**

Tel 01232 666595

www.bgs.ac.uk/gsni/

**Natural Environment Research Council, Polaris House,
North Star Avenue, Swindon SN2 1EU**

Tel 01793 411500

Fax 01793 411501

www.nerc.ac.uk

**UK Research and Innovation, Polaris House,
Swindon SN2 1FL**

Tel 01793 444000

www.ukri.org

Website www.bgs.ac.uk

Shop online at www.geologyshop.com

Foreword

This report is the product of a collaboration between the British Geological Survey (BGS) and Environment Agency (EA) which has aimed to investigate the ranges of typical baseline chemical compositions in groundwater from aquifers in England in places where onshore oil and gas may be explored and/or exploited. The project was initiated at a time when exploration for shale gas was being appraised actively in some areas of northern England and considered through the planning process in others, and before the England-wide moratorium on hydraulic fracturing in England was introduced in November 2019. Although this work has been carried out with specific reference to onshore oil and gas activities, the methodology also has applications for other deep subsurface activities, for example carbon capture and storage and geothermal energy extraction.

This project follows on from earlier baseline groundwater studies carried out by BGS during the 1990s, 2000s and 2010s, which focussed on inorganic chemistry of groundwater in British aquifers to inform aquifer characterisation, regulation and protection. This report forms a final synthesis of three regional summaries (Mallin Martin and Smedley, 2020, Mallin Martin and Smedley, 2021a, Mallin Martin and Smedley, 2021b) of groundwater chemistry (inorganic and organic) and introduces an assessment for the potential presence of deep subsurface compounds in groundwater in English aquifers.

Acknowledgements

Acknowledgements are due to Environment Agency staff, especially Ian Davey, Alwyn Hart, Jim Grundy, Susie Bateson, Andrew Barker and Sian Loveless for helpful discussions on groundwater quality, onshore oil and gas operations and environmental regulation, and to Gary Edwards, Jon Barrett and Danielle Ashton for Environment Agency project management. Acknowledgements are also due to Calum Ritchie (BGS) for figure production.

Contents

Foreword	i
Acknowledgements.....	i
Contents	ii
Summary	v
1 Introduction	1
1.1 Background.....	1
1.2 Report objectives	3
2 Assessment methodology	5
2.1 Compounds related to OOG and other deep subsurface activities	5
2.2 Potential sources of deep sub-surface compounds in groundwater.....	5
2.3 Assessment methodology for groundwater quality	10
3 Aquifer reviews	13
3.1 Quaternary superficial deposits of Fylde peninsula	13
3.2 Quaternary and Jurassic aquifers of the Vale of Pickering	18
3.3 Cretaceous Lower Greensand of south-east England	25
3.4 Triassic Sherwood Sandstone aquifer of Nottinghamshire and South Yorkshire	27
3.5 Pennine Coal Measures of the East Midlands and South Yorkshire.....	31
4 Conclusions	34
5 Recommendations	36
References	37

FIGURES

Figure 1. Study areas included in this report and areas included in previous studies. Aquifer designation maps EA/BGS 1:50k data ©UKRI 2021; OS data ©Crown copyright 2021.	2
Figure 2. Potential pathways for transfer of OOG/deep sub-surface compounds to groundwater	9
Figure 3. Assessment methodology for identifying the potential for OOG-related and other deep subsurface compounds in groundwater	11
Figure 4. Fylde peninsula superficial geology.....	14
Figure 5. Fylde peninsula bedrock geology	14
Figure 6. CORINE Land Cover (CLC) (2018) land classification map for the Fylde peninsula (European Environment Agency (EEA), 2019).....	15
Figure 7. OGA data for the Fylde peninsula. Map shows onshore wells, PEDL locations, onshore conventional hydrocarbon fields, and the joint BGS and OGA dataset for prospective areas for shale gas (data from BGS and OGA (2018); (OGA, 2021a, b, c))......	16
Figure 8. Vale of Pickering superficial geology.....	19
Figure 9. Vale of Pickering bedrock geology	20
Figure 10. CLC (2018) land classification map for the Vale of Pickering (European Environment Agency (EEA), 2019).....	21
Figure 11. OGA data for the Vale of Pickering. Map shows onshore wells, PEDL locations, onshore conventional fields, and the joint BGS and OGA dataset for prospective areas for shale gas (data from BGS and OGA (2018); (OGA, 2021a, b, c))......	21
Figure 12. Vertical separation map of the various shale gas source rocks and the Corallian limestone aquifer (from Loveless et al. (2018), BGS (2018)).	22
Figure 13. Nottinghamshire and South Yorkshire coal-mining information. Primary = generally thick coals at surface, main targets for opencast coal extraction. Secondary = generally thin coals at surface, secondary targets for opencast coal extraction (Jones, 2006).....	28
Figure 14. East Midlands and South Yorkshire coal-mining data. Primary = generally thick coals at surface, main targets for opencast coal extraction. Secondary = generally thin coals at surface, secondary targets for opencast coal extraction (Jones, 2006).	32
Figure 15. Comparison methane data for the study areas.....	35

TABLES

Table 1. Definition of compounds related to OOG and other deep subsurface activities.....	5
Table 2. Supporting analysis to understand the hydrogeological regime and provenance of deep subsurface compounds	5
Table 3. Key considerations for identifying sources of OOG and deep sub-surface compounds in groundwater.	6
Table 4. Assessment matrix for understanding baseline groundwater quality with respect to OOG and other deep subsurface compounds.....	12
Table 5. Links to online resources for baseline assessment.....	12
Table 6. Example from the Fylde peninsula of the overall magnitude and potential scale of influences	13
Table 7. Fylde peninsula superficial deposits aquifer: matrix assessment.....	17
Table 8. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Fylde peninsula superficial deposits	17
Table 9. Vale of Pickering superficial/Kimmeridge aquifer: matrix assessment	23

Table 10. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Vale of Pickering superficial/Kimmeridge deposits.....	23
Table 11. Vale of Pickering marginal Corallian aquifer: matrix assessment.....	24
Table 12. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the marginal Corallian aquifer	24
Table 13. Lower Greensand aquifer: matrix assessment.....	26
Table 14. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Lower Greensand aquifer of south-east England	27
Table 15. Nottinghamshire/South Yorkshire Sherwood Sandstone Group aquifer: matrix assessment	30
Table 16. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Triassic Sherwood Sandstone of Nottinghamshire and South Yorkshire.....	30
Table 17. Pennine Coal Measures aquifer: matrix assessment.....	33
Table 18. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Coal Measures of the East Midlands and South Yorkshire.....	34
Table 19. Summary of potential impact on groundwater quality in superficial deposit aquifers considered in this report.	35
Table 20. Summary of potential impact on groundwater quality in bedrock aquifers considered in this report.	35

Summary

This report is the final of a series of reports resulting from a BGS-EA collaboration to characterise the risks to groundwater from new developments in onshore oil and gas (OOG) exploration in England. The previous three reports (Mallin Martin and Smedley, 2020, Mallin Martin and Smedley, 2021a, Mallin Martin and Smedley, 2021b) were focused on establishing groundwater baseline chemical compositions, particularly of those analytes that are and could be associated with OOG activities, in order to facilitate distinction between current compositions and any new industrial contamination from such activities. This synthesis report uses the experience gained from these earlier reports to develop an assessment methodology for identifying the influence of both the baseline environment and anthropogenic impact on groundwater quality prior to any new OOG activity. The methodology also has relevance for other subsurface activities.

The previous three reports in this series concluded that key influencing factors on baseline groundwater quality when considering OOG-type compounds were not the location of hydrocarbon extraction sites, but instead aquifer lithology and overlying superficial deposits.

The methodology detailed in this report has been designed to provide a rapid assessment for the potential presence of OOG-type contaminants and other deep subsurface compounds in groundwater. The assessment has been designed to consider the magnitude of influence that each factor is likely to have on groundwater quality. The compounds may be either organic or inorganic: each are essential to understanding sources of contamination, but also for understanding the hydrogeological system. The findings from the case study area reports have been used to justify the weighting that each factor has on groundwater quality. The key factors to be considered are geological (e.g. aquifer lithology, proximity to organic rich sediments), hydrogeological (confined, unconfined) and anthropogenic activities (e.g. hydrocarbon extraction, surface activities). Conducting this assessment for a specific aquifer requires a baseline conceptual understanding of both the hydrogeology and hydrogeochemistry which is a key step in the process. The aim is that this can then be used to understand the potential impact a specific aquifer setting may have on groundwater quality, in relation to OOG and other deep subsurface compounds, prior to any development.

1 Introduction

1.1 BACKGROUND

Establishing a good environmental 'baseline' ahead of any new subsurface industrial development is essential for helping to identify changes that may have occurred as a result of new activities. The absence of such data in the US, particularly for unconventional sources of hydrocarbons, has led to major controversy and inability to identify and deal effectively with apparent impacts that have occurred. The UK has a mature conventional onshore oil and gas (OOG) industry and over the past 10 or more years there has been an increased interest in exploration for onshore unconventional oil and gas resources e.g. Coal Bed Methane (CBM) and shale gas. The last batch of onshore Petroleum Exploration and Development Licences (PEDLs) was issued by the Oil and Gas Authority (OGA) in 2015 under the 14th Licensing round, awarding 159 new blocks through 93 licences (UKOOG, 2017). The primary focus of this round was the increase in licensed areas targeting shale-gas exploration and development. Planning permission for shale-gas development at both the Lancashire and Kirby Misperton sites was approved by Local Authorities in 2016 and the first exploration well at Preston New Road was drilled in 2017. A moratorium on high-volume hydraulic fracturing in England was then imposed by the UK Government in November 2019 following a series of earthquakes. This brought England in line with moratoria on hydraulic fracturing imposed in the other UK nations.

Since the inception of this project in 2018, there has been a major shift in the political landscape, from the increased interest in shale-gas development in 2015 to the UK Government's recent commitment to its 2050 decarbonisation target (Net Zero). This now provides a strong driver for identifying low-carbon alternatives to current fossil-fuel-dominated energy sources. The subsurface has the potential to play a significant role in delivering these low-carbon energies, from raw material and energy extraction, to storage, and to disposal of derived wastes (e.g. CO₂). It is also important to recognise that the use or exploitation of the subsurface can introduce a range of environmental risks that need to be understood properly and managed effectively. This includes the physical modification of the subsurface, but also the introduction/extraction of chemicals, substances and temperature changes. These activities can also lead to the mobilisation of natural contaminants as a result of physical, chemical and biological changes that can occur. This nascent low-carbon industry is likely to be the Government's focus over the coming years and therefore there remains a need to better understand the regional water quality in a number of drinking-water aquifers with respect to naturally-occurring organic and inorganic constituents.

Monitoring is an important tool for understanding the impacts of subsurface developments on groundwater, and undertaking a baseline survey of groundwater conditions prior to any future development is an important first step. The Environment Agency (EA) and British Geological Survey (BGS) produced a number of baseline inorganic geochemistry reports for groundwater in major drinking-water aquifers ('principal' and 'secondary') across England and Wales from 2002 to 2005 (BGS, 2016). BGS-only baseline investigations both pre- and post-dated this collaboration, between the 1990s and 2015. The studies were designed to provide a wide-ranging understanding of baseline groundwater quality across the country and are used widely by EA staff and others wanting to understand groundwater quality.

The previous reports only went as far as to consider the dissolved organic carbon (DOC) content within the aquifer, alongside the wider inorganic geochemistry. However, in the context of the nascent British onshore oil and gas industry, dissolved methane and hydrocarbons were not generally included in these baseline reports. More recently, BGS, again with EA support, has also carried out an initial survey of methane (Bell et al., 2016, Bell et al., 2017), and other oil- and gas-related substances in aquifers (e.g. Fylde peninsula and Vale of Pickering environmental baseline monitoring projects and Abandoned Wells project (Bell et al., 2018, Ward et al., 2020)). Many of these projects are linked to the potential impacts of unconventional hydrocarbon exploration (i.e. shale gas) on groundwater, identifying compounds of interest and understanding baseline concentrations of these compounds, although predominately on a local scale. The methane baseline survey covered England, Scotland and Wales, but was limited to methane as the key compound of interest. As there is a perceived risk of contaminant migration to groundwater or the

surface via pathways associated with the exploration and production of both OOG resources and low-carbon technologies, a clearer picture of naturally-occurring organic compounds and pre-existing anthropogenic inputs within aquifers needs to be ascertained, alongside their inorganic compositions. The areas covered by these other reports are highlighted in Figure 1.

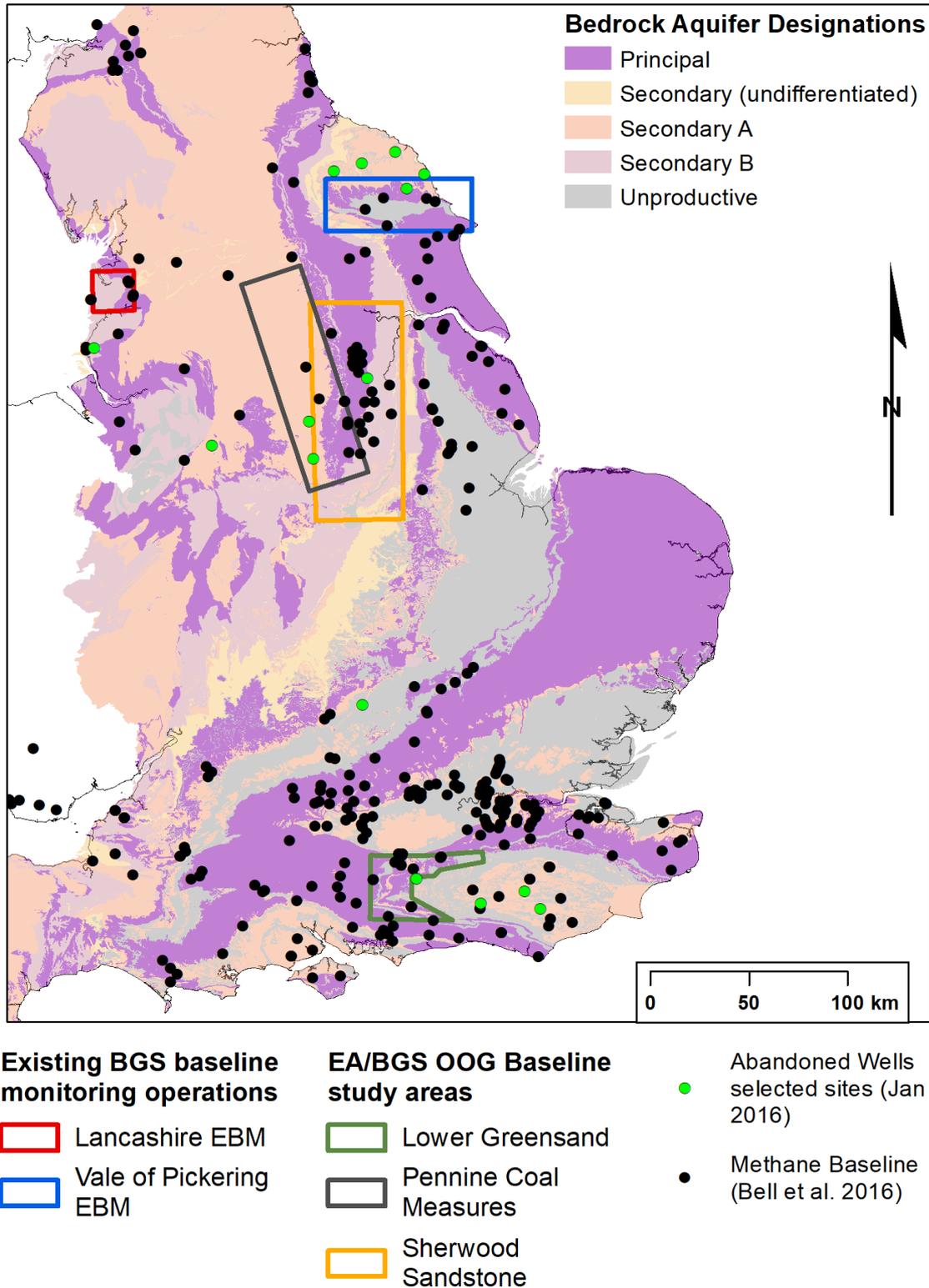


Figure 1. Study areas included in this report and areas included in previous studies. Aquifer designation maps EA/BGS 1:50k data ©UKRI 2021; OS data ©Crown copyright 2021.

This report summarises the important factors to consider when making assessments of the likely baseline conditions of aquifers and is based on findings arising primarily from groundwater baseline investigations carried out in three case study areas. These are the Triassic Sherwood Sandstone aquifer of Nottinghamshire and South Yorkshire, the Lower Greensand aquifer of Surrey and East Sussex and the Coal Measures of Nottinghamshire and South Yorkshire (Mallin Martin and Smedley, 2020, Mallin Martin and Smedley, 2021a, Mallin Martin and Smedley, 2021b):

- The Sherwood Sandstone of Nottinghamshire and South Yorkshire has well-defined spatial variations in groundwater chemistry, controlled by residence time and aquifer redox conditions. Compositions are of Ca-(Mg)-HCO₃ type with increasing concentrations of gypsum-derived SO₄ downgradient in confined groundwaters. Groundwater shows evidence for pollutants (NO₃, SO₄, Cl and occurrences of small quantities of PAHs, solvents and pesticides) in the shallow unconfined sections with young groundwater, and absence of pollutants in the deeper, confined sections with older groundwater. Concentrations of dissolved solids increase downgradient in the confined aquifer in line with residence time and natural water-rock reactions. Concentrations of naturally-occurring organic compounds in the groundwater, including concentrations of dissolved methane, are low (up to 120 µg/L). This is related to the paucity of organic matter in the sandstone.
- The Lower Greensand aquifer of south-east England also shows the impacts of variable groundwater residence time and redox conditions controlled by hydrogeology. Groundwater is of Ca-HCO₃ to Ca-mixed-anion type, with evidence of pollution from NO₃ and small quantities of disinfection by-products in the unconfined section of aquifer and absence in the confined aquifer. Naturally-occurring organic matter is sparse in the sediments and only small quantities of dissolved methane have been found in groundwater from sections of the confined aquifer (up to 460 µg/L).
- The Coal Measures of Nottinghamshire and South Yorkshire have less well-defined spatial distributions of groundwater chemical compositions relative to the other study areas as a result of the complexities in the Coal Measures strata and the subsequent change of the hydrological regime due to mining. Groundwater compositions include Ca-Mg-HCO₃, Ca-Mg-SO₄ and Na-HCO₃ types. The groundwater investigated occurs under reducing to strongly reducing conditions, evidenced by increased concentrations of dissolved Fe, Mn and NH₄ and usually low concentrations of NO₃. The study lacked data for the distributions of dissolved methane in the groundwater but previous studies have reported concentrations up to 9,000 µg/L under the more strongly reducing conditions (Banks et al., 2017). The Coal Measures contain a relative abundance of naturally-occurring organic matter, including coal, which is reflected by comparatively high concentrations of total organic carbon (TOC) (up to 6.45 mg/L) in the groundwater. This may be responsible for the observed higher concentration of dissolved methane.

This report also benefits from recent BGS studies carried out in other areas in England where hydrocarbon exploration activities have previously been planned.

1.2 REPORT OBJECTIVES

As described in the previous reports published as part of this project (Mallin Martin and Smedley, 2020, Mallin Martin and Smedley, 2021a, Mallin Martin and Smedley, 2021b), the overarching aim of this work has been to investigate the presence of compounds in groundwater that could be associated with OOG activities in a variety of aquifers across England & Wales. This report aims to develop an assessment methodology for identifying the influence of both the baseline environment and anthropogenic impact on groundwater quality prior to any new OOG or other deep subsurface activities.

The assessment will identify the degree of influence different factors are likely to have on groundwater quality and specify the compounds related to OOG activities or other deep subsurface activities. This report also aims to include a wider review of previous work on deep subsurface compounds present in groundwater, including not only the sampling and assessment carried out as part of this project, but incorporating additional BGS/EA funded work.

Therefore, the main objectives of this report are to:

- Define OOG and other 'deep subsurface compounds';
- Identify potential sources of these compounds in groundwater;
- Using the conclusions of the previous three project reports, rank these sources in terms of influence on groundwater quality;
- Determine an assessment methodology for likely influence of environmental baseline and anthropogenic impacts on groundwater quality;
- Demonstrate this methodology for aquifers where there are existing data to calibrate the assessment.

The additional datasets to be used to demonstrate this assessment method include summary information from the Fylde peninsula Environmental Baseline Monitoring (EBM) project, Vale of Pickering EBM project, methane baseline (Bell et al., 2016) and Abandoned Wells projects (Bell et al., 2018). The four key aquifer types used to demonstrate the methodology are the; Quaternary superficial deposits, Cretaceous Lower Greensand, Triassic Sherwood Sandstone Group and the Carboniferous Coal Measures. Previous BGS baseline groundwater-quality data have been collated for all these aquifers, although new data were not acquired for the Coal Measures due to sampling and analytical restrictions related to COVID-19.

2 Assessment methodology

2.1 COMPOUNDS RELATED TO OOG AND OTHER DEEP SUBSURFACE ACTIVITIES

The definition of OOG and other deep subsurface compounds within this project encompasses both inorganic and organic analytes. Activities include both hydrocarbon extraction (e.g. OOG and CBM) and low-carbon technologies (e.g. Carbon Capture and Storage, geothermal energy). In this context, these analytes include (Table 1); indicators of salinity, dissolved gases (including CO₂ and CH₄), naturally-occurring radioactive materials (NORM) and organic compounds including volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs) polycyclic aromatic hydrocarbons (PAHs) and Total Petroleum Hydrocarbons (TPH).

Table 1. Definition of compounds related to OOG and other deep subsurface activities

Determinands	Analytes	Reason for analysis
Indicators of salinity	SEC, Na, Cl, SO ₄ , Br	Any water from depth (>450 m) has the potential to be brackish or saline due to long residence time
Dissolved gases	CH ₄ , higher hydrocarbons, CO ₂ , Rn	Both hydrocarbon reservoirs and geothermal aquifers have the potential to contain high concentrations of dissolved gases
NORM	Rn, (U, Ra)	Rn may be associated with U-rich deposits in aquifers/reservoirs
Organic compounds	TPH, PAH, SVOCs, VOCs	Both hydrocarbon reservoirs and deep geothermal aquifers could contain organic compounds

To further understand the hydrogeological regime, other supporting information can be used to help identify groundwater residence times, groundwater redox state and the provenance of some deep subsurface compounds (Table 2).

Table 2. Supporting analysis to understand the hydrogeological regime and provenance of deep subsurface compounds

Determinands	Analytes	Reason for analysis
Water stable isotopes	δ ² H, δ ¹⁸ O, δ ¹³ C-DIC, δ ¹³ C-CH ₄	Residence time/provenance indicators
Redox indicators	DO, Eh, Fe, Mn, NO ₃ , NH ₄ , As	Groundwater redox state

2.2 POTENTIAL SOURCES OF DEEP SUB-SURFACE COMPOUNDS IN GROUNDWATER

There are many potential sources of OOG/deep sub-surface type compounds in groundwater which can be considered as either 'intrinsic', or part of the baseline environment, e.g. deriving from the aquifer geology, or those that result from 'specific' anthropogenic impacts (Table 3). Throughout the previous three project reports these contributing factors have been tested to verify their actual influence on groundwater quality and the magnitude of this influence. As it is not possible to acquire groundwater quality data for every location, a key aim of the assessment methodology is to be able to evaluate these baseline and anthropogenic influences on groundwater quality prior to OOG (or other deep subsurface) activities. This evaluation also needs to consider the likely magnitude of the influences e.g. local or regional. The sources of deep subsurface compounds are also highly dependent on a specific location and aquifer type and need

to be considered in tandem with potential pathways (Figure 2). The key considerations are discussed in more detail below.

Table 3. Key considerations for identifying sources of OOG and deep sub-surface compounds in groundwater.

Influence type	Key consideration	Comments
<i>Baseline environment</i>		
Geological	Soil type/overburden overlying aquifer	Impacts recharge, confinement, and may also be a source of organic material (e.g. peat)
	Aquifer lithology	Will impact hydrogeochemistry, potential source for organic constituents in groundwater, e.g. black shale
	Hydrogeological setting	Degree of confinement of the aquifer, predominant flow regime, depth below surface, and source of recharge. May influence the source of dissolved hydrocarbons and their migration into the aquifer
	Deeper stratigraphy	Geological units that may have a history of OOG exploitation, or known to be organic-rich
<i>Anthropogenic impacts</i>		
Surface activities	Industrial land use	May affect potential contaminant inputs
	Agricultural land use	May affect potential contaminant inputs
	Urban environment	May affect potential contaminant inputs and groundwater recharge
	Hydrocarbon extraction – surface activities	May affect potential contaminant inputs
	Coal mining legacy – open cast	May affect potential contaminant inputs
Hydrocarbon resources	Coal mining legacy – at depth	May affect potential contaminant inputs from below the aquifer
	Oil and gas extraction at depth	May affect potential contaminant inputs from below the aquifer

2.2.1 Soil and superficial deposits

Superficial cover is an important influencing factor when trying to understand the baseline environment for deep subsurface compounds. The role of these deposits is multifaceted. They are a source of organic material e.g. peat, lacustrine deposits, they determine vulnerability to an underlying aquifer from surface pollution, and play a part in the degree of aquifer confinement. For instance, migration of water through peaty soils to the aquifer may transport associated organic material, but this would not be the case for a sandy soil lacking in organic material. The composition of the superficial cover will control recharge inputs to a major aquifer and may allow anthropogenic sources of organic material to enter the aquifer. Whilst this is not naturally-occurring (derived from a geological formation), it could be considered ‘baseline’ in the context of pre-existing conditions before other deep subsurface developments. Identifying specific lithologies and thicknesses of organic-rich superficial deposits that influence groundwater quality is outside the scope of this report.

High concentrations of NO₃ are an example of surface-borne contaminants from agricultural or urban sources that are seen to impact on groundwater quality in the unconfined aquifers of e.g. the Sherwood Sandstone and Lower Greensand aquifers. Observed organic contaminants in these groundwaters also include PAHs, VOCs and disinfection by-products. Presence of such contaminants provides a substantial amount of information on groundwater flow paths and residence times.

2.2.2 Aquifer lithology

As identified from the previous three project reports, aquifer lithology is a key influencing factor of groundwater quality and understanding aquifer hydrogeochemistry is essential to discriminating potential sources of deep subsurface compounds. Aquifer lithology may contribute a naturally-occurring component to both the organic and inorganic baseline water quality. Organic-rich units within the aquifer, such as some shales and coal, will likely contribute to the organic groundwater quality. Methane concentrations may be elevated in such settings, for example, in the Pennine Coal Measures, which is exploited for some private water supplies. Aquifer lithology and its impact on deep subsurface compounds was partly assessed as part of the “BGS methane and carbon dioxide from natural sources and coal mining dataset for Great Britain”, carried out by Appleton (2011). This hazard mapping identified regions of the UK which are more susceptible to methane and carbon dioxide based on underlying geology and soil cover, although due to limitations with the underlying geological data, this dataset is no longer routinely available. Other minerals assessment datasets are available to identify peat and coal resources (Table 4), including shallow opencast coal and deep (50–1200 m and >1200 m).

Organic constituents present within the aquifer may also arise from geological units below, which can migrate depending on the geological sequence and structural features separating them. Source rocks for conventional oil and gas resources (along with reservoir rocks) can contribute to the baseline organic chemical quality of the aquifer, although the potential for this is low. The likelihood of this will be controlled by the distance between the two units, whether or not impermeable units overlie the source/reservoir, and if any major structural features may allow for transmission from depth. Initially as part of this project, it was thought that aquifer proximity (vertically or horizontally) to formations such as the Carboniferous Coal Measures, or Jurassic clays could indicate a source of deep subsurface compounds. An example of this in the East Midlands and South Yorkshire, where the Sherwood Sandstone Group is underlain by the Pennine Coal Measures, separated by the Zechstein Group. Methane has the potential to migrate from the coal-bearing formation via natural pathways, including faults (under buoyancy) and induced fractures from coal mining. Although no evidence of this pathway has been found through the work done as part of this project, it still has the potential to influence groundwater quality therefore has been included as a low magnitude influence in the assessment methodology.

No evidence of inflows of contaminants from deeper formations or laterally from formations such as the Carboniferous Coal Measures were identified from the three studied aquifers.

2.2.3 Surface activities

The fact that surface activities play an important role in groundwater contamination has long been understood, be that through point- or diffuse-source pollution. As part of this assessment, certain surface activities have been identified as having the potential to highly influence the presence of deep subsurface compounds in groundwater. These include mining legacy, urban land use, agricultural activities and industrial activities. Legacy coal mining has impacted significantly on the wider hydrogeology and hydrogeochemistry of these regions, particularly at depth. However, the presence of these coal mines may also impact aquifers through surface pollution and inputs of poor-quality water being discharged into the aquifer during groundwater rebound. Urban land use, agricultural activities and heavy industry can also have a significant impact on water quality and resources. Both paved (impermeable) surfaces and sewerage/drainage systems can have a detrimental impact on groundwater quality by introducing pollutants via recharge and leakage. All three of the project case study assessments identify a strong correlation between these surface land uses and the presence of organic compounds and as such are a major consideration in the subsequent assessment.

Legacy contamination from former coal-mining activities has been potentially identified in some of the groundwaters from the Coal Measures of Nottinghamshire and South Yorkshire although definitive apportionment is difficult because of the similarities in chemical signatures with the products of intrinsic natural water-rock reactions in the Coal Measures.

2.2.4 Hydrocarbon extraction

There are a number of locations with a mature and well-developed conventional OOG industry across the UK. There are a number of potentially polluting activities throughout the lifetime of an onshore oil and gas well, including potential for leakage of drilling and flowback and production fluids via surface spills, pre-existing and induced geological pathways (faults and fractures), well casing breaches and longer-term well decommissioning failures. In addition to the OOG industry, there are other hydrocarbon schemes to be considered, including mine-gas recovery schemes and coal-bed methane. The three case study reports and other previous BGS/EA work (Bell et al., 2018) identified no correlation between the regional groundwater quality and the proximity to hydrocarbon infrastructure, therefore this influence has been considered to be low as part of this assessment. However, this previous work has been on a regional scale and cannot consider local impacts.

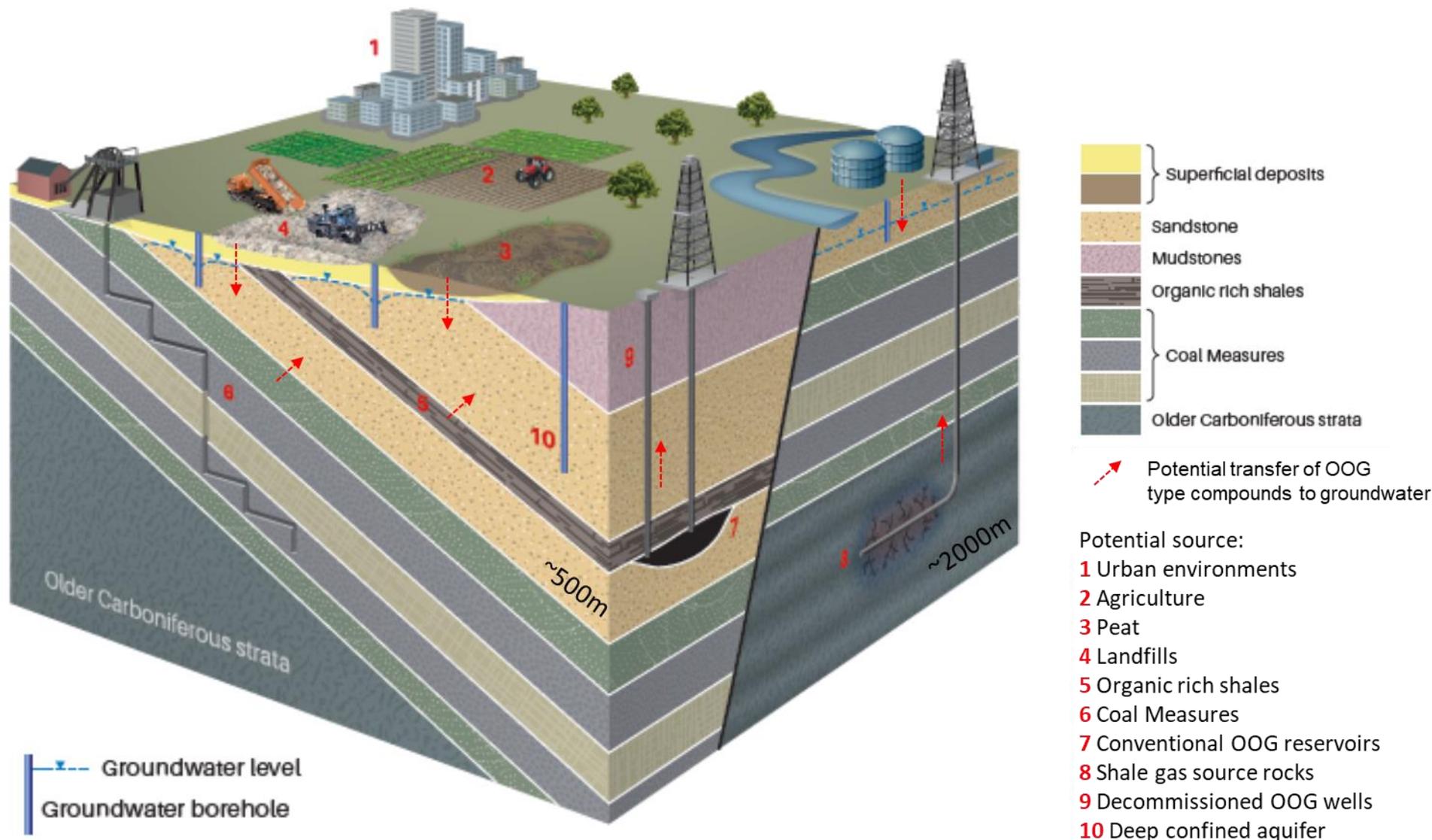


Figure 2. Potential pathways for transfer of OOG/deep sub-surface compounds to groundwater

2.3 ASSESSMENT METHODOLOGY FOR GROUNDWATER QUALITY

The methodology will enable an informed assessment about the potential for the presence of compounds related to OOG contamination or other deep subsurface activities in groundwater baselines. It uses the findings from the project study areas to identify important factors to consider when making an assessment of likely baseline groundwater quality with respect to extraneous compounds in an area with limited data.

The methodology divides the potential influencing factors into the two distinct types, environmental baseline and anthropogenic impacts. The environmental baseline factors include the nature of the aquifer itself, the lithology, overlying deposits and hydrogeological setting. The anthropogenic impacts are surface activities including mining and land use, plus hydrocarbon exploration. Figure 3 shows these factors and whether or not they have high, medium or low influence on groundwater quality. An assessment matrix (Table 4) outlines the influencing factors and the magnitude of influence, the specific compounds likely to be impacted and the datasets required to enable the assessment. Suggested datasets are open source and should be used in conjunction with their corresponding metadata to gain an appreciation of why the data were collected, since this could impact the assessment (Table 5).

The second part of the assessment identifies where influences are likely to be on a local scale (e.g. isolated areas of peat, one hydrocarbon well) or widescale (e.g. large urban environments, significant organic-rich aquifer).

Once the assessment has been carried out, the overall magnitude and potential scale of influences and spatial distribution can be summarised, for example in Table 6. This table links to the initial assessment but summarises the compounds that may be impacted to make data assessment easier. Example assessments using the data from this project and other study areas (Figure 1) are described in Section 3.

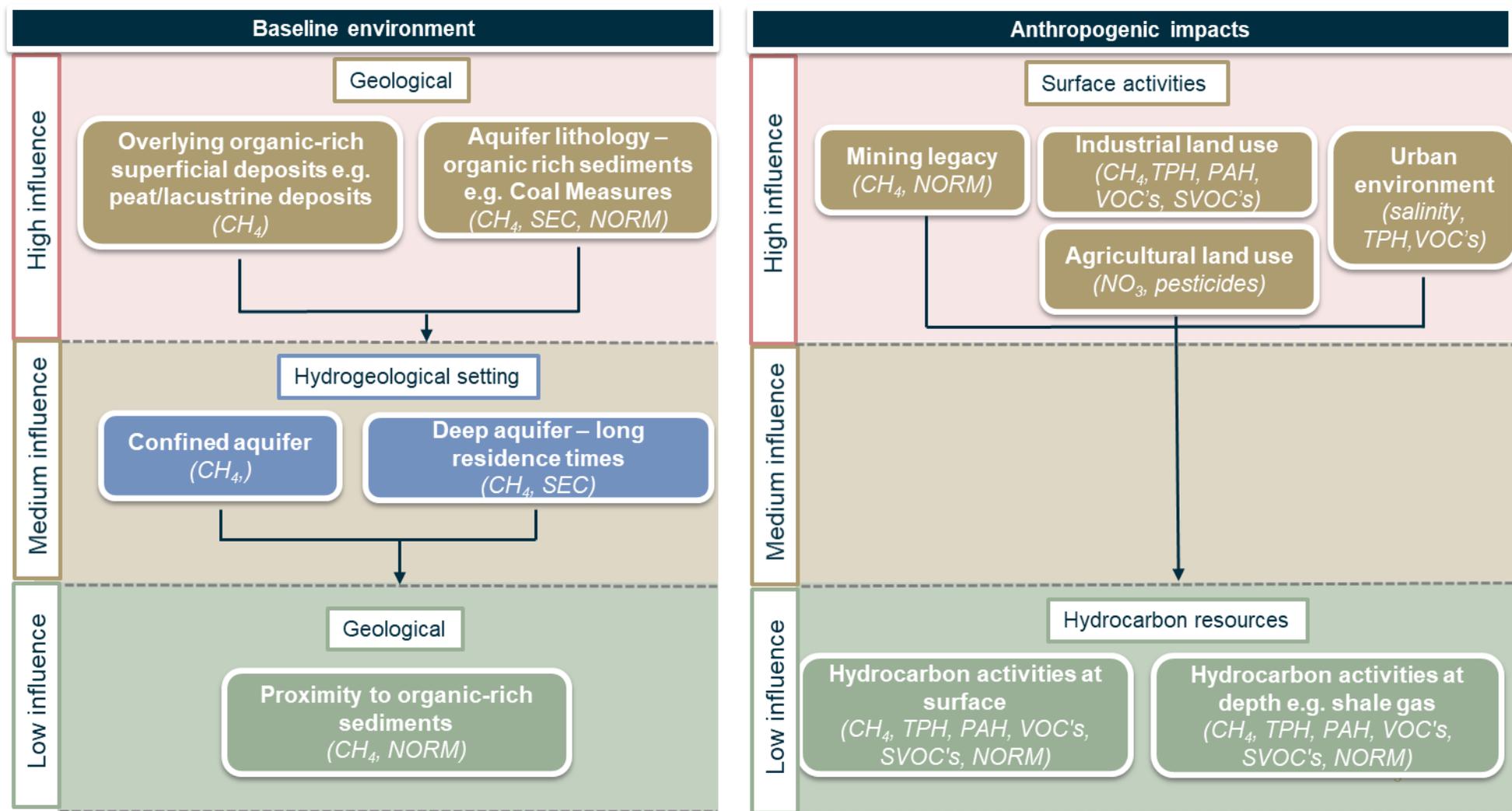


Figure 3. Assessment methodology for identifying the potential for OOG-related and other deep subsurface compounds in groundwater

Table 4. Assessment matrix for understanding baseline groundwater quality with respect to OOG and other deep subsurface compounds

Influence type	Influence	Factor	Presence	Substance(s) potentially influenced	Datasets
Baseline environment	High	Overlying organic-rich superficial deposits	Y/N	CH ₄	BGS Superficial geology
		Aquifer lithology – organic-rich sediments	Y/N	CH ₄ , SEC, NORM	BGS bedrock geology, EA WIMS
	Medium	Confined aquifer	Y/N	CH ₄	EA/BGS baseline reports, aquifer properties manual
		Deep aquifer – long residence times	Y/N	CH ₄ , SEC	EA/BGS baseline reports, aquifer properties manual
	Low	Aquifer proximity to organic-rich sediments	Y/N	CH ₄ , NORM	BGS coal-mining datasets, BGS/EA aquifer shales dataset
Anthropogenic impacts	High	Mining legacy	Y/N	CH ₄ , NORM, trace metals	BGS Coal mining datasets
		Industrial land use	Y/N	CH ₄ , TPH, PAH, VOCs, SVOCs, trace metals	CORINE land classification
		Urban environment	Y/N	Salinity, TPH, VOCs, PAH	CORINE land classification
		Agricultural land use	Y/N	Nitrate (NO ₃), pesticides	EA WIMS
	Medium	-	-	-	-
	Low	Hydrocarbon activities at surface	Y/N	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM	OGA datasets
		Hydrocarbon activities at depth	Y/N	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM	OGA datasets, BGS/EA aquifer shales dataset

Table 5. Links to online resources for baseline assessment

Dataset	Data owner	Links to resources
BGS Superficial geology*	BGS	www.bgs.ac.uk/map-viewers/geoindex-onshore/
BGS bedrock geology*	BGS	
BGS Coal Mining (shallow& deep)	BGS	www.bgs.ac.uk/map-viewers/geoindex-onshore/ and nora.nerc.ac.uk/id/eprint/7456/1/CR06159N.pdf
CORINE land classification	EEA**	land.copernicus.eu/pan-european/corine-land-cover
EA/BGS baseline reports	EA/BGS	www.bgs.ac.uk/groundwater/quality/BaselineUK/home.html
Aquifer properties manual	BGS	Major aquifers: nora.nerc.ac.uk/id/eprint/13137/1/WD97034.pdf Minor aquifers: nora.nerc.ac.uk/id/eprint/12663/1/WD00004.pdf
OGA datasets	OGA	www.ogauthority.co.uk/data-centre/interactive-maps-and-tools/
BGS/EA aquifer and shales	BGS	www2.bgs.ac.uk/groundwater/shaleGas/aquifersAndShales/home.html
EA WIMS	EA	environment.data.gov.uk/water-quality/view/landing

* Scale of maps used will depend on the complexity of the superficial and bedrock geology. 1:250 k maps may be overly complex depending on the size of the study area.

** European Environment Agency

Table 6. Example from the Fylde peninsula of the overall magnitude and potential scale of influences

Potential influenced compounds	Overall influence	Widespread or localised	Factor
Dissolved solids/SEC	High	Localised	Urban environment
TPH, VOCs, CH ₄	High	Localised	Urban environment, hydrocarbon activities
PAH, SVOCs, NORM	Low	Localised	Aquifer lithology, confined aquifer, hydrocarbon activities
NO ₃ , pesticides	High	Widespread	Agricultural land use

3 Aquifer reviews

Although there are many potential sources of OOG-type compounds in groundwater, these sources will vary spatially and have varying degrees of influence on baseline groundwater quality. To be able to assess the potential for deep subsurface compounds in groundwater at a specific location, a robust conceptual understanding of the area is essential. The geology and hydrogeology of a region underpins the understanding of baseline groundwater quality and enables a further assessment of the potential for influx of deep subsurface compounds into the aquifer. Due to this initial requirement for understanding of site-specific factors, and an appreciation that many factors can impact on groundwater quality, it is not possible to develop national typologies of aquifer types in this case. Instead, it is recommended that an assessment be undertaken to identify the potential for movement of OOG-type subsurface compounds in groundwater when required.

This section demonstrates the assessment methodology for aquifers in the study areas highlighted in Figure 1 to identify the likely influences on baseline groundwater quality in relation to OOG compounds.

3.1 QUATERNARY SUPERFICIAL DEPOSITS OF FYLDE PENINSULA

3.1.1 Baseline environment

The Fylde peninsula is dominated by Quaternary-age glacial deposits (Figure 4) comprising clay-rich till, glaciofluvial sand and gravel and some glaciolacustrine clays and silts. These tills, sands and gravels are of variable thickness and lateral extent due to the varying character of depositional environments and physical processes (Cripps et al., 2016). The most widespread unit at the surface is till, with the associated glaciofluvial deposits forming linear outcrops. In general, the sequence broadly comprises a basal till overlain by glaciofluvial sand and gravel, which is overlain in turn by an upper till. There are major local variations to this succession and the units are both laterally and vertically variable.

Holocene deposits occur around Blackpool and in both the River Wyre and River Ribble estuaries. These consist mostly of clays, silts and sands of alluvium and tidal-flat origin. A large area of wind-blown cover sand is present around Blackpool and Lytham St Anne's. Importantly, areas of peat (organic deposits in Figure 4) are also present at surface occupying a roughly north-south channel east of Blackpool, with some sub-surface layers (2–3 m thick) around Lytham St Anne's and Blackpool.

The bedrock geology below the superficial deposits is the Mercia Mudstone Group for a significant thickness (>200 m) which is unlikely to impact on groundwater quality, there are no significant Coal Measures or other organic rich sediments in close proximity to the superficial aquifer (Figure 5).

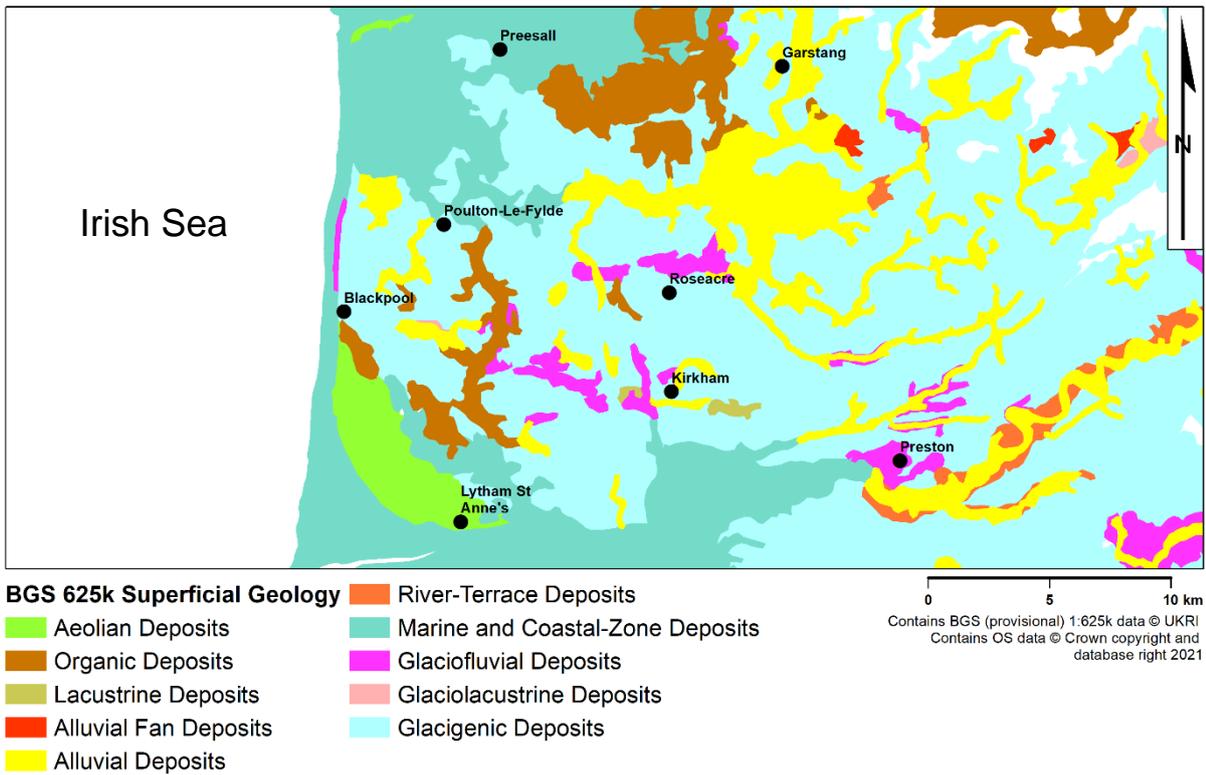


Figure 4. Fylde peninsula superficial geology

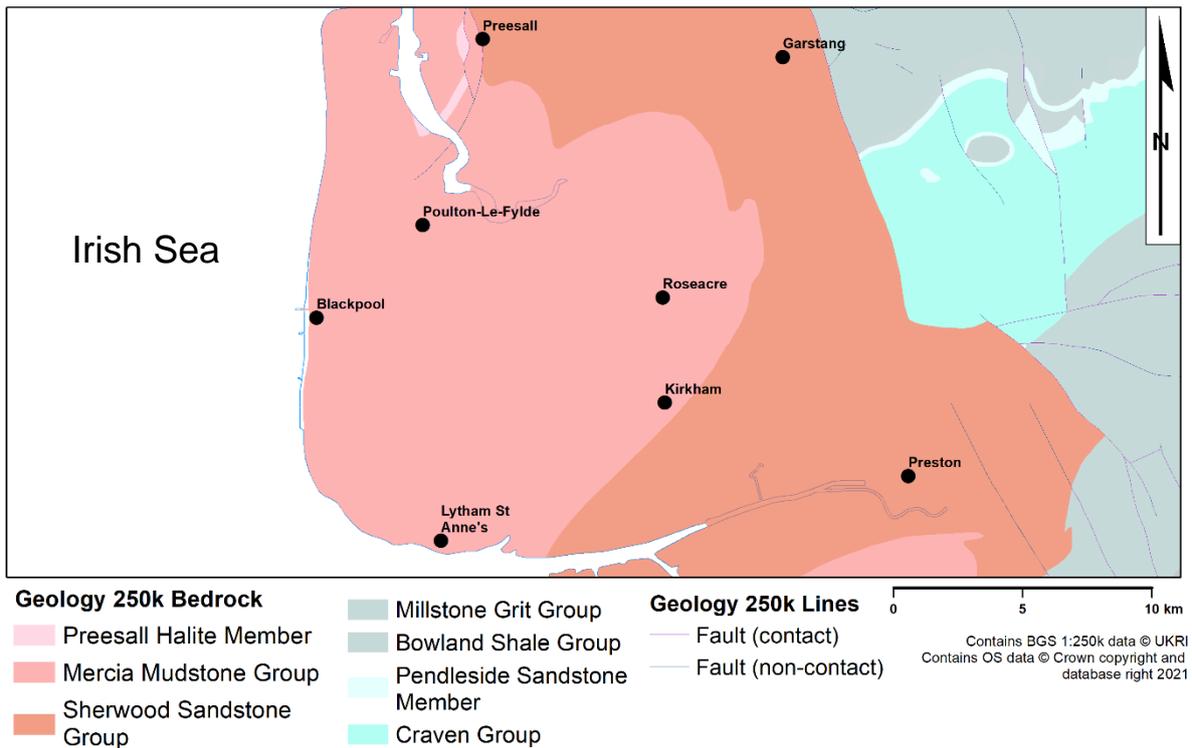


Figure 5. Fylde peninsula bedrock geology

The glacial sands and gravels of the Quaternary superficial deposits form the main aquifer in the west of the Fylde peninsula and are underlain by poorly-permeable upper and lower boulder clay/glacigenic deposits. The glacial sands and gravels form the main aquifer in the Fylde, although they do not occur as one laterally continuous aquifer unit. In general, the sand and gravel units form discontinuous lenses interbedded with clays, and are confined by the upper boulder clay. The variability in the thickness (or presence) of the upper boulder clay will affect the degree of

confinement and hence the hydrogeological conditions within the shallow aquifer. The sands and gravels are mostly defined as a Secondary (undifferentiated) Aquifer by the Environment Agency. These glaciofluvial deposits are used locally by small businesses, farms and golf courses (not for drinking water) but problems with water quality (mostly iron) and groundwater yields are not uncommon. Groundwater levels are generally shallow (1–2 m below ground surface) and are artesian in parts, especially in topographic lows located near to surface drainage.

3.1.2 Anthropogenic impacts

The Fylde peninsula is a flat, low-lying area, forming part of the West Lancashire Plain. It is dominated by the urban centres of Lytham St Anne’s and Blackpool, but surrounded by agricultural land, both pasture and arable (Figure 6). The western coastline is predominately urban, with industrial/commercial units interspersed. The topography is mostly flat, ranging from 0–47 mAOD, with the Kirkham Moraine forming a subtle topographic high towards the east (Cripps et al., 2017). Two major rivers bound the Fylde: the River Wyre to the north and the River Ribble to the south. Across the Fylde are multiple flooded brick pits; small hollows or depressions where clay has previously been extracted and have now formed small ponds.

There is no mining legacy in the area, but it does have a previous history of hydrocarbon exploration/development and five hydrocarbon wells have previously been drilled across the Fylde (Figure 7). One (Elswick) is classed as a production well, while three are decommissioned (Preese Hall, Thistleton and Anna’s Road) and plans are in place for abandonment of the fourth (Grange Hill). Over the past 10 years, the region has also been explored for shale gas, with the Carboniferous Bowland Shale considered prospective at depth.

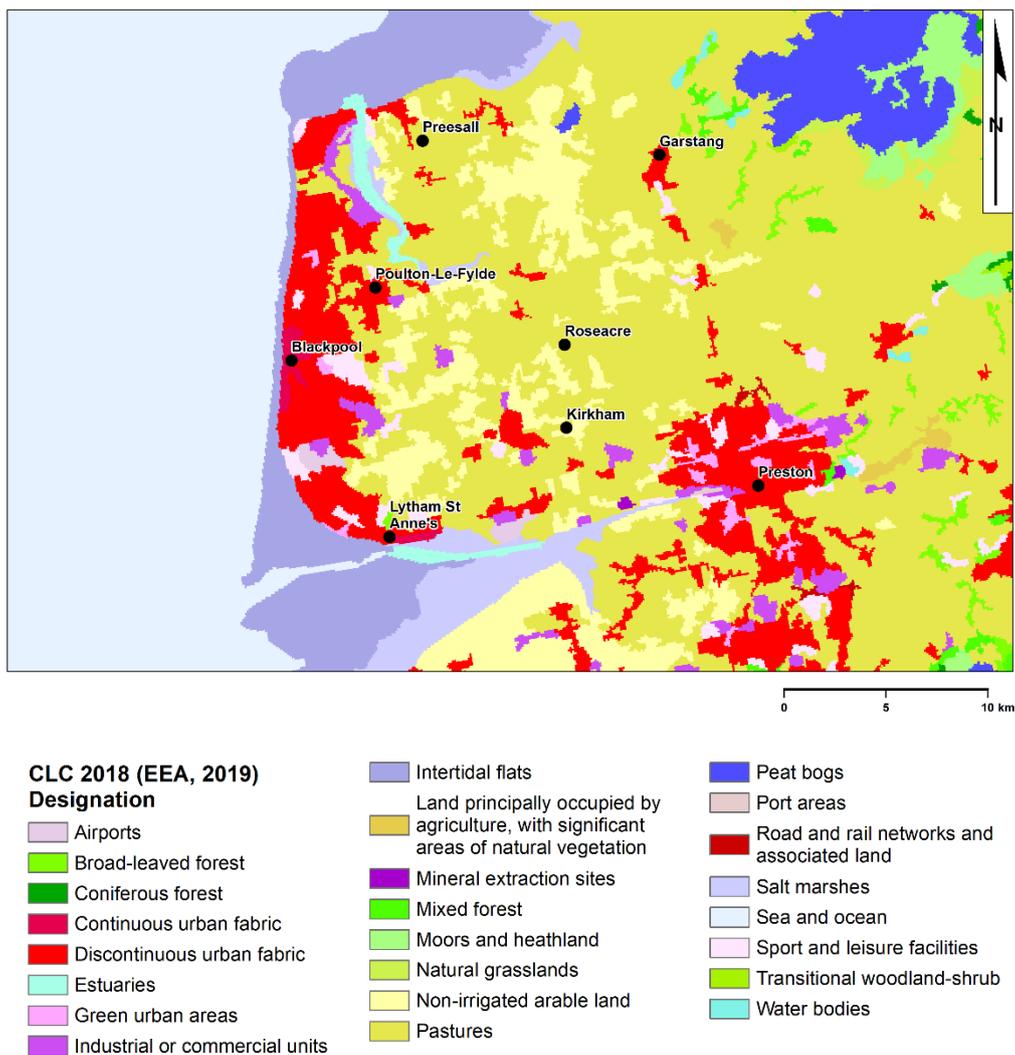


Figure 6. CORINE Land Cover (CLC) (2018) land classification map for the Fylde peninsula (European Environment Agency (EEA), 2019)

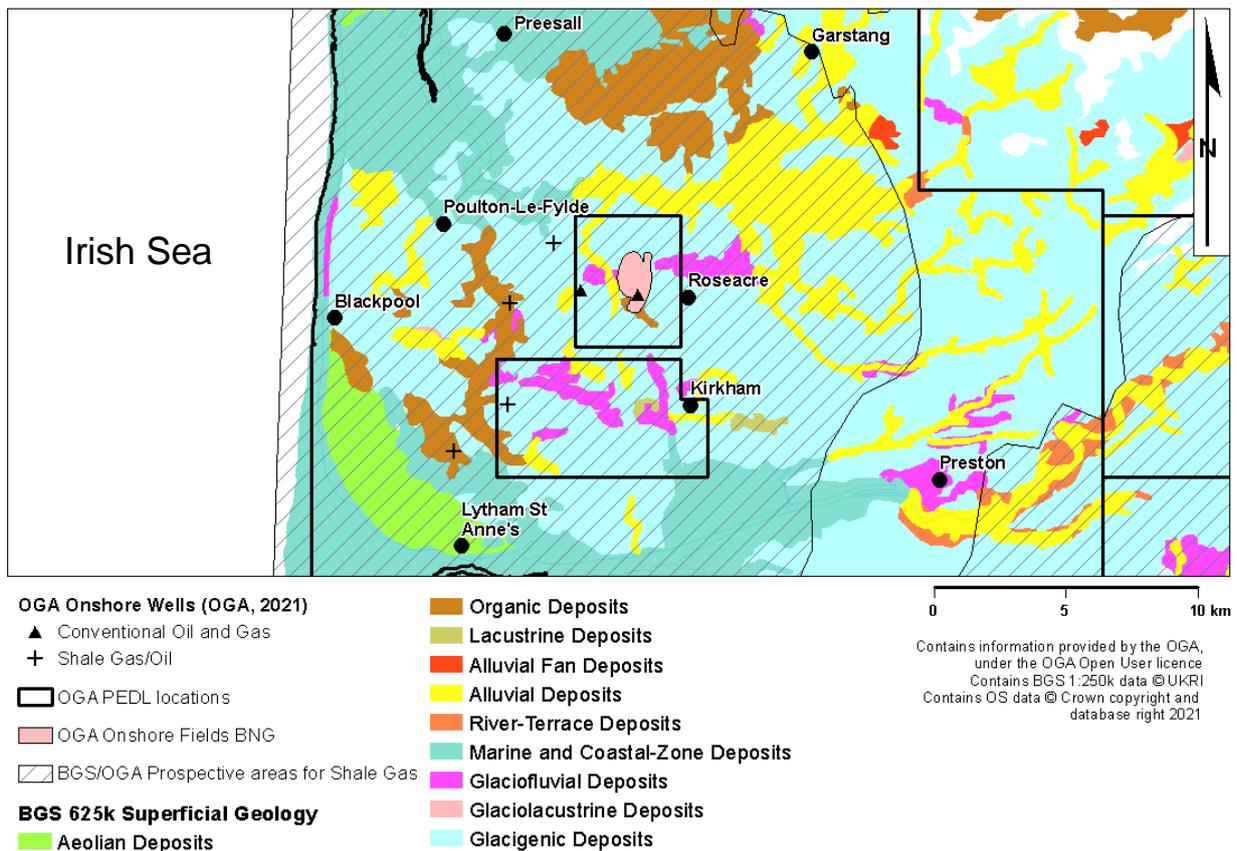


Figure 7. OGA data for the Fylde peninsula. Map shows onshore wells, PEDL locations, onshore conventional hydrocarbon fields, and the joint BGS and OGA dataset for prospective areas for shale gas (data from BGS and OGA (2018); (OGA, 2021a, b, c)).

3.1.3 Assessment of baseline groundwater quality in relation to OOG and deep subsurface compounds

An assessment of this Fylde glacial deposits aquifer (Table 7) identifies that it is unlikely that the baseline environment is highly influencing groundwater quality in terms of OOG/deep subsurface-type contamination on a regional scale. There are no overlying organic-rich superficial deposits or organic-rich sediments present within the aquifer itself, with the exception of localised peat deposits. The aquifer is shallow, with likely short flow paths and residence times, although it is confined in places by an upper layer of glacigenic clays which has the potential to influence redox-controlled solutes including dissolved methane concentrations, albeit on a local scale. Anthropogenic impacts may have a higher influence on groundwater quality in this area. Although there is no mining legacy and only limited industrial land use, the western region is dominated by urban environments, which have the potential (on a local scale) to influence compounds such as major ions (increased salinity) and organic compounds related to vehicle use and industry. Widescale agricultural land use will also impact on nitrate and pesticide concentrations in the aquifer. The vulnerability of this shallow aquifer to these sources of surface pollution is, however, relatively low due to the confined nature of the aquifer which affords a degree of protection.

Table 7. Fylde peninsula superficial deposits aquifer: matrix assessment

	Influence	Factor	Presence	Substance(s) potentially influenced
Baseline environment	High	Overlying organic-rich superficial deposits	N	CH ₄
		Aquifer lithology – organic-rich sediments	Y	CH ₄ , SEC, NORM (Rn)
	Medium	Confined aquifer	Y	CH ₄
		Deep aquifer – long residence times	N	CH ₄ , SEC
	Low	Aquifer proximity to organic rich sediments	N	CH ₄ , NORM (Rn, U)
Anthropogenic impacts	High	Mining legacy	N	CH ₄ , NORM (depending on mined minerals)
		Industrial land use	N	CH ₄ , TPH, PAH, VOCs, SVOCs
		Urban environment	Y	Salinity (from gritted roads), TPH, VOCs (from vehicles)
		Agricultural land use	Y	Nitrate (NO ₃), pesticides
	Medium	-	-	-
	Low	Hydrocarbon activities at surface	Y	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM
		Hydrocarbon activities at depth	Y	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM

The overall likelihood of there being an influence on the presence of OOG and other deep subsurface compounds from the contributing factors is outlined in Table 8. These impacts are likely to be seen at the local scale where there are urban environments, locally confined anoxic conditions within the aquifer or the presence of peat. Water-quality data collected as part of the Lancashire Environment Baseline Monitoring programme have indicated that this aquifer is typically anoxic, with low specific electrical conductivity (SEC). Methane is often detected in this shallow aquifer, though rarely at high concentrations. The highest impact is seen at a local scale where peat is present, and elevated CH₄ concentrations have been found. Isotopic analysis of this methane is indicative of a biogenic origin, possibly linked to the degradation of peat within the aquifer. For components of NORM measured in the groundwater (Rn, U), activities/concentrations have been found to be low. The high potential influence of urban environments has been reduced by the confined nature of the aquifer, and there is no evidence of elevated concentrations of organic compounds such as TPH and PAHs.

Table 8. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Fylde peninsula superficial deposits

Potential influenced compounds	Overall influence	Widespread or localised	Factor
Dissolved solids/SEC	High	Localised	Urban environment
TPH, VOCs,	High	Localised	Urban environment, hydrocarbon activities
CH ₄	High	Localised	Aquifer lithology, confined aquifer, hydrocarbon activities
PAH, SVOCs, NORM	Low	Localised	Hydrocarbon activities
NO ₃ , pesticides	High	Widespread	Agricultural activities

3.2 QUATERNARY AND JURASSIC AQUIFERS OF THE VALE OF PICKERING

3.2.1 Baseline environment

Previous work on the Vale of Pickering has investigated water quality in two aquifers: a shallow group including Quaternary lacustrine and glaciolacustrine deposits with underlying weathered Jurassic Kimmeridge Clay Formation, and an older aquifer in the Jurassic Corallian Group. This section assesses both aquifers.

The Vale of Pickering, North Yorkshire, is an east-west-trending fault-bounded graben which forms part of the Cleveland Basin of north-east England. The Vale forms a flat-lying plain with an elevation of less than 60 m AOD. It is bounded by the lower slopes of the Corallian North York Moors to the north, the Corallian and older Howardian and Hambleton Hills to the south-west, and to the south by the Chalk escarpment of the East Yorkshire Wolds.

Quaternary superficial deposits cover much of the low-lying area, especially in the eastern part. The sediments are predominantly of Late Devensian lacustrine origin, with glaciofluvial deposits at many of the margins (Figure 8). Much of the lacustrine material was deposited by a former proglacial lake, Lake Pickering, which occupied the valley during the Devensian until ice retreat 10,000 years ago (Evans et al., 2017). These sediments are of variable thickness, typically up to 40 m (Ford et al., 2015), but are thin or absent around the north-west, and around Kirby Misperton in the central part of the Vale (Ward et al., 2017). Isolated patches of glacial till occupy topographic highs near Kirby Misperton and around the northern margins, and discontinuous lenses of sand and gravel occur elsewhere within the Quaternary sediments (Figure 8). There are no records of peat among the superficial deposits of the area.

The Quaternary deposits are underlain by thick Jurassic strata of marine origin. On the valley floor, the uppermost Jurassic deposits comprise the Upper Jurassic Kimmeridge Clay Formation (Figure 9). The northern boundary is fault-bounded with a downthrow of some 150 m on the south wall (Williams, 1986). Kimmeridge Clay thicknesses vary due to faulting, but some 300 m of organic-rich mudstone was proven in the Fordon No 1 borehole (Powell, 2010). The Kimmeridge Clay is dominated by dark grey mudstone, with grey calcareous mudstone and black fissile organic-rich mudstone but with occasional bands of siltstone, and sporadic occurrences of pyrite or weathered gypsum (Cope, 1974). The strata are inferred to have been deposited under anoxic marine bottom-water conditions. Kerogen is abundant in the Kimmeridge Clay of the Cleveland Basin, with high organic-matter content even in the calcareous horizons, although organic horizons are noted to be immature for hydrocarbon production and burial history too shallow for oil production (Williams, 1986, Powell, 2010). A 48 m thickness of mudstone equivalent to the Ampthill Clay Formation of southern England underlies the Kimmeridge Clay Formation in the region (Powell, 2010).

Upper Jurassic (Oxfordian) limestones of the Corallian Group, totalling 70–120 m in thickness are found at outcrop in areas surrounding the Vale of Pickering (Newell et al., 2016, Tattersall and Wilkinson, 1974) (Figure 9). The Corallian Group includes the Coralline Oolite Formation (60–70 m thick) and underlying Lower Calcareous Grit (22–50 m thick). The Corallian Oolite strata formed during a marine regression and comprise mostly grey, ooidal limestone and buff yellow calcareous sandstone, with micritic limestone (Powell, 2010). The Lower Calcareous Grit comprises yellow calcareous sandstone with ooidal limestone. The Corallian underlies the Kimmeridge Clay Formation beneath the valley floor, its upper surface reaching depths up to 295 m in sections due downfaulting (Kent, 1980).

Underlying the Corallian Group, the Jurassic Oxford Clay comprises up to 45 m of grey-green silty mudstone and calcareous mudstone and siltstone deposited under further marine transgressive conditions (Powell, 2010). In cores from Scarborough, the Oxford Clay is described as a grey calcareous siltstone and silty mudstone with pyritised and/or limonitised burrows, formed in a lower shoreface depositional environment (Powell and Riding, 2016).

The Oxford Clay is underlain in turn by the sandstone-dominated Callovian Osgodby Formation, described as a bioturbated, lower to upper shoreface, silty sandstone deposit (Powell and Riding, 2016). The Osgodby Formation includes green-grey units of sandstone and calcareous sandstone with berthierine ooids, calc siltstone and limestone and in the Hambleton Hills is some 20–23 m thick (Powell, 2010). Berthierine ooids in the upper part of the Osgodby have been associated with oscillating tidal conditions in topographic highs with redeposition on the seafloor. Pyrite ooids in the

lower part give indications of strongly reducing conditions within an otherwise oxic sandy sequence. These have been attributed to ooid development in shallow, nearshore muddy lagoons with abundant organic matter, and with subsequent dispersal offshore by storm surges (Powell and Riding, 2016).

The argillaceous units within the Jurassic sequence clearly contain organic-rich deposits. These are of marine origin; terrestrial organic matter (coal) is not represented.

The permeable units of the Quaternary and underlying Kimmeridge Clay deposits are exploited by small-scale abstractions for agricultural and domestic use, albeit not for drinking water. The units commonly have an indistinct boundary and several of the boreholes have insufficiently detailed logs to be able to distinguish units. However, local sandy horizons and weathered sections in the Kimmeridge deposits at the interface with the lacustrine sediments can host locally important supplies of groundwater.

The Corallian Group at outcrop and subcrop around the periphery of the Vale of Pickering is defined as a principal aquifer, that is unconfined or semi-confined. It is used for public and private drinking-water supply, agriculture and industry. This is distinct from that part of the Corallian Group confined beneath the Kimmeridge Clay Formation in the central part of the Vale. Here, the depth of the aquifer and its unfavourable groundwater chemistry (mineralised, alkaline) restricts its use for water supply. The earlier-proposed shale-gas exploration borehole, KM8, is located at Kirby Misperton (Figure 9) and underlain by Quaternary lacustrine sediments and Kimmeridge Clay, with the top of the Corallian Group at around 190 m depth below surface.

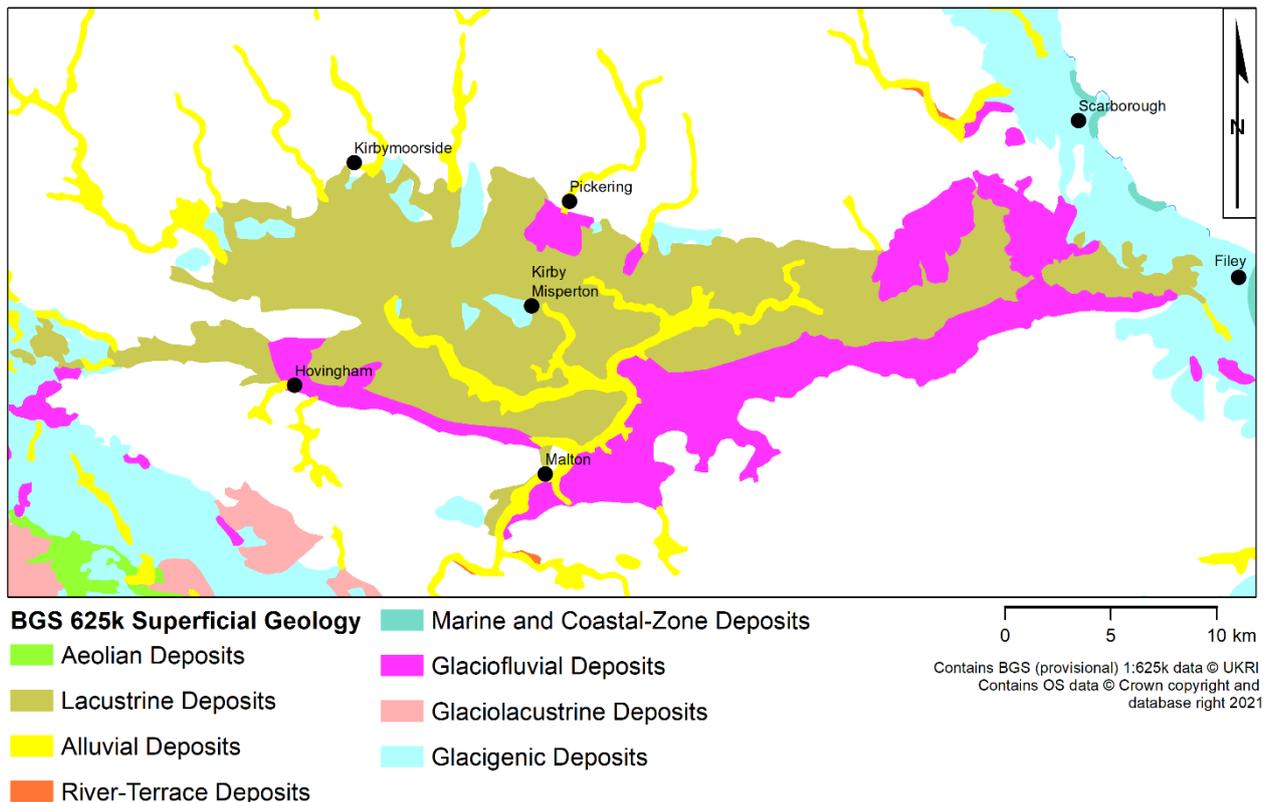


Figure 8. Vale of Pickering superficial geology

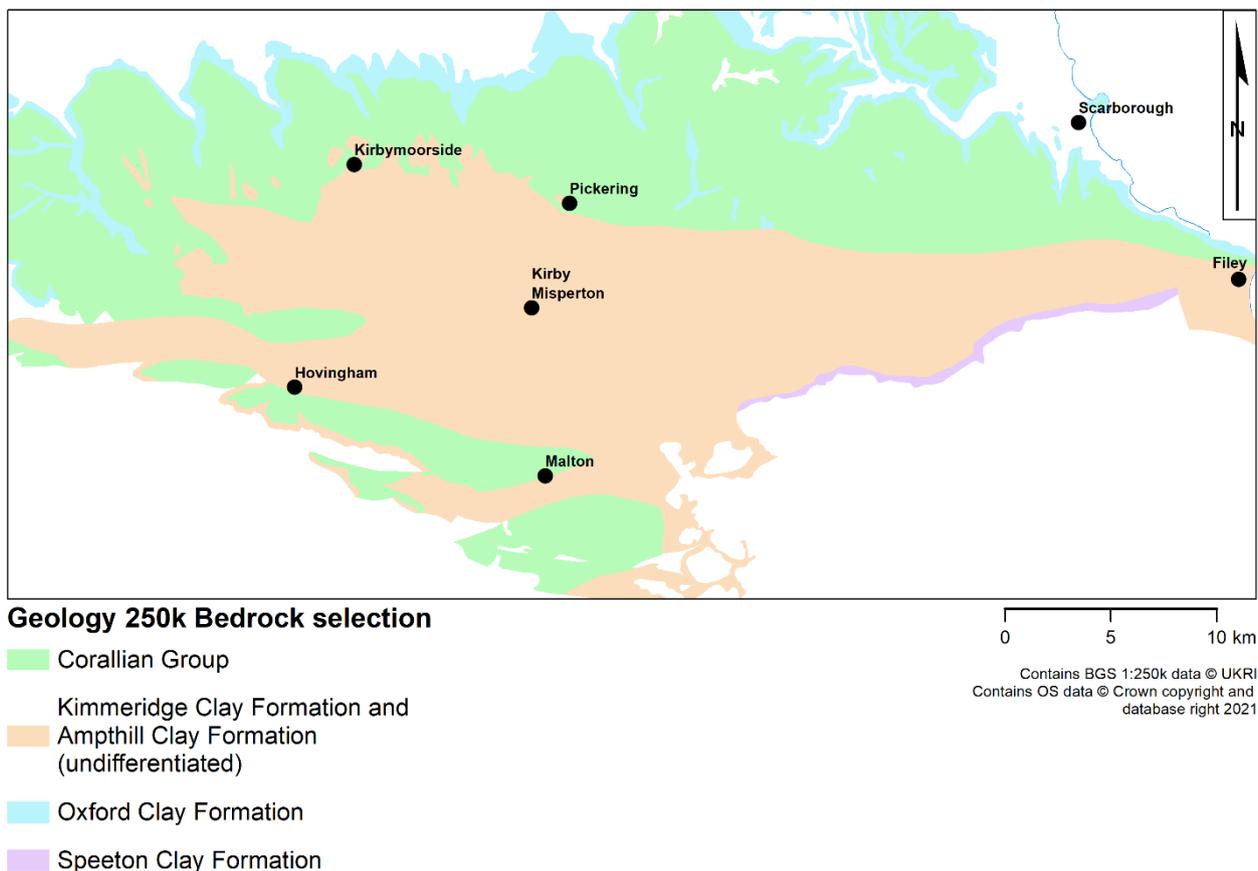


Figure 9. Vale of Pickering bedrock geology

3.2.2 Anthropogenic impacts

With the exception of the urban areas (e.g. Pickering and Malton) around the margins of the Vale, land use is overwhelmingly rural and dominated by arable agriculture (Figure 10). The urban centres are located on the edge of the unconfined Corallian aquifer and therefore constitute a potential risk for surface-borne urban contaminants. Within the Vale, the surface clay-dominated superficial deposits and underlying Kimmeridge Clay limit infiltration of surface contaminants including nitrogenous fertilisers and pesticides.

There exists a legacy of conventional onshore gas activity, with 12 ‘active’ (non-decommissioned) hydrocarbon wells across the Vale of Pickering (Figure 11). Gas production from these wells has diminished significantly over the last decade and the associated Knapton Generating Station has now closed; the site is being developed for new sources of power generation and energy storage, including consideration of geothermal energy.

Previous work by BGS on aquifer separation from potential shale gas units only included principal aquifers so did not assess the shallow Kimmeridge/superficial aquifer, although an assessment was made for the area by Loveless et al. (2018) (Figure 12).

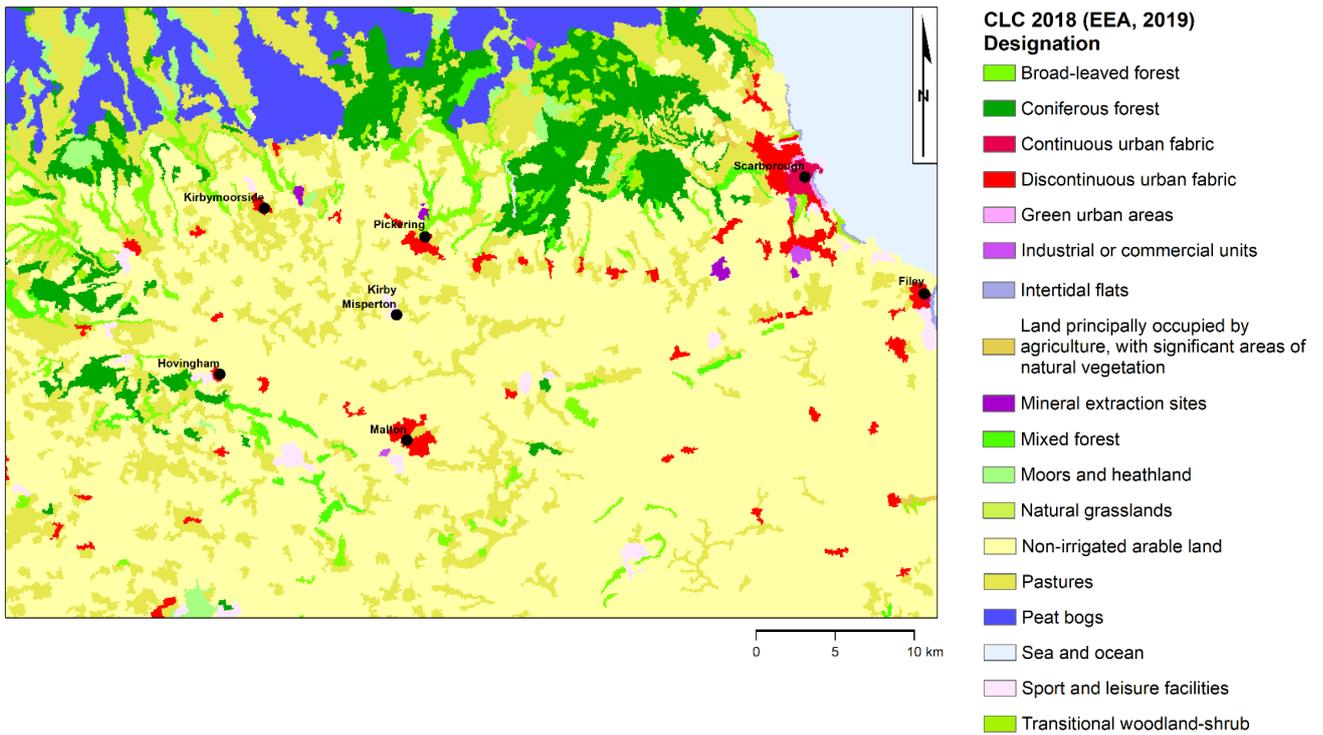


Figure 10. CLC (2018) land classification map for the Vale of Pickering (European Environment Agency (EEA), 2019)

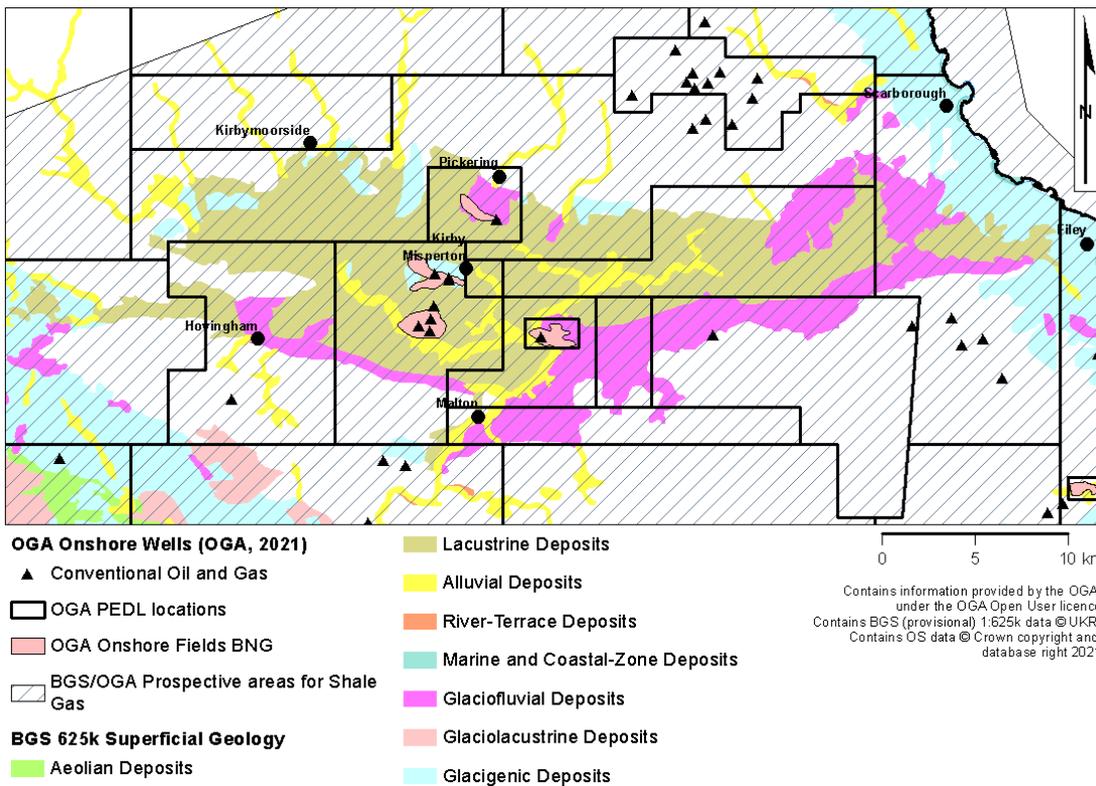
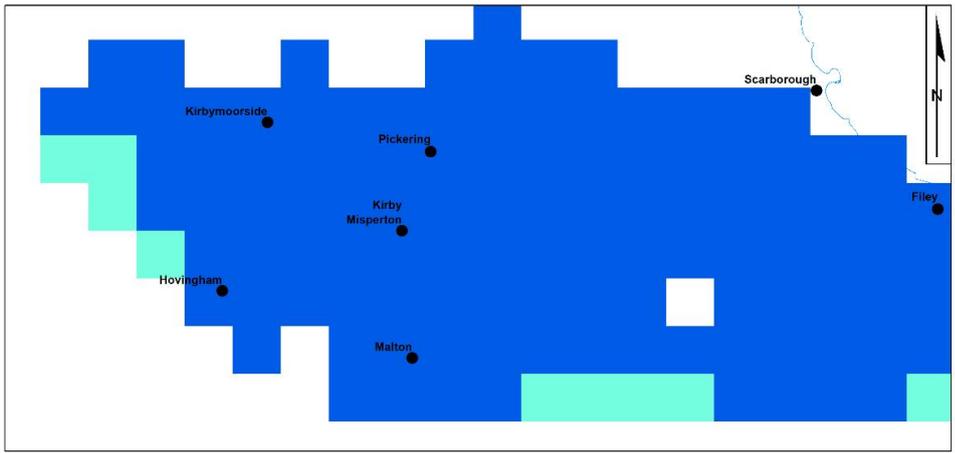


Figure 11. OGA data for the Vale of Pickering. Map shows onshore wells, PEDL locations, onshore conventional fields, and the joint BGS and OGA dataset for prospective areas for shale gas (data from BGS and OGA (2018); (OGA, 2021a, b, c)).



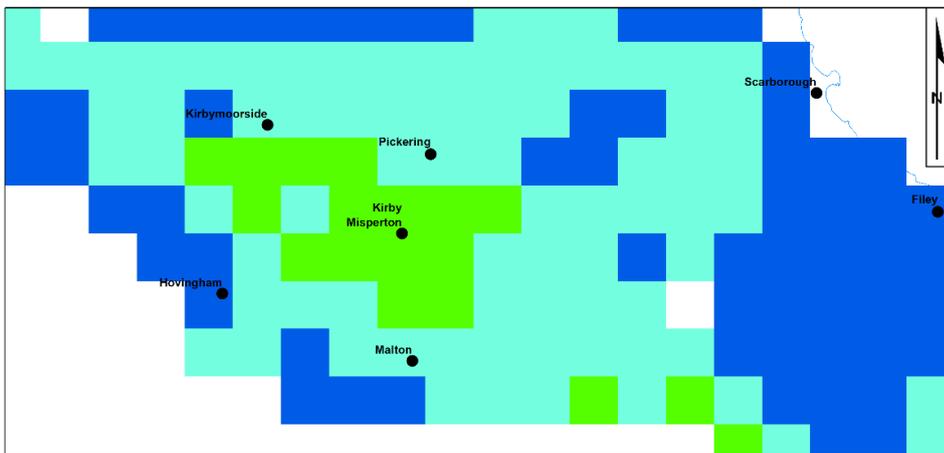
Corallian limestone/Oxford Clay

Vertical separation (m)

■ Less than 200

■ 200 to 400

Contains British Geological Survey materials © UKRI 2021
Contains OS data © Crown copyright and database right 2021



Corallian limestone/Lias

Vertical separation (m)

■ Less than 200

■ 200 to 400

■ 400 to 800

Contains British Geological Survey materials © UKRI 2021
Contains OS data © Crown copyright and database right 2021



Corallian limestone/Bowland Shale

Vertical separation (m)

■ More than 1,600

Contains British Geological Survey materials © UKRI 2021
Contains OS data © Crown copyright and database right 2021

Figure 12. Vertical separation map of the various shale gas source rocks and the Corallian limestone aquifer (from Loveless et al. (2018), BGS (2018)).

3.2.3 Assessment of baseline groundwater quality in relation to OOG and other deep subsurface compounds

The superficial deposits covering the floor of the Vale of Pickering flat-lying plain are not known to be organic-rich (Table 9) but are dominated by argillaceous sediments, apart from in marginal areas where a larger proportion of sand and gravel deposits exists in the sequence. The dominance of clay lithology in most of these deposits has a large impact on aquifer recharge and redox conditions in the Vale and groundwater is dominantly Fe- and Mn- reducing. In the underlying organic-rich Kimmeridge Formation, groundwater is more typically strongly reducing, with evidence of SO₄ reduction in some areas and associated high concentrations of dissolved CH₄ (mg/L quantities). In some locations, minor quantities of dissolved C₂H₆ (µg/L quantities) are also represented. Concentrations of Fe and NH₄ can be high (mg/L range commonly) and Mn also relatively high (hundreds of µg/L range). Dominance of clay lithology also gives rise to slightly increased salinity (SEC typically up to 3000 µS/cm). Of NORM constituents, concentrations of dissolved U are typically low (a few µg/L or less), as are dissolved Rn (20 Bq/L or less) (Table 10). Groundwater is generally unsuitable for drinking.

Table 9. Vale of Pickering superficial/Kimmeridge aquifer: matrix assessment

Influence type	Influence	Factor	Presence	Substance(s) potentially influenced
Baseline environment	High	Overlying organic-rich superficial deposits	N	CH ₄
		Aquifer lithology – organic-rich sediments	Y	CH ₄ , salinity, NORM (Rn)
	Medium	Confined aquifer	Y	CH ₄
		Deep aquifer – long residence times	N	CH ₄ , salinity
	Low	Aquifer proximity to organic-rich sediments	N	CH ₄ , salinity, NORM (Rn, U)
Anthropogenic impacts	High	Mining legacy	N	CH ₄ , NORM
		Industrial land use	N	CH ₄ , TPH, PAH, VOC's, SVOC's
		Urban environment	N	Salinity (from gritted roads), TPH, VOCs (from vehicles)
		Agricultural land use	Y	Nitrate (NO ₃), pesticides
	Medium	–	–	–
	Low	Hydrocarbon activities at surface	Y	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM
		Hydrocarbon activities at depth	Y	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM

Table 10. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Vale of Pickering superficial/Kimmeridge deposits

Potential influenced compounds	Overall influence	Widespread or localised	Factor
Dissolved solids/SEC	High	Widespread	Aquifer lithology
TPH, VOCs	Low	Localised	Past hydrocarbon activities
CH ₄	High	Widespread	Aquifer lithology, confined aquifer
PAH, SVOCs, NORM	Low	Localised	Past hydrocarbon activities
NO ₃ , pesticides	High	Widespread	Agricultural activities

The Corallian aquifer around the margins of the Vale of Pickering crops out for much of its extent and is dominantly unconfined. A few boreholes abstract water from the feather edge of the confined aquifer as it becomes confined by the overlying Kimmeridge Clay Formation further into the Vale. Redox conditions in the Corallian groundwater from the marginal areas therefore varies between fully oxic and mildly (Fe-, Mn-) reducing (Table 11). Groundwater is nonetheless fresh (SEC <1000 µS/cm), and dominated by reaction with carbonate minerals in the limestone, and is therefore pH-neutral and of Ca-HCO₃ type. Conditions in the confined aquifer are insufficiently reducing to sustain SO₄ reduction or methanogenesis. Concentrations of CH₄ are therefore low (usually <500 µg/L) (Table 12). For the NORM components measured (Rn, U), activities/concentrations were low (Rn <30 Bq/L; U <1 µg/L). Groundwater in the unconfined sections of the aquifer is vulnerable to surface-borne contaminants of urban origin. Lack of major industrial activity render this source unlikely.

Table 11. Vale of Pickering marginal Corallian aquifer: matrix assessment

Influence type	Influence	Factor	Presence	Substance(s) potentially influenced	
Baseline environment	High	Overlying organic-rich superficial deposits	Y	CH ₄	
		Aquifer lithology - organic rich sediments	N	CH ₄ , SEC, NORM (Rn)	
	Medium	Confined aquifer	Y	CH ₄	
		Deep aquifer – long residence times	N	CH ₄ , SEC	
	Low	Aquifer proximity to organic rich sediments	Y	CH ₄ , NORM (Rn, U)	
	Anthropogenic impacts	High	Mining legacy	N	CH ₄ , NORM
			Industrial land use	N	CH ₄ , TPH, PAH, VOCs, SVOCs
Urban environment			Y	Salinity (from gritted roads), TPH, VOCs (from vehicles)	
Agricultural land use			Y	Nitrate (NO ₃), pesticides	
Medium		–	–	–	
Low		Hydrocarbon activities at surface	N	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM	
		Hydrocarbon activities at depth	N	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM	

Table 12. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the marginal Corallian aquifer

Potential influenced compounds	Overall influence	Widespread or localised	Factor
Dissolved solids/SEC	Low	Localised	Urban environment
TPH, VOCs	Low	Localised	Urban activities e.g. vehicles
CH ₄	Low	Localised	Proximity to organic-rich sediments/overlying organic-rich deposits, confined aquifer
PAH, SVOCs, NORM	Low	Localised	Proximity to organic-rich sediments
NO ₃ , pesticides	High	Widespread	Agricultural activities

3.3 CRETACEOUS LOWER GREENSAND OF SOUTH-EAST ENGLAND

This section is based on the work compiled in Mallin Martin and Smedley (2021a) on the Lower Greensand Group which contains all the relevant figures.

3.3.1 Baseline environment

The Lower Greensand Group (LGS), is composed of four formations: the Atherfield Clay Formation, the Hythe Formation, the Sandgate Formation and the Folkestone Formation. The Atherfield Clay is predominantly silty clay, becoming progressively sandier towards its upper surface in contact with the Hythe Formation. The Hythe Formation is a fine-grained sandstone, with progressively greater cementation towards its top compared to its base. Glauconite and carbonate-cemented beds are present within the Hythe Formation. Overlying the Hythe, the Sandgate Formation is a muddier and more chert-rich sequence of poorly-sorted sands, again with evidence of glauconite, and additionally limonitic grains. At the top of the LGS sequence, the Folkestone Formation is a poorly-consolidated sandstone, with notable ferruginous coatings and ironstone bands. The Folkestone Formation shows evidence of cross-bedding, with minor clay draping over ripple structures.

The Lower Greensand Group is overlain by the Gault Formation, a blue-grey clay/mudstone formation, sandier at its base, but with notable glauconite, pyrite and phosphatic nodules.

There are no significant Coal Measures or other organic-rich sediments in close proximity to the aquifer.

The Lower Greensand Group is considered a principal aquifer and supports a number of public and private abstractions. The group itself is subdivided into two distinct aquifer units, the Hythe and Folkestone formations, both with differing water chemistries. The two units are separated by the Sandgate Formation, which partially confines the underlying Hythe Formation. The Folkestone formation is in turn confined by the Gault Formation. Groundwater flow in the Hythe Formation is controlled by the degree of cementation. Fracture flow dominates in well-cemented zones, whilst intergranular flow dominates in locations with poor cementation. Groundwater flow in the Folkestone Formation is dominantly intergranular in nature.

The superficial geology consists of alluvial and river terrace deposits, bounding the major surface-water courses across the region, alongside “Residual” (clay/flint/gravel infill deposits) where Chalk is at outcrop, to the north and west of the study area. Soils are typically sandy or silty loams, with the most well-draining soils situated over the unconfined sections of the Hythe and Folkestone formations (Shand et al., 2003, Cranfield University, 2021). Superficial deposits are thin, typically 1 m thick, or absent across much of the study area (Lawley and Garcia-Bajo, 2010) but thicken to the west, typically greater than 5 m at the onset of the “Residual deposits”.

3.3.2 Anthropogenic impacts

The topography is controlled by the geological outcrop of the region. An elevated crag line around Goldalming, Haslemere and Pulborough follows the basal boundary of the Lower Greensand Group outcrop, where it slopes away towards the west (at a maximum elevation of c. 300 m AOD around Leith Hill, between Dorking and Godalming). The boundary with the Chalk Group at the south, west and north edges of the study area (around Guildford and south of Petersfield) marks the next topographic high feature. The general topography decreases in elevation towards the south.

Over 50% of the total land use within the study area is agriculture, with 30% dedicated to pasture and livestock. Urban land use cover is only 11% of the total area, most of which is “discontinuous urban fabric”, or smaller settlements. The major urban settlements within the study area are Dorking and Redhill/Reigate in the north-east, Guildford and Farnham in the north/north-west, and Haslemere and Liphook in the centre.

The study area is situated in the Weald Basin, a mature OOG setting. A total of 13 onshore fields are located in the wider Weald basin, with three in the study area; Brockham, Albury and Humbly Grove (OGA, 2019). Major reservoir units include the Wealden Sandstone, Great Oolite, Corallian, and Portland Sandstone (Andrews, 2014). The Weald Basin is considered to be a location with potential unconventional shale-oil deposits, found within the Jurassic Shale sequence below the

study area (Andrews, 2014). Some recent conventional oil and gas exploration has taken place in the region, including the Horse Hill (east of Horsham) and Broadford Bridge sites (north-east of Pulborough), operated by UK Oil & Gas PLC (UKOG PLC, 2020). Neither exploration site is situated on the Lower Greensand aquifer.

3.3.3 Assessment of baseline groundwater quality in relation to deep sub-surface compounds

Groundwater from the Lower Greensand aquifer is unconfined at outcrop. The lowermost Hythe Formation may be confined below the poorly-permeable Sandgate Formation and the whole Lower Greensand sequence may be confined where it underlies the Gault Formation. Groundwater at outcrop can be acidic in places (pH 4–5) but is otherwise pH-neutral, being buffered by the presence of matrix calcite. Groundwater is fresh and of Ca-HCO₃ or mixed-anion type throughout the studied aquifer. It is oxic in the unconfined sections, but becomes Fe- and Mn-reducing in the confined parts of the aquifer. Dissolved and solid organic matter are sparse and concentrations of dissolved methane are consequently typically low (µg/L range). Old, more evolved Na-HCO₃ waters, observed elsewhere in the deep confined LGS aquifer (e.g. Slough area), are not observed in the study area (Table 13, Table 14).

Table 13. Lower Greensand aquifer: matrix assessment

Influence type	Influence	Factor	Presence	Substance(s) potentially influenced
Baseline environment	High	Overlying organic-rich superficial deposits	N	CH ₄
		Aquifer lithology – organic-rich sediments	N	CH ₄ , SEC, NORM
	Medium	Confined aquifer	Y	CH ₄
		Deep aquifer – long residence times	N	CH ₄ , SEC
	Low	Aquifer proximity to organic-rich sediments	N	CH ₄ , NORM
Anthropogenic impacts	High	Mining legacy	N	CH ₄ , NORM
		Industrial land use	N	CH ₄ , TPH, PAH, VOCs, SVOCs
		Urban environment	Y	Salinity (from gritted roads), TPH, VOCs (from vehicles)
		Agricultural land use	Y	Nitrate (NO ₃), pesticides
	Medium	–	–	–
	Low	Hydrocarbon activities at surface	Y	CH ₄ , TPH, PAH, VOCs, SVOC's, NORM
		Hydrocarbon activities at depth	Y	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM

Table 14. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Lower Greensand aquifer of south-east England

Potential influenced compounds	Overall influence	Widespread or localised	Factor
Dissolved solids/SEC	Low	Widespread	Urban environment
TPH, VOCs	Low	Localised	Hydrocarbon activities and urban environment
CH ₄	Low	Widespread	Confined aquifer and hydrocarbon activities
PAH, SVOCs, NORM	Low	Localised	Hydrocarbon activities
NO ₃ , pesticides	High	Widespread	Agricultural activities

3.4 TRIASSIC SHERWOOD SANDSTONE AQUIFER OF NOTTINGHAMSHIRE AND SOUTH YORKSHIRE

This section is based on the work compiled in Mallin Martin and Smedley (2020) on the Sherwood Sandstone Group which contains all the relevant figures.

3.4.1 Baseline environment

The Sherwood Sandstone Group (SSG) aquifer of Nottinghamshire and South Yorkshire is a Triassic red-bed sandstone sequence of fine- to medium-grained sandstone, with interbedded mudstone, and some pebbles throughout (Allen et al., 1997a, Smedley and Brewerton, 1997, Ambrose et al., 2014). The SSG thickens progressively towards the north, from around 60 m near Nottingham, to 250 m thick around Worksop, and up to approximately 400 m thick around the Humber Estuary. The SSG appears at outcrop, ranging from 8–20 km wide east-west in Nottinghamshire, becoming progressively covered by Quaternary superficial deposits towards the north, where 10% at most is visible at outcrop around Doncaster.

The SSG dips gently, around 1–4° towards the east, where it transitions into the overlying Triassic Mercia Mudstone Group (MMG). The MMG comprises a sequence of mudstone and siltstone, with some evaporitic deposits. The transition zone consists of interbedded mudstones and sandstones, with some small veins and nodules of anhydrite occurring infrequently. The MMG covers much of east Nottinghamshire, and within the study area extends from south of Nottingham to the east coast at Teesside (Hobbs et al., 2002).

The SSG rests disconformably on the Permian Lenton Sandstone Formation, which in turn overlies the formations of the Zechstein Group (Ambrose et al., 2014). The Permian Zechstein Group is a mixture of dolostone, limestone, evaporite and mudstone. The Carboniferous Pennine Coal Measures (PCM) underlie the Zechstein Group and form an interbedded sequence of sandstones, mudstones and coal seams, the latter of which have been mined historically.

The superficial cover across the study area consists primarily of glacial, periglacial and glaciolacustrine deposits, with some more recent alluvial deposits following the major river courses (the Trent, Don and Humber). Superficial cover is thin or absent in the southern area around Nottingham, becoming progressively thicker northwards (in excess of 50 m) towards and beyond Doncaster (Price et al., 2006).

Across much of west Nottinghamshire the SSG is unconfined, and is exploited for private and public water supply. Towards the east and north, the SSG becomes confined, by superficial deposits in the north and the MMG to the east. Groundwater flow is dominantly intergranular and anisotropic, with horizontal conductivity around ten times greater than vertical conductivity (Allen et al., 1997a). Localised fracturing results in zones of higher permeability and yield, but fracture permeability declines with both depth and confinement. Groundwater flow is from west to east, with a gradient of 1 in 250 (unconfined) and 1 in 900 (confined). Recharge occurs through the SSG outcrop, or where sandy superficial deposits overlie the bedrock. Recharge is hindered by the clay-rich glacial and glaciolacustrine superficial deposits towards the north (Doncaster and South Yorkshire), and the MMG to the east.

3.4.2 Anthropogenic impacts

The topography across the region is relatively low-lying, sloping downwards towards the north and east from the relatively elevated topography around Mansfield (c. 200 m AOD). Major watercourses include the rivers Trent (Nottingham and Newark), Don (Doncaster) and Humber (Goole, Pontefract, Knottingley), including the Humber Estuary.

Agricultural land makes up the principal land use/classification across the study area (over 65%), with a smaller percentage of urban land (around 19% for all urban land use types). This is concentrated around the major centres of Nottingham, Mansfield, and Doncaster.

The local area has a longstanding legacy of coal mining (from the underlying Pennine Coal Measures), with the Nottinghamshire, Derbyshire and South Yorkshire coal fields in operation between the early 1800s and 2015 (Northern Mine Research Society, n.d.-c, Northern Mine Research Society, n.d.-b, Northern Mine Research Society, n.d.-a) (Figure 13). Notable former collieries include Maltby, Thoresby and Annesley Bentinck. As a result of the coal-mining legacy, the wider hydrogeology and hydrogeochemistry of the Nottingham and Yorkshire region has been affected (Allen et al., 1997a).

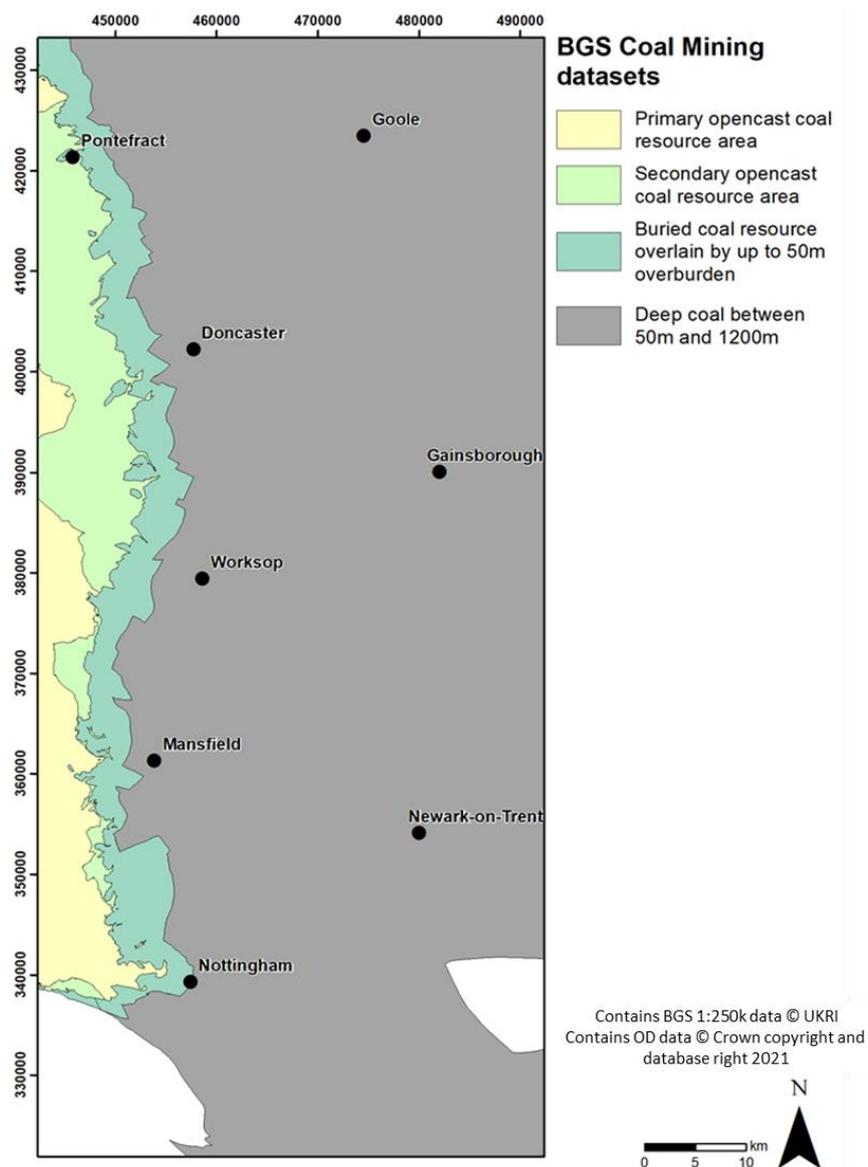


Figure 13. Nottinghamshire and South Yorkshire coal-mining information. Primary = generally thick coals at surface, main targets for opencast coal extraction. Secondary = generally thin coals at surface, secondary targets for opencast coal extraction (Jones, 2006).

Across the Nottinghamshire coal field, long-wall mining of the coal seams has resulted in the settlement of the overlying strata and an increase in localised fracturing within the sandstone, modifying the local permeability above these historic workings (Shepley et al., 2008). Whilst these may not provide connections from the worked seams to the aquifer, they modify the local hydrogeology and may make the aquifer more susceptible to pollution from the surface (Shepley et al., 2008).

Nottinghamshire, South Yorkshire and neighbouring Lincolnshire have a history of exploration and production of a number of onshore oil and gas resources, both for conventional and unconventional resources. Conventional oil and gas fields include Beckingham, Bothamsall, Egmanton, Eakring, Gainsborough and Hatfield. Only two locations earmarked for shale-gas exploration exist in the wider region: Tinker Lane, Torworth and Springs Road, Misson. The two sites, operated by iGas, were drilled in 2018 and 2019 respectively. The Tinker Lane well failed to prove the Bowland Shale and was decommissioned in 2019 (iGas Energy PLC, 2019). The moratorium on hydraulic fracturing imposed in England in late 2019 has halted much of the OOG-related industrial development since then (BEIS et al., 2019).

3.4.3 Assessment of baseline groundwater quality in relation to deep sub-surface compounds

The unconfined Sherwood Sandstone aquifer is potentially vulnerable to infiltration of surface contaminants from urban, agricultural and industrial sources, depending on local land use. It is also vulnerable to contamination from mine drainage in areas proximal to former coal-mine workings (Table 15). Groundwater is typically oxic in such conditions, with presence of NO_3 indicative of modern agricultural pollution. Groundwater is influenced by reaction of matrix calcite and is Ca-HCO_3 type. Where confined by superficial deposits (north-west) or Mercia Mudstone Group (east), groundwater is much less vulnerable to surface pollution, and groundwater is fresh and mildly (Fe- and Mn-) reducing. Fresh groundwater has been observed to depths of some 500 m in the confined aquifer around Gainsborough (Smedley et al., 2018). Residence time increases progressively downgradient eastwards and with depth and solute chemistry evolves as a result of water-rock interaction. Further east (east of Lincoln), old groundwater in the deeper confined aquifer becomes brackish (Cl of 5000 mg/L). Baseline concentrations of dissolved CH_4 remain low ($\mu\text{g/L}$) throughout the confined aquifer because of a general paucity of organic matter in both the sediment and groundwater (Table 16).

Table 15. Nottinghamshire/South Yorkshire Sherwood Sandstone Group aquifer: matrix assessment

Influence type	Influence	Factor	Presence	Substance(s) potentially influenced
Baseline environment	High	Overlying organic-rich superficial deposits	N	CH ₄
		Aquifer lithology – organic-rich sediments	N	CH ₄ , SEC, NORM
	Medium	Confined aquifer	Y	CH ₄
		Deep aquifer – long residence times	Y	CH ₄ , salinity, SO ₄
	Low	Aquifer proximity to organic rich sediments	N	CH ₄ , NORM
Anthropogenic impacts	High	Mining legacy	Y	CH ₄ , NORM
		Industrial land use	Y	CH ₄ , TPH, PAH, VOCs, SVOCs
		Urban environment	Y	Salinity (from gritted roads), TPH, VOCs (from vehicles)
		Agricultural land use	Y	Nitrate (NO ₃), pesticides
	Medium	–	–	–
	Low	Hydrocarbon activities at surface	Y	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM
		Hydrocarbon activities at depth	Y	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM

Table 16. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Triassic Sherwood Sandstone of Nottinghamshire and South Yorkshire

Potential influenced compounds	Overall influence	Widespread or localised	Factor
Dissolved solids/SEC	High	Widespread (confined)	Deep aquifer and urban environment
TPH, VOCs	Low	Localised	Industrial land use, urban environment, hydrocarbon activities
CH ₄	Low	Widespread	Confined, deep aquifer mining legacy industrial land use, hydrocarbon activities
PAH, SVOCs, NORM	Low	Localised	Hydrocarbon activities, industrial land use, mining legacy
NO ₃ , pesticides	High	Widespread	Agricultural activities

The unconfined Sherwood Sandstone Group (SSG) aquifer in Nottinghamshire has overlying thin and sandy soils with little organic material. Therefore, we would not anticipate the make-up of the overburden to impact significantly on the organic chemical quality of the aquifer. However, the aquifer may be more vulnerable to pollution from surface activities due to the sandy nature, which may include synthetic organic contaminants. The Sherwood Sandstone is covered by Quaternary superficial deposits in places which has variable permeability depending on lithology and texture. The aquifer is also located adjacent to and overlying the Carboniferous Coal Measures, so in certain areas this may have an impact on water chemistry including dissolved methane and salinity of the groundwater. There are also areas of the SSG in Nottinghamshire/Lincolnshire that are

much deeper and confined below the Mercia Mudstone Group (MMG). It might therefore be anticipated that the methane concentrations in this deep confined zone may be higher due to more strongly reducing conditions (Darling and Goody, 2006; Goody and Darling, 2005).

3.5 PENNINE COAL MEASURES OF THE EAST MIDLANDS AND SOUTH YORKSHIRE

This section is based on the work compiled in Mallin Martin and Smedley (2021b) on the Pennine Coal Measures which contains all the relevant figures.

3.5.1 Understanding the baseline environment

The Pennine Coal Measures Group is subdivided into three distinct units: the Pennine Lower, Middle and Upper Coal Measures. Across the investigation area, all three crop out, with the Upper Coal Measures present only to the east and north of Sheffield. They comprise a series of interbedded siltstones/mudstones, with alternating grey sandstones, and sequences of coal, palaeosols and ironstones and volcanic rocks in the base of the Lower Coal Measures sequence (Aitkenhead et al., 2002, Cheney, 2007, Jones et al., 2000). Sandstones within the Pennine Coal Measures are typically thin and discontinuous, but a few units cover a large area (>100 km²); small channels/horizons are typically less than 8 m thick, less than 1 km wide and a few kilometres in length, whilst larger deposits may be in excess of 20 m thick, 20 km wide, and tens of kilometres long (Jones et al., 2000, Cheney, 2007). Sandstone units are at their thickest in the northern half of the Pennine Coal Measures (in South Yorkshire), progressively thinning towards the south and east of the outcrop (towards Nottingham and Derby) (Jones et al., 2000). Structurally, the Pennine Coal Measures are heavily jointed and faulted, and gently inclined towards the east. Many of the sandstone units throughout the Pennine Coal Measures are juxtaposed against mudstones and siltstones, owing to their discontinuous nature (Jones et al., 2000, Cheney, 2007).

The superficial cover across the study area consists of a number of alluvial deposits, with notable glacial deposits just north of the study area. Superficial cover has been estimated to reach a maximum thickness of over 25 m in the vicinity of Bradford, but is typically less than 10 m thick or absent across much of the study area (Lawley and Garcia-Bajo, 2010).

The Pennine Coal Measures are considered a secondary aquifer (EA and BGS, 2018). The formation supports a number of local private abstractions. The aquifer is “multi-layered”, with discontinuous water-bearing sandstones being confined and isolated from each other by interbedded mudstones and siltstones (Jones et al., 2000, Cheney, 2007). Sandstones tend to be thinner and drier in the Lower and Middle Pennine Coal Measures (Jones et al., 2000), but a number of water-bearing horizons can be found in the Lower and Middle Coal Measures, including the Crawshaw Sandstone, and Wingfield Flags members. Groundwater flow in the Pennine Coal Measures is via fractures, with some intergranular flow within sandstone units. The conditions of the Pennine Coal Measures have been heavily modified by the legacy of coal mining. Increased fracturing following subsidence and new connections between once hydraulically isolated units via roadways and mines, has changed the natural behaviour of the Coal Measures (Banks, 1997, Jones et al., 2000). Regional flow is primarily from west to east, but also controlled by the folding and jointing/faulting across the region, alongside the historic mine workings, resulting in a complex 3D and potentially “karstic” like flow regime (Banks, 1997).

3.5.2 Anthropogenic impacts

To the west of Bradford, Huddersfield, and Sheffield lies the Peak District, which forms a major upland and divides the Pennine Coal Measures between the East Midlands and east Cheshire and Manchester. Across the study area, the terrain slopes predominantly towards the east, from a high point of 636 m (Kinder Scout, west of Sheffield). Over 55% of the study area is classified as agricultural land use, principally being divided by arable practices (>30%) and pasture (20%). Urban land use accounts for 37% of the total land cover, with “discontinuous urban fabric” forming the majority of this at 26%. Many of the urban developments are concentrated in the north around Leeds, Bradford, Huddersfield and Wakefield. Sheffield and Rotherham are the major urban centres in the central portion, whilst the southern half of the study area includes some of the smaller settlements outside of Nottingham and Derby. The extent of the Peak District can be

observed in Figure 26 **Error! Reference source not found.** of Mallin Martin and Smedley (2021b) (blue and green), to the west, being dominated by Peat Bogs and Moors/Heathland.

The East Pennine coal field has historically been a major resource in the UK, having produced a total of 21 million tonnes of coal from deep underground and open-cast workings between 1998 and 1999 (Aitkenhead et al., 2002) (Figure 14). The East Pennine Coalfield was producing coal up until the closure of both Hatfield and Kellingley Collieries in 2015. Across South Yorkshire and Derbyshire, there were over 200 nationalised coal mines (Northern Mine Research Society, 2021c, Northern Mine Research Society, 2021a, Northern Mine Research Society, 2021b). As the coal mining industry progressively closed, dewatering of the workings also ceased, resulting in minewater rebound across much of the eastern extent of the Pennine Coal Measures. This rebound has been a cause for concern with respect to drinking-water quality, especially in the adjacent Sherwood Sandstone aquifer to the east (Allen et al., 1997b, Morris, 2005). Many of the collieries through the East Pennine coalfield are hydraulically connected, and have previously been subject to a number of investigations with respect to minewater rebound upon cessation of dewatering activities (Banks, 1997, Burke et al., 2005, Dumpleton et al., 2001, Gandy and Younger, 2007, Gee et al., 2020). Groundwater interaction with these now-abandoned mine workings results in acidic and metal-rich waters, some of which can be discharged at surface via adits or soughs (Younger and Adams, 1997, Younger et al., 2002, Banks, 1997). The UK Coal Authority manages discharges of acid mine drainage via treatment schemes. Across the wider study area, the Coal Authority manages three treatment sites; Woolley Mine water treatment scheme, Barnsley, and Sheephouse Mine scheme, Stocksbridge, both of which are passive, reed-bed treatment schemes, and the “A” Winning minewater treatment scheme, near Alfreton, where water is pumped to surface and treated in a series of cascades, lagoons and a wetland (Coal Authority, 2018, Coal Authority, 2017, Coal Authority, 2021).

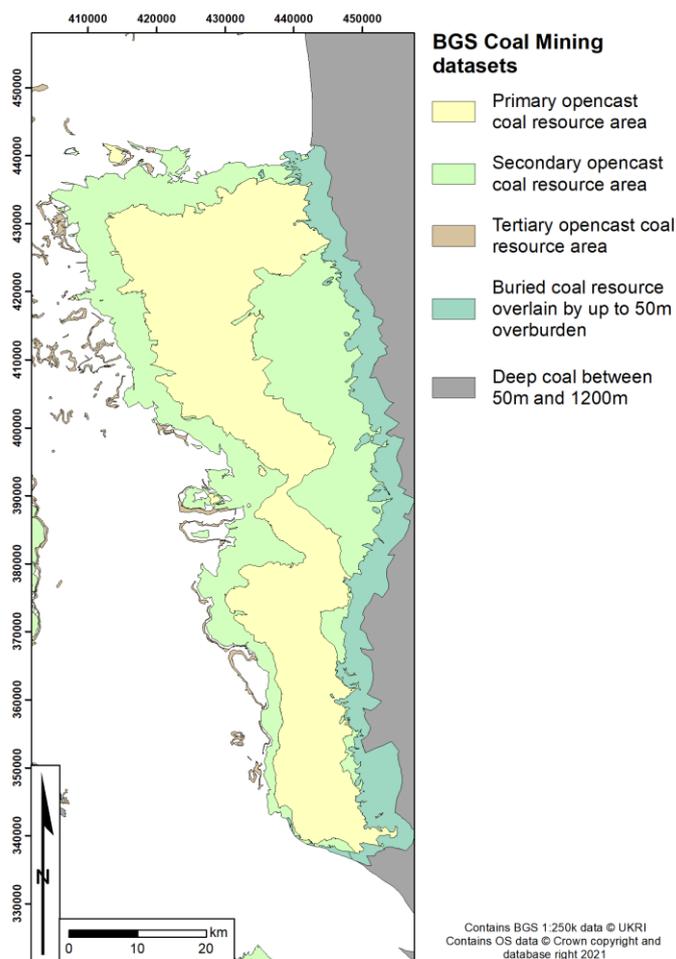


Figure 14. East Midlands and South Yorkshire coal-mining data. Primary = generally thick coals at surface, main targets for opencast coal extraction. Secondary = generally thin coals at surface, secondary targets for opencast coal extraction (Jones, 2006).

There are only two conventional gas fields situated in the study area: Calow and Ironville (OGA, 2021), situated in north Derbyshire near Chesterfield and Ripley respectively. The Pennine Coal Measures have been considered a notable source of mine gas: releases of natural gas that naturally build up in abandoned mine workings, derived from the coal. One such site was Markham Colliery (east of the study area, near Bolsover), operated by Alkane Energy. As of 2006, this is no longer harvesting gas (Banks et al., 2017). Within the study area, wells drilled with the intention of harvesting mine gas have principally been exploration wells.

3.5.3 Assessment of baseline groundwater quality in relation to OOG and deep subsurface compounds

The Pennine Coal Measures are the most complex aquifer studied because the interbedded sandstones and clay-dominated facies are heavily faulted and in places, have been further modified by coal-mine workings. Groundwater occurs overwhelmingly under reducing conditions, with high concentrations of Fe, Mn and NH₄ and low concentrations of NO₃. Dissolved solids concentrations are relatively high due to interactions of groundwater with host clay minerals. Some groundwater samples show evidence of pyrite oxidation with consequent increased concentrations of SO₄ (with or without acid production). Strongly reducing conditions consistent with SO₄ reduction occur in places but are localised and less common. Concentrations of solid and dissolved organic carbon are elevated (groundwater in the 1–5 mg/L range) (Table 17) and dissolved methane may be present sporadically under the most strongly reducing conditions in the mg/L range. Evidence exists for small quantities of PAHs and VOCs in the groundwater, which could relate to natural organic matter or localised minor pollution (Table 18).

Table 17. Pennine Coal Measures aquifer: matrix assessment

Influence type	Influence	Factor	Presence	Substance(s) potentially influenced
Baseline environment	High	Overlying organic-rich superficial deposits	N	CH ₄
		Aquifer lithology – organic-rich sediments	Y	CH ₄ , dissolved solids, NORM
	Medium	Confined aquifer	Y	CH ₄
		Deep aquifer – long residence times	N	CH ₄ , salinity
	Low	Aquifer proximity to organic-rich sediments	Y	CH ₄ , NORM
		–	–	–
Anthropogenic impacts	High	Mining legacy	Y	CH ₄ , NORM, trace metals
		Industrial land use	Y	CH ₄ , TPH, PAH, VOCs, SVOCs
		Urban environment	Y	Salinity (from gritted roads), TPH, VOCs (from vehicles)
		Agricultural land use	N	Nitrate (NO ₃), pesticides
	Medium	–	–	–
	Low	Hydrocarbon activities at surface	Y	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM
		Hydrocarbon activities at depth	Y	CH ₄ , TPH, PAH, VOCs, SVOCs, NORM

Table 18. Overall likelihood of OOG and other deep subsurface compounds in groundwater from the Coal Measures of the East Midlands and South Yorkshire

Potential influenced compounds	Overall influence	Widespread or localised	Factor
Dissolved solids/SEC	High	Widespread	Aquifer lithology and urban environment
TPH, VOCs	Low	Localised	Industrial land use, urban environment, hydrocarbon activities
CH ₄	High	Widespread	Aquifer lithology and proximity to organic-rich sediments, confined aquifer, mining legacy, industrial land use and hydrocarbon activities
PAH, SVOCs, NORM	High	Widespread	Aquifer lithology and proximity to organic-rich sediments, mining legacy, industrial land use, hydrocarbon activities
NO ₃ , pesticides	Low	Localised	Agricultural activities

4 Conclusions

This methodology has been designed to provide a rapid assessment for the potential presence of OOG-type contaminants and other deep subsurface compounds in groundwater. The assessment has been designed to consider the magnitude of influence that each factor is likely to have on groundwater quality. The compounds may be either organic or inorganic: each are essential to understanding sources of contamination, but also for understanding the hydrogeological system. Conducting this assessment for a specific aquifer requires a baseline conceptual understanding of both the hydrogeology and hydrogeochemistry which is a key step in the process. The aim is that this can then be used to understand the potential impact a specific aquifer setting may have on groundwater quality, in relation to OOG and other deep subsurface compounds.

The previous three reports in this series concluded that key influencing factors on baseline groundwater quality when considering OOG-type compounds were not location of hydrocarbon extraction sites, but instead aquifer lithology and overlying superficial deposits. The findings from these case study area reports have been incorporated into justifying the magnitude of influence that each factor has on groundwater quality. The key factors to be considered in assessment of OOG and other deep subsurface activities are geological (e.g. aquifer lithology, proximity to organic rich sediments), hydrogeological (confined, unconfined) and anthropogenic activities (e.g. hydrocarbon extraction, surface activities).

The assessments carried out above have identified that all groundwaters are influenced by their baseline environment, to the extent of producing poor-quality groundwater in the Pennine Coal Measures and the Vale of Pickering Kimmeridge Clay. These two aquifers have a greater risk of having compositions with elevated dissolved solids contents and raised concentrations of dissolved methane as they have multiple high influencing factors that are likely to be widespread. A summary of the potential for OOG-type compounds in the different aquifers is summarised in Tables 19 and 20. Methane is one of the most diagnostic analytes and these assessments compare well to methane data collected as part of previous projects (Figure 15) for the six different aquifers.

Table 19. Summary of potential impact on groundwater quality in superficial deposit aquifers considered in this report.

Potential influenced compounds	Fylde peninsula Quaternary		Pickering Kimmeridge Clay	
	Influence	Scale	Influence	Scale
Dissolved solids	High	Local	High	Widespread
TPH, VOCs,	High	Local	Low	Local
CH ₄	High	Local	High	Widespread
PAH, SVOCs, NORM	Low	Local	Low	Local
NO ₃ , pesticides	High	Widespread	High	Widespread

Table 20. Summary of potential impact on groundwater quality in bedrock aquifers considered in this report.

Potential influenced compounds	Corallian		Lower Greensand Group		Sherwood Sandstone Group		Pennine Coal Measures	
	Influence	Scale	Influence	Scale	Influence	Scale	Influence	Scale
Dissolved solids	Low	Local	Low	Wide-spread	High	Wide-spread (confined)	High	Wide-spread
TPH, VOCs,	Low	Local	Low	Local	Low	Local	Low	Local
CH ₄	Low	Local	Low	Wide-spread	Low	Wide-spread	High	Wide-spread
PAH, SVOCs, NORM	Low	Local	Low	Local	Low	Local	High	Wide-spread
NO ₃ , pesticides	High	Wide-spread	High	Wide-spread	High	Wide-spread	Low	Local

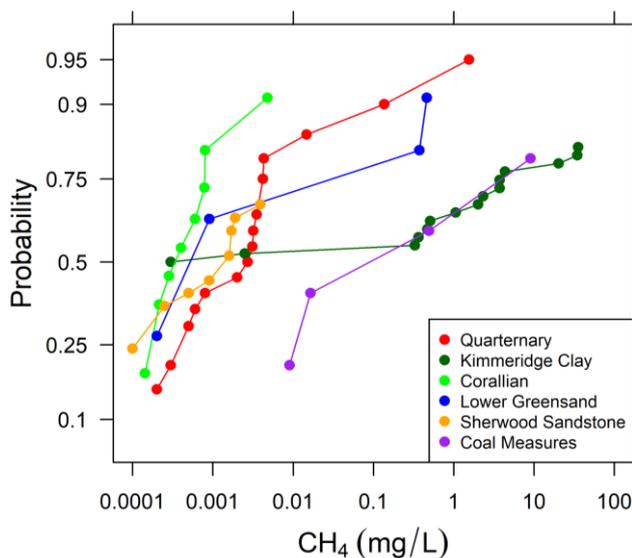


Figure 15. Comparison methane data for the study areas

5 Recommendations

This project has attempted to identify the key vulnerabilities of groundwater in English aquifers in terms of OOG-type and other deep subsurface activities. However, the topic is complex and the vulnerabilities spatially variable and the project has only been able to go so far in establishing key factors and their impacts on groundwater quality. Some key recommendations for future investigations are outlined below.

- The BGS Appleton (2011) dataset identifying sources of methane and carbon dioxide from natural sources and mining has recently been withdrawn from circulation. An update to this work would generate a valuable mapping tool which could also be built upon to potentially include pathways (structural data and permeable pathways) and groundwater methane data. This could incorporate both natural geogenic sources of methane and anthropogenic sources e.g. certain land use types and current OOG sites.
- A more detailed vulnerability-type assessment could also be carried out with an in-depth understanding of the specific factors underpinning this assessment, for example, the thicknesses of peat likely to be required to influence groundwater quality.
- Identification of specific superficial deposits (e.g. peat) that may influence groundwater quality in relation to deep-subsurface compounds should be carried out, with generation of maps of these 'at risk' locations. This would require discussions around which sediment types have the most influence and subsequent GIS processing.
- The same process could also be carried out for aquifer lithology. All the Coal Measures units have been identified previously, but other sediment types that have the potential to be a source for OOG and deep subsurface compounds could also be mapped.
- Although this work has been carried out with specific reference to onshore oil and gas activities, the methodology also has applications for other deep subsurface activities, for example carbon capture and storage and geothermal energy extraction. These technologies are key to a low-carbon future, although their impact on the subsurface and groundwater are relatively unknown. This methodology could be developed further and amended to incorporate these types of activity.

References

- AITKENHEAD, N., BARCLAY, W. J., BRANDON, A., CHADWICK, R. A., CHRISHOLM, J. I., COOPER, A. H. & JOHNSON, E. W. 2002. *British regional geology: the Pennines and adjacent areas*, London, HMSO for the British Geological Survey.
- ALLEN, D. J., BREWERTON, L. J., COLEBY, L. M., GIBBS, B. R., LEWIS, M. A., MACDONALD, A. M., WAGSTAFF, S. J. & WILLIAMS, A. T. 1997a. The physical properties of major aquifers in England and Wales. *In*: ALLEN, D. J., BLOOMFIELD, J. P. & ROBINSON, V. K. (eds.).
- ALLEN, D. J., BREWERTON, L. J., COLEBY, L. M., GIBBS, B. R., LEWIS, M. A., MACDONALD, A. M., WAGSTAFF, S. J. & WILLIAMS, A. T. 1997b. The physical properties of major aquifers in England and Wales. *In*: ALLEN, D. J., BLOOMFIELD, J. P. & ROBINSON, V. K. (eds.). Environment Agency R&D Publication 8.: British Geological Survey.
- AMBROSE, K., HOUGH, E., SMITH, N. J. P. & WARRINGTON, G. 2014. Lithostratigraphy of the Sherwood Sandstone Group of England, Wales and south-west Scotland. Keyworth: British Geological Survey.
- ANDREWS, I. J. 2014. The Jurassic shales of the Weald basin: geology and shale oil and shale gas resource estimation. London, UK: British Geological Survey for Department of Energy and Climate Change.
- APPLETON, J. D. 2011. BGS methane and carbon dioxide from natural sources and mining. British Geological Survey.
- BANKS, D. 1997. Hydrogeochemistry of Millstone Grit and Coal Measures groundwaters, south Yorkshire and north Derbyshire, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, 30, 237-256.
- BANKS, D., ATHRESH, A., AL-HABAIBEH, A. & BURNSIDE, N. 2017. Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. *Sustainable Water Resources Management*, 5, 29-50.
- BEIS, OGA, THE RT HON KWASI KWARTENG MP & THE RT HON ANDREA LEADSOM MP. 2019. *Government ends support for fracking* [Online]. Available: <https://www.gov.uk/government/news/government-ends-support-for-fracking> [Accessed 06/04/2020].
- BELL, R. A., BEARCOCK, J. M., BOWES, M. J., MILNE, C. J., SCHEIDEGGER, J. M., WHITE, D., TAYLOR, H., LISTER, T. R., SMEDLEY, P. L. & WARD, R. S. 2018. Impacts on Groundwater Quality from Abandoned Hydrocarbon Wells - Final Report.: British Geological Survey Commissioned Report.
- BELL, R. A., DARLING, W. G., MANAMSA, K. & O DOCHARTAIGH, B. E. O. 2016. The baseline concentrations of methane in Great British groundwater : the National Methane Baseline Survey.
- BELL, R. A., DARLING, W. G., WARD, R. S., BASAVA-REDDI, L., HALWA, L., MANAMSA, K. & BE, O. D. 2017. A baseline survey of dissolved methane in aquifers of Great Britain. *Sci Total Environ*, 601-602, 1803-1813.
- BGS. 2016. *Baseline chemistry of groundwater in UK aquifers* [Online]. Available: <https://www.bgs.ac.uk/research/groundwater/quality/BaselineUK/baselineEngWales.html> [Accessed 11/05/2020].
- BGS. 2018. *Aquifer/shale separation maps* [Online]. Available: <https://www.bgs.ac.uk/research/groundwater/shaleGas/aquifersAndShales/maps/separationMaps/home.html> [Accessed 06/05/2020].
- BURKE, S. P., POTTER, H. A. B. & JARVIS, A. Groundwater Rebound in the South Yorkshire Coalfield: A review of initial modelling. *In*: LOREDO, J. & PENDÁS, F., eds. 9th International Mine Water Association Congress: Mine Water 2005 – Mine Closure, 2005 Oviedo, Spain. University of Oviedo, 223-227.
- CHENEY, C. S. 2007. The hydrogeology of the Chesterfield, Matlock and Masnfield district (Geological Map Sheet 112). British Geological Survey.
- COAL AUTHORITY. 2017. *Sheephouse Wood mine water treatment scheme* [Online]. Available: <https://www.gov.uk/government/case-studies/sheephouse-wood-mine-water-treatment-scheme> [Accessed 10/02/21].

- COAL AUTHORITY. 2018. *A-Winning mine water treatment scheme* [Online]. Available: <https://www.gov.uk/government/case-studies/a-winning-mine-water-treatment-scheme> [Accessed 10/02/20].
- COAL AUTHORITY. 2021. *The Coal Authority's Mine Water Treatment Schemes* [Online]. The Coal Authority. Available: <https://www.arcgis.com/apps/MapTour/index.html?appid=143ec3c560654e53acd2d88031a13068> [Accessed 10/02/21].
- COPE, J. C. W. 1974. New information on the Kimmeridge Clay of Yorkshire. *Proceedings of the Geologists' Association*, 85, 211-221.
- CRANFIELD UNIVERSITY. 2021. *0571e FYFIELD 2 - Land Information System* [Online]. Available: <https://www.landis.org.uk/services/soilsguide/mapunit.cfm?mu=57105> [Accessed 09/02/21].
- CRIPPS, C., BURKE, H., LEE, J. & HOUGH, E. 2016. The Fylde, Lancashire: Summary of the quaternary geology. British Geological Survey.
- CRIPPS, C., BURKE, H. F., LEE, J. R. & HOUGH, E. 2017. The Fylde, Lancashire: summary of the Quaternary geology. Keyworth, UK: British Geological Survey.
- DUMPLETON, S., ROBINS, N. S., WALKER, J. A. & MERRIN, P. D. 2001. Mine water rebound in South Nottinghamshire: risk evaluation using 3-D visualization and predictive modelling. *Quarterly Journal of Engineering Geology and Hydrogeology*, 34, 307-319.
- EA & BGS. 2018. *Aquifer Designation Dataset* [Online]. Available: <https://www.bgs.ac.uk/products/hydrogeology/aquiferDesignation.html> [Accessed 05/03/19 2019].
- EUROPEAN ENVIRONMENT AGENCY (EEA) 2019. CORINE Land Cover (CLC) - 2018 v2. In: EUROPEAN ENVIRONMENT AGENCY (EEA) (ed.) 2.0 ed.
- EVANS, D. J. A., BATEMAN, M. D., ROBERTS, D. H., MEDIALDEA, A., HAYES, L., DULLER, G. A. T., FABEL, D. & CLARK, C. D. 2017. Glacial Lake Pickering: stratigraphy and chronology of a proglacial lake dammed by the North Sea Lobe of the British-Irish Ice Sheet. *Journal of Quaternary Science*, 32, 295-310.
- FORD, J., HUGHES, L., BURKE, H. & LEE, J. 2015. The Vale of Pickering: an initial summary of the Quaternary/superficial geology and data holdings. Keyworth, UK: British Geological Survey.
- GANDY, C. J. & YOUNGER, P. L. 2007. Predicting Groundwater Rebound in the South Yorkshire Coalfield, UK. *Mine Water and the Environment*, 26, 70-78.
- GEE, D., BATESON, L., GREBBY, S., NOVELLINO, A., SOWTER, A., WYATT, L., MARSH, S., MORGENSTERN, R. & ATHAB, A. 2020. Modelling groundwater rebound in recently abandoned coalfields using DInSAR. *Remote Sensing of Environment*, 249.
- HOBBS, P. R. N., HALLAM, J. R., FORSTER, A., ENTWISLE, D. C., JONES, L. D., CRIPPS, A. C., NORTHMORE, K. J., SELF, S. J. & MEAKIN, J. L. 2002. Mudstones of the Mercia Mudstone Group. *Engineering geology of British rocks and soils*. British Geological Survey.
- IGAS ENERGY PLC 2019. Operational Update - Tinker Lane and Springs Road.
- JONES, H. K., MORRIS, B. L., CHENEY, C. S., BREWERTON, L. J., MERRIN, P. D., LEWIS, M. A., MACDONALD, A. M., COLEBY, L. M., TALBOT, J. C., MCKENZIE, A. A., BIRD, M. J., CUNNINGHAM, J. & ROBINSON, V. K. 2000. The physical properties of minor aquifers in England and Wales. British Geological Survey.
- JONES, N. S. 2006. Coal Resource Appraisal Maps: methodology and datasets used. BGS.
- KENT, P. F. 1980. *British Regional Geology: Eastern England from the Tees to The Wash*, London, HMSO for the British Geological Survey.
- LAWLEY, R. & GARCIA-BAJO, M. 2010. The National Superficial Deposit Thickness Model (version 5). British Geological Survey.
- LOVELESS, S. E., BLOOMFIELD, J. P., WARD, R. S., HART, A. J., DAVEY, I. R. & LEWIS, M. A. 2018. Characterising the vertical separation of shale-gas source rocks and aquifers across England and Wales (UK). *Hydrogeol J*, 26, 1975-1987.
- MALLIN MARTIN, D. & SMEDLEY, P. L. 2020. Baseline groundwater chemistry: the Sherwood Sandstone aquifer of the East Midlands and South Yorkshire. British Geological Survey Open Report.
- MALLIN MARTIN, D. & SMEDLEY, P. L. 2021a. Baseline groundwater chemistry: The Lower Greensand aquifer of South East England. British Geological Survey Open Report.

- MALLIN MARTIN, D. & SMEDLEY, P. L. 2021b. Baseline groundwater chemistry: the Pennine Coal Measures of the East Midlands and South Yorkshire. British Geological Survey Open Report.
- MORRIS, B. L. 2005. Hydrogeological notes for the Sheffield district (sheet 100). British Geological Survey.
- NEWELL, A. J., WARD, R. S. & FELLGETT, M. W. 2016. A 3D geological model of post-Permian aquifers and aquitards in the Vale of Pickering, North Yorkshire, UK. Keyworth, UK: British Geological Survey.
- NORTHERN MINE RESEARCH SOCIETY. 2021a. *Derbyshire Coalfield - Chesterfield Area* [Online]. Available: <https://www.nmrs.org.uk/mines-map/coal-mining-in-the-british-isles/derbynotts/chesterfield/> [Accessed 10/02/21].
- NORTHERN MINE RESEARCH SOCIETY. 2021b. *Derbyshire Coalfield - Derby Area* [Online]. Available: <https://www.nmrs.org.uk/mines-map/coal-mining-in-the-british-isles/derbynotts/derby/> [Accessed 10/02/21].
- NORTHERN MINE RESEARCH SOCIETY. 2021c. *Yorkshire Coalfield* [Online]. Available: <https://www.nmrs.org.uk/mines-map/coal-mining-in-the-british-isles/yorkshire-coalfield/> [Accessed 10/02/21].
- NORTHERN MINE RESEARCH SOCIETY. n.d.-a. *Nottinghamshire Coalfield - Mansfield Area* [Online]. Available: <https://www.nmrs.org.uk/mines-map/coal-mining-in-the-british-isles/derbynotts/mansfield/> [Accessed 06/04/2020].
- NORTHERN MINE RESEARCH SOCIETY. n.d.-b. *Nottinghamshire Coalfield - Nottingham Area* [Online]. Available: <https://www.nmrs.org.uk/mines-map/coal-mining-in-the-british-isles/derbynotts/nottingham/> [Accessed 06/04/2020].
- NORTHERN MINE RESEARCH SOCIETY. n.d.-c. *Yorkshire Coalfield* [Online]. Available: <https://www.nmrs.org.uk/mines-map/coal-mining-in-the-british-isles/yorkshire-coalfield/> [Accessed 10/02/21].
- OGA. 2019. *OGA Fields BNG [Shapefile]* [Online]. OGA Open Data. Available: <https://data-ogauthority.opendata.arcgis.com/datasets/oga-onshore-fields-bng> [Accessed 05/03/19].
- OGA. 2021. *OGA Fields BNG [Shapefile]* [Online]. OGA Open Data. Available: <https://data-ogauthority.opendata.arcgis.com/datasets/oga-onshore-fields-bng?geometry=-43.445%2C48.571%2C40.183%2C57.748> [Accessed 10/02/21].
- POWELL, J. H. 2010. Jurassic sedimentation in the Cleveland Basin: a review. *Proceedings of the Yorkshire Geological Society*, 58, 21-72.
- POWELL, J. H. & RIDING, J. 2016. Stratigraphy, sedimentology and structure of the Jurassic (Callovian to Lower Oxfordian) succession at Castle Hill, Scarborough, North Yorkshire, UK. *Proceedings of the Yorkshire Geological Society*, 61, 109-133.
- PRICE, S. J., BANKS, V., COOPER, A. H., WILDMAN, G., KESSLER, H., BURKE, H. F., TERRINGTON, R., BRIDGE, D. & SHEPLEY, M. 2006. 3-D hydrogeological characterisation of the superficial deposits between Doncaster and Retford. British Geological Survey.
- SHAND, P., COBBING, J., TYLER-WHITTLE, R., TOOTH, A. F. & LANCASTER, A. 2003. Baseline Report Series: 9. The Lower Greensand of southern England. British Geological Survey, Environment Agency,.
- SHEPLEY, M. G., PEARSON, A. D., SMITH, G. D. & BANTON, C. J. 2008. The impacts of coal mining subsidence on groundwater resources management of the East Midlands Permo-Triassic Sandstone aquifer, England. *Quarterly Journal of Engineering Geology and Hydrogeology*, 41, 425-438.
- SMEDLEY, P. L. & BREWERTON, L. J. 1997. The Natural (Baseline) Quality of Groundwaters in England and Wales: The Triassic Sherwood Sandstone of the East Midlands and South Yorkshire. British Geological Survey.
- SMEDLEY, P. L., SHAND, P. & BUTCHER, A. S. 2018. Age and quality stratification of groundwater in the Triassic Sherwood Sandstone aquifer of South Yorkshire and the East Midlands, UK. *Applied Geochemistry*, 97, 109-122.
- TATTERSALL, K. H. & WILKINSON, W. B. 1974. Groundwater Investigation in the Vale of Pickering: Final report on preliminary investigation. Yorkshire River Authority and Water Resources Board.

- UKOG PLC. 2020. *Asset Portfolio Map* [Online]. Available: <https://www.ukogplc.com/images/assets/UKOG%20Portfolio%20Map.pdf> [Accessed 26/04/21].
- UKOOG. 2017. *Where we operate: Licensed Areas* [Online]. Available: <http://www.ukoog.org.uk/onshore-extraction/where-we-operate> [Accessed 05/03/19].
- WARD, R. S., SMEDLEY, P. L., ALLEN, G., BAPTIE, B. J., BARKER, P., BARKWITH, A. K. A. P., BATES, P., BATESON, L., BELL, R. A., COLEMAN, M., CREMEN, G., CREWDSON, E., DARAKTCHIEVA, Z., GONG, M., HOWARTH, C. H., FRANCE, J., LEWIS, A. C., LISTER, T. R., LOWRY, D., LUCKETT, R., MALLIN MARTIN, D., MARCHANT, B. P., MILLER, C. A., MILNE, C. J., NOVELLINO, A., PITT, J., PURVIS, R. M., RIVETT, M. O., SHAW, J., TAYLOR-CURRAN, H., WASIEKIEWICZ, J. M., WERNER, M. & WILDE, S. 2020. Environmental monitoring : phase 5 final report (April 2019 - March 2020). BGS, Nottingham, UK.
- WARD, R. S., SMEDLEY, P. L., ALLEN, G., BAPTIE, B. J., DARAKCHIEVA, Z., HORLESTON, A., JONES, D. G., JORDAN, C. J., LEWIS, A. N., LOWRY, D., PURVIS, R. M. & RIVETT, M. O. 2017. Environmental Baseline Monitoring Project: Phase II - Final Report. Keyworth, UK: British Geological Survey.
- WILLIAMS, P. F. V. 1986. Petroleum geochemistry of the Kimmeridge Clay of onshore Southern and Eastern England. *Marine and Petroleum Geology*, 3, 258-281.
- YOUNGER, P. L. & ADAMS, R. 1997. Predicting Mine Water Rebound. Environment Agency.
- YOUNGER, P. L., BANWART, S. A. & HEDIN, R. S. 2002. *Mine Water: Hydrology, Pollution, Remediation*, Springer Netherlands.