Mapping brackish aquifers and deep-sourced springs

Chief Scientist’s Group report

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Professor Doug Wilson
Chief Scientist

Executive summary

The Environment Agency recognises the heavy reliance on near-surface freshwater aquifers for the supply of drinking water and other purposes in many parts of England. Deeper aquifers that contain brackish groundwater might also provide a valuable resource in water-stressed areas but there is currently very little known about the location of these waters and their potential value. There is also limited understanding of the origin of thermal and other 'deep' spring waters, some of which have reputed health benefits and have been used as spa waters, and further uses should be explored.

This report attempts to address this by:

- reviewing where these resources occur
- providing methods to identify and map these resources
- producing outline guidance to protect these resources

The main objective is to help us develop our position on protecting brackish groundwaters and deep-sourced springs in England.

Brackish groundwater

Brackish groundwater is defined here as groundwater with total dissolved solids (TDS) concentrations in the range 1,625mg/l to 10,000mg/l. TDS is the term used to describe the inorganic salts and small amounts of organic matter present in solution in water. The principal constituents are usually calcium, magnesium, sodium, and potassium cations and carbonate, hydrogen carbonate, chloride, sulphate, and nitrate anions. For brackish groundwater this TDS range covers groundwater identified in literature as slightly to moderately saline.

Complementary methods are proposed for developing a national map to show the possible presence of 'useful' brackish groundwater throughout England, and for carrying out a high-level site-specific assessment to determine if 'useful' brackish groundwater is likely to be present (and the confidence in this assessment). The focus of the mapping is on bedrock geology and the proposed method uses the British Geological Survey (BGS) 3D geology cross sections. Brackish groundwater in superficial deposits cannot be mapped using the proposed technique and should be assessed as part of a site-specific risk assessment.

On a national level, useful brackish groundwater is defined here as a function of aquifer permeability and the TDS concentration. The geothermal data catalogue (Appendix A) is used to provide estimates of TDS variation with depth. Aquifer designation is used to quantify aquifer permeability and formations designated as unproductive are marked as not useful. The outcome of the high-level national mapping exercise is a series of 3D cross sections displaying the presence of useful brackish groundwater at depth. A case study demonstrating both mapping methods is presented for a site in the Cheshire Basin.

Deep-sourced springs

Springs need protecting due to their value as sources of drinking water, their recreational or therapeutic use and their importance to ecosystems. It is difficult to define deep-sourced springs because of the many and often site-specific features associated with water discharging from depth. A high-level literature review to identify and catalogue known deep-sourced springs was carried out. However, despite significant previous scientific research effort, the origin of some of the most widely studied deep-sourced springs in the UK still remains uncertain. As deep-sourced springs are usually controlled by specific hydrogeological circumstances, and for many deep-sourced springs there is little data to determine their origin, no national mapping method is proposed. Instead, a number of lines of evidence to support a deep-sourced origin are identified. These include water quality parameters, age dating, uniformity of spring discharge, and favourable geological structures. In addition, three areas are detailed for potentially mapping the origin of each known spring, including location, hydrogeological conceptualisation and the value of the spring.

As with the brackish groundwater review, the review of deep-sourced springs suggests there is groundwater at depth that must be protected due to its connection to deep-sourced springs. It is also recommended that the protection of deep-sourced springs should fall under the existing risk assessment framework for groundwater protection.

Conclusions and recommendations

The detailed review and discussion of brackish groundwater and deep-sourced springs indicates there is groundwater at depth that requires protection because either:

- the water is of good enough quality that it may be directly useful (brackish groundwater)
- it supports or is connected with deep-sourced springs that have a value due to their use by people or their support of ecosystems

Protecting these resources should fall under the existing groundwater risk assessment framework. Therefore, the following principles are recommended:

- the possible presence or absence of these resources should be identified by a site-specific risk assessment
- the identified resources should be treated as receptors at risk from a proposed activity
- the risk to these receptors should be assessed as part of tiered risk assessment (in alignment with the current risk-assessment framework)
- the value of the resources (springs or brackish groundwater) should be derived from their use or potential use value
- a ‘precautionary principle’ should be taken: the author of the risk assessment should demonstrate that these resources are not present or they are not at risk from a proposed activity. Where this is uncertain, further investigation is required to screen them out from further risk-assessment

Contents

1 Introduction and scope of work

There is currently very little known about the location of deeper aquifers that contain brackish groundwater and their potential resource value. There is also limited understanding of the origin of thermal and other ‘deep’ spring waters, some of which have reputed health benefits and have been used as spa waters. Consequently, there is little current guidance on the level of groundwater protection that may be suitably applied to these resources.

To help the Environment Agency develop its position on protecting brackish groundwaters and thermal and other deep-sourced springs across England, Mott MacDonald (project SC180009, January 2018) was tasked with reviewing the occurrence of these resources and providing outline guidance on identifying, mapping and protecting them. This report is a potential precursor to future work proposed on mapping deeper brackish groundwater and springs, which will be needed if these resources are to be appropriately protected from increasing exploitation in the future.

The project objectives and scope of work are as follows.

1.1 Brackish groundwater

1.1.1 Define brackish groundwater

- Review criteria for defining brackish groundwater against a selection of water quality standards and justify the choice of appropriate standards.
- Compare the selected standard with international definitions of brackish groundwater presented in the literature.

1.1.2 Describe degree of protection that should be applied to brackish groundwater resources

- Assess the degree of protection that should be applied to brackish groundwater in the context of existing Environment Agency groundwater protection guidance (Environment Agency 2018) and also in relation to the recently published 3D groundwater vulnerability approach (Loveless and others 2018)
- Identify the most appropriate elements or methodologies that apply to brackish groundwater based on their main strengths and weaknesses.

1.1.3 Set out a method for identifying and mapping geological formations containing brackish groundwater

- Develop a method for mapping geological formations containing brackish groundwater based on the definition developed in section 1.1.1.
- Comment on the information currently available and consider information gaps.

- Set out considerations for further work particularly related to the current lack of information on brackish aquifers in England.
- Provide a case study demonstrating the proposed method.

1.1.4 Scope outline guidance

- Develop outline guidance setting out the principles upon which detailed guidance can be developed during future projects.

1.2 Thermal and deep-sourced sourced springs

1.2.1 Define criteria for thermal and deep-sourced springs

- Develop a set of criteria for characterising known sources as well as identifying and characterising new sources in the future. The criteria include regional flow paths, geological structures, issuing formations, hydrochemistry and age dating (where available).

1.2.2 Catalogue the locations and origin of 'known' deep-sourced springs

- Develop a catalogue of known springs using available published (journals and books) and grey literature (for example, academic theses, Environment Agency groundwater modelling reports).
- Categorise identified springs by sedimentary basin (or other geology), potential depth, geological formation, hydrochemistry, discharge, age dating, usage, Water Framework Directive (WFD) waterbody receiving spring flow and other associated WFD water bodies.

1.2.3 Develop an approach for identifying where protection of springs is needed

- Set out a systematic approach for identifying the location, value and possible catchment area of the identified deep-sourced springs.

1.2.4 Scope outline guidance for protection of springs

- Develop outline guidance setting out the principles upon which detailed guidance can be developed during future projects.

Please note that this report is primarily a high-level review. Areas of further work to consolidate the positions developed within this report are identified and recommendations made.

2 Definition, protection and proposed method for identifying brackish groundwater

2.1 Definition of brackish groundwater

2.1.1 Sources of salinity in brackish groundwater

Groundwater may be saline due to a variety of reasons. The main causes of salinisation are (after van Weert, 2012):

- dissolution of naturally occurring mineral salts
- geological deposition of sea water (connate saline groundwater)
- marine transgression
- saline intrusion
- coastal flooding
- coastal sprays
- irrigation
- evaporation at or near the land surface
- anthropogenic groundwater pollution
- igneous activity

Each cause is discussed in detail in the paragraphs below.

- **Dissolution of naturally occurring mineral salts** present along groundwater flow paths. Carbonate and particularly evaporite strata may be highly soluble. However, all bedrock minerals are to some extent soluble and the degree of mineralisation of groundwater is frequently related to the time in which it remains in contact with aquifer materials. This process occurs on all geological timescales from days to millions of years.
- **Connate saline groundwater.** Where sedimentary formations are deposited in the sea (for example, limestone), seawater is incorporated together with the sediments of the rock matrix, and will remain present unless flushed over geological timescales. Migration of connate waters, is likely to occur only very slowly (greater than millennia).
- **Marine transgression.** Sea level is variable over time due to many factors, but particularly climate change and tectonic processes. During marine transgressions, low-lying land becomes flooded with seawater, which infiltrates into underlying aquifers, and can displace freshwater due to its greater density. This process occurs on short geological timescales

(centuries to millennia) when driven by climate, and greater than millennia when driven by tectonics.

- **Saline intrusion.** This process occurs naturally in coastal aquifers where saline water naturally underlies a coastward-thinning lens of fresh groundwater. Saline intrusion may also be induced by anthropogenic processes such as over-pumping coastal aquifers, or over-abstraction from rivers leading to saline incursion along river channels followed by lateral movement into alluvial or other aquifers. This process may occur over years or decades. The existing Environment Agency approach to groundwater protection (Environment Agency 2018) provides a framework for protecting groundwater against anthropogenic causes of saline intrusion.

- **Coastal flooding.** A similar mechanism to marine transgression, but on a much shorter timescale (weeks to years). Saline water may be introduced to aquifers by, for example, storm surges or coastal defence failure.

- **Coastal sprays.** Where shallow coastal aquifers receive significant sea sprays this may be reflected in salinisation of groundwater. This process may occur across different timescales.

- **Irrigation.** Particularly in arid and semi-arid areas, evaporation of irrigation waters leads to their enhanced salinity, and this water may then recharge local groundwater. It can then be abstracted and used again for irrigation. This process occurs over decades to millennia.

- **Evaporation at or near the land surface** related to shallow water table conditions. This is most likely to occur in arid and semi-arid climates, particularly where regional basinal groundwater flow discharges within the landscape.

- **Anthropogenic groundwater pollution.** A wide range of other human activities (besides agriculture) may lead to enhanced salinity of groundwater, for example, applying road salts, fertilisers and effluents to the land.

- **Groundwater salinised by igneous activity.** Increases in groundwater temperature and pressure due to igneous intrusions may greatly enhance the capacity of native groundwater to dissolve host rocks. This process is likely to be relatively localised and occur over several hundreds of years.

The most important contributors to brackish groundwater reserves in England are likely to be (Shand and others 2007):

- dissolution of naturally occurring mineral salts (most significantly in confined aquifers such as beneath areas of thick till deposits in the Vale of York or at depth in the chalk (beneath the zone of active circulation)

- historical or recent seawater intrusion in coastal areas, for example, in the Permo-Triassic sandstones of Liverpool or Manchester

- connate groundwater, for example, at depth in the Cheshire Basin

2.1.2 Review of water quality standards and literature definitions

To help define brackish groundwater a range of literature sources were reviewed, including several national and international standards. These sources and the resulting values are summarised in Table 2.1.

Table 2.1 Groundwater classification schemes (adapted from J Stanton and others 2017)

Total Dissolved-Solids (TDS) concentration [mg/l]	Robinove, Langford and Brookhart (1958)	Winslow, Hillier and Turcan (1968)	Freeze and Cherry (1979)	Rhoades, Kandiah and Mashali (1992)	Reese (1994)	Yobbi (1996)	Bureau of Reclamation (2003)	National Groundwater Association (2010)	Meyer, Wise and Kalaswad (2011)	JS Stanton and others (2017)
0	Fresh	Fresh	Fresh	Non-saline	Fresh	Fresh	Fresh	Fresh	Fresh	Fresh
500				Slightly saline		Slightly saline (brackish)				
1,000	Slightly saline	Slightly saline	Brackish		Brackish		Mildly brackish	Slightly saline (brackish)	Brackish	Slightly saline (brackish)
1,500				Moderately saline						
2,000										
2,500										
3,000	Moderately saline	Moderately saline				Moderately brackish		Moderately saline (brackish)		Moderately saline (brackish)
3,500										
4,000										
4,500										
5,000							Moderately brackish			
5,500										
6,000										
6,500										
7,000				Highly saline						
7,500										
8,000										
8,500										
9,000										
9,500										
10,000	Very saline	Very saline	Saline		Slightly saline	Very saline		Highly saline	Saline	Highly saline
15,000							Heavily brackish			
20,000										

25,000				Very highly saline		(salt water)				
30,000										
35,000	Brine	Brine		Brine	Saline	Briny	Seawater	Seawater		
40,000								Unclassified		
45,000										
50,000										
≥100,000			Brine							

2.1.3 Summary of uses and restrictions on using brackish water supplies

Typical water quality limits for most industrial and all agricultural applications apart from some aquaculture uses are below 3,000mg/l (United States Department of the Interior 2003). Some other industries, such as power plant cooling and hydraulic fracturing are able to use more saline waters.

The cost of desalination increases with increasing salinity of source waters such that the least saline waters are clearly preferred. For example, the majority of desalination plants in the United States use source waters below 3,000mg/l. However, in other parts of the world, such as the Middle East, groundwater with salinity greater than 15,000mg/l may be used in desalination (Marakami 1995).

Besides high total dissolved solids (TDS), brackish and high salinity waters may also have other chemical constituents that limit their use. Some of the potential limitations include:

- toxicity of specific constituents, for example arsenic, fluoride, uranium, boron, strontium that may limit use for drinking water or irrigation
- scaling (mineral precipitation) during conveyance, storage, or treatment
- damage to desalination membranes (for example, from high silica concentrations)
- difficulty removing specific constituents
- increasing soil sodicity and clay dispersion through using high sodium waters for irrigation
- corrosion (aggressivity of high TDS waters) depending on water type and use

In addition, the lack of consistent and comprehensive data may be problematic in successfully exploiting brackish groundwater. Additional requirements for data gathering may include:

- increased hydraulic testing of aquifers for determining permeability characteristics at depth
- geochemical modelling with respect to the end use
- studies on potential replenishment necessary to understand potential impacts of exploitation

Anecdotal evidence suggests that brackish groundwater has been considered as a possible new option for water supply in water stressed parts of England. Using brackish groundwater as a resource may be increasingly important in the future due to the combined influence of population growth and climate change.

2.1.4 Known occurrence of brackish groundwater in England

The known occurrences of brackish groundwater in England have been compiled mainly from the geothermal data catalogue (Burley, Edmunds and Gale 1984), (Rollin 1987). Figure 8.1 and Table 8.1 show considerable range in TDS for any given depth. Groundwater residence time, and, therefore, mineralisation, typically increase with depth and, notably from Figure 8.1, a lower bound on TDS can be seen with depth. For example, Figure 8.1 indicates that groundwater below the Drinking Water Inspectorate DWI drinking water limit of 1,625mg/l has not been identified at depths greater than 900 metres below ground level (mbgl) apart from a single sample from the Millstone Grit.

Similarly, groundwater with a TDS concentration of less than 10,000mg/l, that is the concentration adopted in this report as the upper limit of TDS concentration for brackish groundwater, has not been observed below a depth of ~1,500mbgl, again apart from the single Millstone Grit sample. Such a depth may, therefore, potentially serve as a lower depth bound below which groundwater requires less protection.

Appendix 3 of Loveless and others 2018 provides a breakdown of Figure 8.1 by aquifer. The Millstone Grit and Carboniferous Limestone exhibit the freshest and least brackish waters with depth of all the principal aquifers, although data for the Chalk and Permo-Triassic sandstones are very limited with greater depth. You can refer to Loveless and others 2018 for more detailed discussion and presentation of this data.

Cumulative frequency plots of specific conductivity are provided in the groundwater natural (baseline) quality report (Shand and others 2007) for many of the principal aquifers of England. Specific conductivity is a function of the ionic composition and, therefore, conversion to TDS is not straightforward. However, for a rough conversion, a factor of 0.65 can be used to convert specific conductivity to TDS (Rice, Baird and Eaton 2017). Key points from these plots include:

- the highest conductivity values are observed in the chalk (specifically the East Norfolk, Yorkshire and Kent Chalk), the crag, the Lincolnshire Limestone and the Permo Triassic Sandstones (Manchester, Liverpool and Cheshire)
- the chalk aquifers show the least variability in conductivity by location
- the Permo Triassic sandstone aquifers show the greatest variance in conductivity

2.1.5 Discussion

The UK Drinking Water Standard (DWS) for electrical conductivity is 2,500μS/cm, which is equivalent to 1,625mg/l TDS at 20°C. This limit is used in the water supply regulations for England which specify the maximum admissible concentrations and values for parameters in drinking water for both public supply (The Water Supply (Water Quality) Regulations (2016)) and private water supplies for human consumption (Private Water Supplies (England) Regulations

(2016)). It is understood that this value is drawn directly from The Council of the European Union (1998).

There is no World Health Organisation WHO health-based guideline for TDS (WHO 2017), although WHO suggests that TDS greater than 1,000mg/l becomes increasingly unpalatable. The lowest value identified in the literature is from the US Environmental Protection Agency USEPA (USEPA 2017)with a guideline of 500mg/l for drinking water. The main reason for the discrepancy between the UK DWS and WHO (and other) standards is due to palatability rather than any known health effects.

The UK DWS of 1,625mg/l is one of the highest of the standards reported in the literature. Above this value drinking water may be assumed to be unpalatable. Elsewhere (Table 2.1) saline groundwater often refers to any groundwater having a dissolved-solids concentration of at least 1,000mg/l. For example, the US Geological Survey USGS (USGS 2017) defines saline groundwater as "…groundwater having a dissolved-solids concentration ranging from 1000 to 10,000 milligrams per litre (mg/l)." Accordingly, brackish groundwater may be considered as a subset of saline groundwaters.

A value of 3,000mg/l is cited in a number of places in the literature (Table 1) as a threshold between 'slightly' and 'moderately' saline water. The reason for the threshold at 3,000mg/l is due mainly to livestock and agricultural considerations and water may still be fit for purpose with these TDS concentrations depending on plant and animal species.

A value of 10,000mg/l is widely cited as a threshold between 'moderately' and 'saline' 'highly saline', 'very saline' or in one case 'heavily brackish' water (Table 2.1). 10,000mg/l is cited in Freeze and Cherry 1979, which is probably one reason why this value is widespread among later authors, including van Weert and van der Gun 2012 and USGS 2017.

Significant technological advances have been made over the last decades in treating saline waters, bringing these waters within usable reach, and that trend may continue. It, therefore, seems that there is a strong argument for some protection of waters in the 3,000 to 10,000mg/l range on the basis of being able to support a range of demands.

It should be noted that certain applications of saline waters, such as for power plant cooling and hydraulic fracturing fluids, may exploit waters of salinity greater than 10,000mg/l.

While TDS is a useful measure of water quality, there may be other specific hydrochemical limitations, such as high arsenic concentrations, for drinking water supply. Certain industries have specific limits on hardness and dissolved constituent concentrations that may restrict the use of water which, on the basis of TDS alone, may otherwise seem acceptable.

2.1.6 Recommendations

The UK DWS, equivalent to 1,625mg/l TDS at 20°C, is an appropriate lower bound for a working definition of what constitutes 'brackish' groundwater. This is due mainly to its precedent in English law, and as an upper limit of what may constitute potential drinking water supplies without desalination treatment.

Similarly, 10,000mg/l TDS forms a useful upper bound on the basis of suitability for a large variety of industrial supplies and desalination plants, as well as having international precedents in both the US and Europe, and elsewhere in the literature.

We, therefore, recommend adopting the range 1,625mg/l to 10,000mg/l as a suitable working definition of 'brackish' or, in other words, slightly to moderately saline groundwater.

2.2 Level of protection of brackish groundwater

2.2.1 Discussion

Appendix B provides a review of the protection given to groundwater in England under current legislation. Recent methods (Loveless and others 2018) for assessing groundwater vulnerability at depth in the context of onshore oil and gas exploration are also summarised.

The review illustrates that the fundamental basis for protecting groundwater is derived from its use for people and its role in supporting ecosystem services, such as, for example, baseflow to rivers. This is mirrored in the current Environment Agency approach to groundwater protection, which characterises aquifers (Table 8.3) based on their capacity to store and transmit significant quantities of water (a volumetric cut off of 50 people or $10m^3$/day is used). Aligned with this is the recent 3D Groundwater Vulnerability 3DGWV approach, which relates receptor classification to storage and transmission properties, and to groundwater quality where data is available.

Groundwater protection, as approached by the Environment Agency and the 3DGWV method is risk-based. Groundwater receptors are characterised based on their extent and value. A 'precautionary principle' is used. That is, where little information exists, precautionary scenario is assumed. Delineation and risk assessment take a tiered approach, with increasingly complex conceptualisation and assessment required where uncertainty and/or the assessed risks are high.

Groundwater bodies are initially delineated on the basis of geology (Allen and others 2002). The UK Technical Advisory Group UKTAG 2012 suggests a default[1] maximum depth of 400m for delimiting groundwater body[2] extent in the UK under the WFD. Where groundwater quality data is unavailable, this depth forms the basis for receptor classification cut offs in the 3DGWV approach (Table 8.4). However, several important principal and secondary aquifers can achieve

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[1] This cut off is a suggested default where no other data is available and should not be taken as an assumed maximum groundwater body depth in every case.

[2] Care should be taken not to conflate groundwater with groundwater bodies. All groundwater, unless permanently unsuitable for use, must be protected. Groundwater bodies are designated for Water Framework Directive WFD reporting.

thickness of greater than 400m (for example, the Chalk, Coal Measures and Permo-Triassic Sandstones can all achieve this thickness). Additionally, as discussed in section 2.1.4, above, water of drinking quality has been found at more than twice this depth.

In the context of the guidance, the limiting factor for determining whether specific protection is required is whether or not it is 'permanently unsuitable for use' (UKTAG 2012). This groundwater might, for example, have a salinity greater than seawater.

2.2.2 Recommendations

Protecting brackish groundwater can and should align with current groundwater protection principles. Therefore, mapping brackish groundwater should follow these principles:

- be based on the use of the groundwater by people or ecosystems
- facilitate a risk-based approach to groundwater protection and allow for a tiered approach, so that simple conceptualisations give way to more complete conceptualisation and understanding where risk or uncertainty is higher
- adopt groundwater value designations (a function of a formation's groundwater quality and ability to store and transmit water) that align with current approach
- allow a precautionary principle to be used

To date, formations containing brackish groundwater have not been identified as significant resources that need actively managing to achieve specific objectives, and have not been delineated as groundwater bodies for this purpose.

Section 2.3 presents a method for identifying and mapping brackish groundwater following these principles.

2.3 Method for identifying and mapping geological formations containing brackish groundwater

2.3.1 Overview of method

Complementary methods are proposed for:

- developing a national map to indicate the possible presence of brackish groundwater throughout England
- carrying out a high-level site-specific risk assessment to determine if 'useful' brackish groundwater is likely to be present (and the confidence in this assessment). This risk assessment could provide the basis for

determining if the brackish groundwater should be included as a receptor at risk from a proposed activity, for example, injection of fracking fluid

Here, the focus is on bedrock geology. Brackish groundwater in superficial deposits may be present locally or be of local use. These brackish superficial aquifers may have dependent ecosystems and, therefore, need protecting. However, it is not possible to map this groundwater using the proposed technique. The presence of these aquifers, which are most likely to be coastal, should be assessed during a site-specific risk assessment.

It is likely that developing a national map and carrying out a high-level risk assessment would use many of the same data sources. If the high-level risk assessment indicates the possible presence of useful brackish groundwater, local data should be used for further hydrogeological investigations.

Brackish groundwater is defined as groundwater with TDS concentrations of between 1,625mg/l and 10,000mg/l (section 2.1.6). The 'usefulness' of brackish groundwater is a function of its salinity and the (hydro) geological properties of the formation.

Pumping-induced movement of saline water from depth in aquifers is a known issue (Younger, Boyce and Waring 2015) and may limit the use of some brackish groundwater reserves. However, the approach proposed here does not consider the possible interaction with, and negative impacts on, overlying and underlying groundwater if useful brackish groundwater is abstracted. Interaction between groundwater in different formations under ambient conditions is also excluded from this approach. Formations are considered in isolation. Other interactions could be screened for under Tier 2 or 3 investigation.

2.3.2 Review of nationally available datasets

Table 2.2 summarises nationally available datasets.

Table 2.2 Review of nationally available datasets

Source	Description
BGS 3D Geology viewer	Online interactive visualisation of 3D geology in Great Britain along cross sections.
3D GWV LithoFrame viewer	3D geology and 3D aquifer designations in England

Geological memoirs and regional guides	Detailed regional geology. Useful for formation thickness variations, depth and faults.
Borehole records	For formation thickness variation, depth, faults and TDS. 3DGWV GIS layer shows the location of all those deeper than 400m. Open access borehole depth and logs available from BGS website.
Legacy coal mine plans	Available from the Coal Authority, may have location of faults.
MagicMaps	Aquifer designations (2D for geological units at lands surface) for England, derived from 1:50,000 geological mapping.
Aquifer property manuals	For all major and minor (now principal and secondary) aquifers in England and Wales. Data on variation in hydrogeological properties with depth (hydraulic conductivity and porosity).
Aquifer (baseline) quality reports	For all major aquifers in England, Scotland and Wales. Baseline water quality data. Data on TDS variation with depth.
Geothermal data catalogue	See Loveless and others 2018 Appendix 3 for a summary. National data set with TDS vs depth for many of the major aquifers of the UK.

Source: Mott MacDonald, (Loveless and others 2018)

2.3.3 Definition of potential usefulness of brackish groundwater

At a national level, the resource value (usefulness) of brackish groundwater would be defined using two measurements (TDS and aquifer designation (or qualitative description of hydrogeological properties)) in Table 2.3.

Table 2.3 National brackish aquifer mapping relative usefulness

	Groundwater TDS

		1,625 – 3,500 mg/l	3,500 – 5,000 mg/l	5,000 – 7,500 mg/l	7,500 – 10,000 mg/l
Aquifer designation	Principal/higher permeability	Useful			
	Secondary/lower permeability				
	Unproductive				Not useful

Source: Mott MacDonald

The definition of useful brackish groundwater for site risk assessments expands on that used to make the national map. A value of 0 (not useful) to 4 (very useful) is assigned to six measurements that define the usefulness of brackish groundwater for all formations that are not designated as unproductive. Together, these values provide an overall brackish groundwater usefulness score. Table 2.4 discusses measurements that define useful groundwater.

Table 2.4 Site-specific useful groundwater definition

Measurement	**Value**	**Weight**	**Data sources (confidence determined by source of data)**	**Notes**
TDS	4 - <1,625 3 – 1,625 – 3500 mg/l 2 – 3,500 – 5,000 mg/l 1 – 5,000 – 10000 mg/l 0 – > 10,000 mg/l	Very High	Geothermal data catalogue Baseline quality reports Proximity to evaporite deposits Local borehole logging/water quality sampling	TDS – sum of cations and anions if no other data available For formations with a significant vertical extent, TDS and permeability may vary significantly with depth. For these formations, it may be appropriate to split the formation into several layers or use the most conservative (permeability x TDS) value

Measurement	Value	Weight	Data sources (confidence determined by source of data)	Notes
Hydrogeological properties – regional aquifer designation	4 – Principal 3 – Secondary A 2 – Secondary (undifferentiated) 1 – Secondary B	High	3DGWV MAGIC maps	
Hydrogeological properties – permeability and storage	4 – very high permeability 3 – high permeability 2 – moderate permeability 1 – low permeability	High	Aquifer properties manuals Local borehole logs/ hydrogeological testing	Rankings should be relative to all formations. For formations with a significant vertical extent, TDS and permeability may vary significantly with depth. For these formations, it may be appropriate to split the formation into several layers or use the most conservative (permeability x TDS) value
Extent of formation present beneath site	4 – Present beneath site area 3 – Present local to site area 2 – Present at a	High	3D geology Borehole logs Geological mapping Base of major aquifers – https://www.bg	Medium/low confidence if not supported by borehole logs local to site

Measurement	Value	Weight	Data sources (confidence determined by source of data)	Notes
	distance from the site area 1 – Not present in area		s.ac.uk/research/groundwater/shaleGas/aquifersAndShales/data.html)	
Water quality (other contaminants)	4 – probably no additional contaminants 3 – possibly no additional contaminants 2 – possibly additional contaminants 1 – probably additional contaminants	Medium	Local data Potentially defined as a contaminant if above DWS A (non-exhaustive) discussion of contaminants that may impact the usefulness of brackish groundwater is given in 2.1.3	
Volume of water and/or renewability of resource	4 – Probably renewable/large volume 3 – possibly renewable/ moderately large volume 2 – possibly not renewable/ moderately small volume	Low	Data relating to water quantity (aquifer storage) and regional flows Likely to be qualitative – professional judgement as to which value to assign	

Measurement	Value	Weight	Data sources (confidence determined by source of data)	Notes
	1 – probably not renewable/small volume			

Source: Mott MacDonald

A site-specific brackish groundwater assessment should consider all measurements in Table 2.4 or provide evidence-based justification as to why some measurements were excluded. Overall usefulness is the sum of the values from each measurement multiplied by weights that define the relative importance of the difference measurements.

Each measurement is also assigned a confidence value ranging from 1 (very low confidence) to 4 (high confidence), which will also be multiplied by the measurement weight. The sum of these define the overall confidence score for the brackish groundwater risk assessment.

Confidence in conclusions is defined after Loveless and others 2018 as:

- **high to medium:** Conclusions based on site-specific information from nearby boreholes. Confidence depends on quality of borehole logs, proximity to site of interest and local (hydro)geological variability
- **medium to very low:** Conclusions based on national brackish groundwater map, regional aquifer properties and quality reports. Site near or far from cross sectional slice. Formation well characterised or poorly characterised

The usefulness score and the confidence score combine to give, for each formation at the site, an assessment of the usefulness of the brackish groundwater and the confidence in this estimate (Table 2.5). This information could be used to inform the need for further investigation to improve confidence in the assessment or if the brackish groundwater should be treated as a receptor at risk from a proposed activity.

Table 2.5 Site-specific useful groundwater assessment

	High ← usefulness of brackish water → Low			
High ↑ confidence in data ↓ Low	Very useful brackish groundwater likely to be present (high confidence)	Useful brackish groundwater likely to be present (high confidence)	Low usefulness brackish groundwater likely to be present (high confidence)	Useful brackish groundwater unlikely to be present (high confidence)
	Very useful brackish groundwater likely to be present (medium confidence)	Useful brackish groundwater likely to be present (medium confidence)	Low usefulness brackish groundwater likely to be present (medium confidence)	Useful brackish groundwater unlikely to be present (medium confidence)
	Very useful brackish groundwater likely to be present (low confidence)	Useful brackish groundwater likely to be present (low confidence)	Low usefulness brackish groundwater likely to be present (low confidence)	Useful brackish groundwater unlikely to be present (low confidence)

Source: Mott MacDonald. Note: Colour indicates brackish groundwater usefulness; colour depth indicates confidence.

2.3.4 Linking lithostratigraphy to aquifers

To link lithostratigraphy to aquifers nationally, two items are needed:

- England-wide variation in lithology with depth
- link between lithological names and aquifer designations

The joint Environment Agency/BGS 3DGWV project Loveless and others 2018 already links 3D geology to aquifer designation (Table 2.2). A formation may be assigned a variable designation, for example principal, secondary and unproductive. The variable designation reflects how lithological properties may vary spatially. Loveless and others 2018 indicate that a variable designation can be constrained on a site-specific basis by determining the aquifer designation at the nearest outcrop.

We assume that the data underlying the 3DGWV project will be available for the national brackish aquifer mapping exercise.

2.3.5 Develop relationships describing TDS with depth

It is likely that the relationships describing how TDS varies with depth across the principal and secondary aquifers of England will introduce the greatest source of uncertainty to the national brackish aquifer map. Confidence in the results is mainly based on the confidence in the data used to derive the TDS relationships.

Therefore, effort should be focused on obtaining the best possible data to support these relationships.

Data taken from the geothermal data catalogue suggests a broadly log-linear relationship between minimum TDS and depth. Therefore, unless the data strongly suggests otherwise, linear relationships will be developed. The proposed method for developing the TDS/depth relationships is described below. For each principal and secondary aquifer in England we will:

- review nationally available data, mainly the geothermal data catalogue and the aquifer baseline quality manuals
- plot all available TDS data as a function of depth below ground
- identify a relationship to describe data that, where appropriate, fits a best-fit straight line to the available data
- or a more complex relationship to describe variation of TDS with depth

It is likely that for many aquifers, mostly secondary aquifers but possibly some principal aquifers, there may be insufficient data to develop adequate relationships from observed data. Here, relationships would be averages determined from national data. A precautionary approach should be taken where brackish groundwater is assumed to be present if the method suggests this is the case.

The relationships may also be informed by other available data, for example the presence of evaporates. In a recent US mapping exercise (J Stanton and others 2017), these were found to be strongly linked to the presence of brackish groundwater. The US brackish groundwater mapping approach is summarised in Appendix C.

It may also be appropriate to split aquifers based on hydrogeological characteristics of importance to brackish groundwater (compare with the US approach). For example, one might want to have different relationships for the confined and unconfined East Yorkshire Chalk.

There will be exceptions to the approach above of increasing TDS with depth such as the West Midlands Permo Triassic Sandstone aquifer. Here, layering effects due to interleaved gypsiferous strata, and the influence of near-surface-derived pollution, mean that better quality water underlies low quality (high TDS) water near the surface. When determining site-specific salinity relationships, any locally available data to support the assessment should also be considered and this would take precedence over national data. Therefore, the site-specific assessment allows for a tiered approach such that simple conceptualisations give way to more complete conceptualisation and understanding. This type of approach would be required for the example of the West Midlands given above.

2.3.6 Develop relationships describing hydrogeological properties with depth

For the national mapping exercise, the following approach is suggested:

- develop relationships to describe the variation in hydrogeological properties with depth

For each principal and secondary aquifer:

- review nationally available data, mainly aquifer properties manuals
- develop simple conceptual models for variation in hydrogeological properties with depth
- build simple relationships to assign a qualitative description of the hydrogeological properties to each formation with depth

Aquifer designation (from 3DGWV) is used as a default if there is insufficient data to support anything more sophisticated.

2.3.7 High-level 3D map visually displaying location of potentially useful brackish groundwater

The outcome for the national brackish groundwater mapping would be a 3D map for England indicating where useful brackish groundwater is likely to be found.

Table 2.6 summarises the steps needed to develop a 3D map of brackish groundwater across England.

Table 2.6 Summary of steps required to develop 3D brackish groundwater map for England

Step	Notes
1. Link 3D geology for England to aquifers	Already completed as part of 3DGWV
2. Develop relationships to describe TDS with depth	See section 2.3.5
3. Develop relationships to describe hydrogeological properties with depth	See section 2.3.6
4. Define cut offs for TDS and hydrogeological properties	For the relationships derived in steps 3 and 4, cut-offs are specified to allow a usefulness score to be assigned (Table 2.3)
5. Build 3D map to visually display location of useful brackish groundwater	Automatically create coloured cross sections using the 3DGWV cross sections and relationships/cut offs determined in Steps 2-4

Source: Mott MacDonald

Those aquifers designated as unproductive will be marked as not useful. The national mapping exercise should focus on where principal and secondary aquifers are present.

Section 3 of this report gives an example of how the proposed national and site-specific brackish groundwater assessment method could be applied.

3 Brackish groundwater case study

3.1 Introduction

This section presents two case studies:

- development of two national-scale map cross sections
- a high-level site-specific risk assessment

These case studies use the same site area as case study 2 in the 3DGWV report of Loveless and others 2018. Two of the 3D geological sections that cross the study area (Region 8 – section 147 and Region 8 – section 285) are the focus here. The site area and the lateral extent of the two cross sections are shown in Figure 3.1 along with the underlying 1:625,000 bedrock geology.

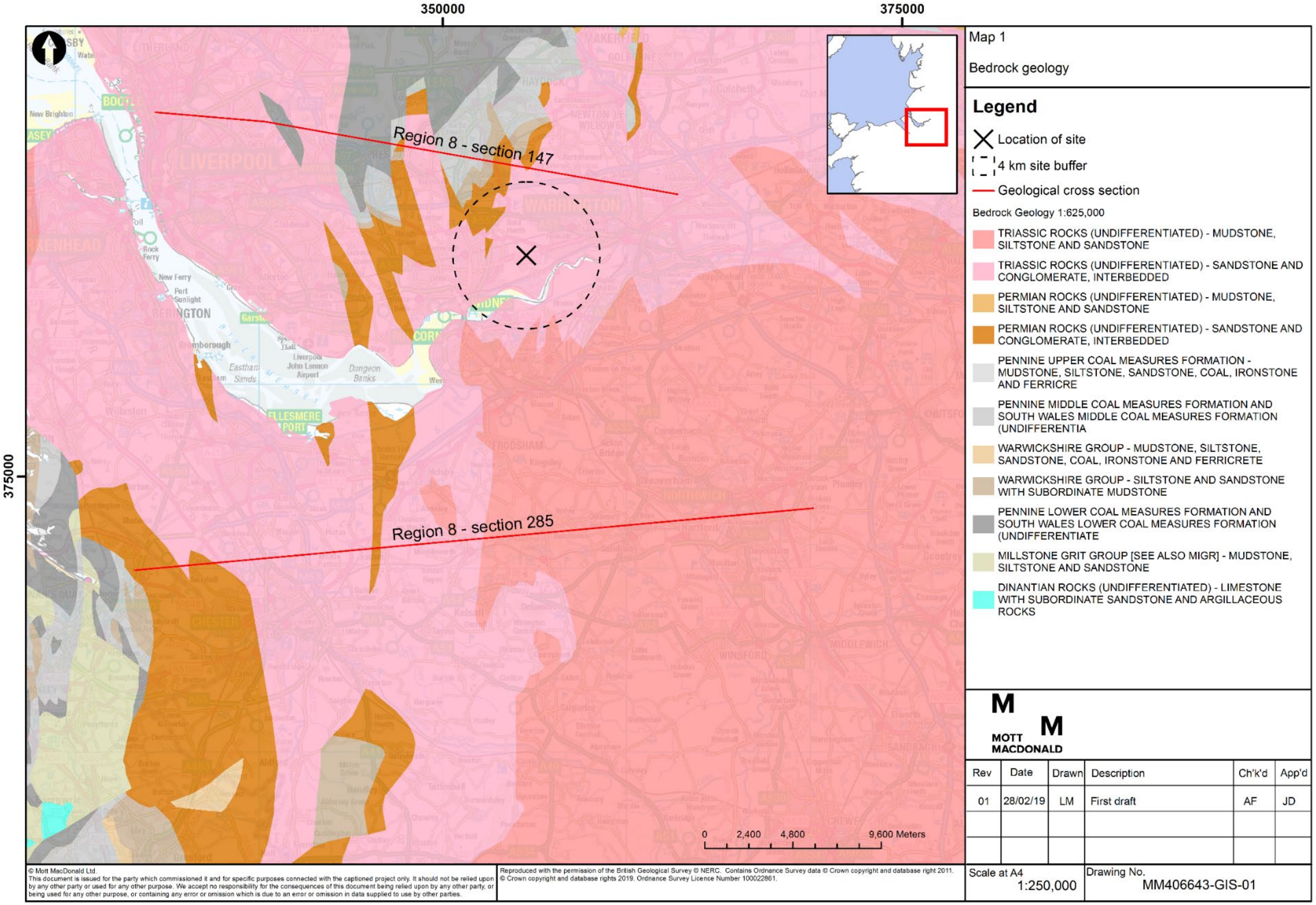
The site area is discussed in detail in Loveless and others 2018. In summary:

- the site lies towards the northern edge of the Cheshire Basin, approximately 15km east of Liverpool
- the Cheshire Basin is mainly filled with Permo-Triassic sandstones and mudstones with some halite beds. The infill can reach up to 4km in depth
- varying thickness Carboniferous beds (mainly coal measures and Millstone Grit) underlie the Permo-Triassic beds; the coal measures crop out around the basin margins
- Carboniferous limestones and older Silurian and Ordovician mudstone/siltstone/sandstone deposits are found at depth
- regionally, the dip is towards the basin centre (to the south-east)
- numerous north-northwest – south-southeast trending faults are present

The national mapping exercise case study and the site-specific case study are detailed in the sections below.

NB: Region 08 – section 285 is labelled as section 161 in Figure A6.7 of the 3DGWV report.

Figure 3.1: Site area and lateral extent of cross sections



3.1.1 Mapping of brackish groundwater

National map

Introduction

The national mapping exercise case study presents the construction of two example cross sections to indicate, at a high-level, areas where useful brackish groundwater might be found. As discussed in section 2.3, these sections are constructed using relationships derived from high-level national data sets including 3D cross sections from the BGS. As indicated by (Loveless and others 2018), it is not appropriate to infer geology between the 3D cross sections due to uncertainty in geological variation.

The 3D geology of the two cross sections and the aquifer designations, both taken from 3DGWV, are shown in Figure 3.3 to Figure 3.6. The geological succession is summarised in Table 3.1.

(Please note that the top of the right-hand series of formations follow on from (are located beneath) the bottom of the left-hand series of formations as shown in the table).

Table 3.1 Summary of geological succession

Formation	Description	TDS code	Formation	Description	TDS code
Mercia mudstone group	Mudstone, siltstone and sandstone	OTH	Pennine Upper Coal Measures Formation	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	CM
Bromsgrove Sandstone Formation	Sandstone	SS	Pennine Middle Coal Measures Formation and South Wales Middle Coal Measures Formation (undifferentiated)	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	CM
Wilmslow Sandstone Formation	Sandstone	SS	Pennine Lower Coal Measures Formation and South Wales Lower Coal Measures Formation (undifferentiated)	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	CM
Kidderminster Formation	Sandstone	SS	Millstone Grit Group	Mudstone, siltstone	MG

				and sandstone	
Kinnerton Sandstone Formation	Sandstone	SS	Craven Group	Mudstone and limestone, interbedded	OTH
Cumbrian Coast Group	Mudstone, siltstone and sandstone	OTH	Dinantian rocks	Limestone	CL
Appleby Group	Interbedded sandstone and conglomerate	OTH	Dinantian rocks (undifferentiated	Limestone with subordinate sandstone and argillaceous rocks	CL
Warwickshire Group	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	OTH	Wenlock Rocks (undifferentiated)	Mudstone, siltstone and sandstone	OTH
			Ordovician rocks (undifferentiated)	Mudstone, siltstone and sandstone	OTH

Source: Loveless and others 2018, Defra 2018, BGS 2019. Note: Formations on the right underlie those on the left. Note: TDS code determines the TDS/depth relationship each formation takes. These are discussed in the TDS relationship section below and shown in in Figure 3.2.

Most of the Permo-Triassic formations have been designated as principal aquifers. The exceptions are the Mercia Mudstone Group, which has been designated variable (principal, secondary and unproductive) and the Cumbrian Coast Group, which has been designated variable (secondary and unproductive). Except for the Warwickshire Group, designated variable (principal and secondary) and the Dinantian Limestone, designated a principal aquifer, all underlying beds are designated secondary (A and B).

For comparison, the results of the construction of a third (Chalk) cross section (in North East Anglia) are presented in Appendix CD.

TDS relationship

As discussed in section 2.3.5, during the national mapping exercise, each formation must be assigned to a TDS code, which is used to determine how TDS varies with depth within that formation. The TDS codes that have been assigned to each formation in the two cross sections are shown in Table 3.1. Here, the TDS/depth relationships were derived from the log TDS versus depth plots in

Appendix 3 of Loveless and others 2018. The relationships used for each lithology and ‘other’ lithologies are shown in **Figure 3.2**.

Some formations did not show a good log-linear relationship, for example, Zechstein Group of the Sherwood Sandstone. However, for the purposes of this example, log-linear relationships were used for all lithologies. For the national mapping exercise, it may be more appropriate to develop different relationship, for example, TDS cut offs above or below a certain depth.

For formations that did not fall into one of the lithologies plotted in Loveless and others 2018 (‘other’ lithologies), a general relationship was derived using all data. This line ‘other’ (OTH) follows the minimum values of all observed data (the most log-linear part of the graph). For ‘other’ lithologies, the importance of local data to inform the site-specific assessment assumes even more importance.

The TDS/depth relationships that have been derived are broadly similar. The exception is the chalk where much higher salinity values are found at shallower depths. This likely reflects the permeability distribution in the chalk with very low permeabilities, and, therefore, long residence times expected at depth. The coal measures are the most brackish at shallow depths.

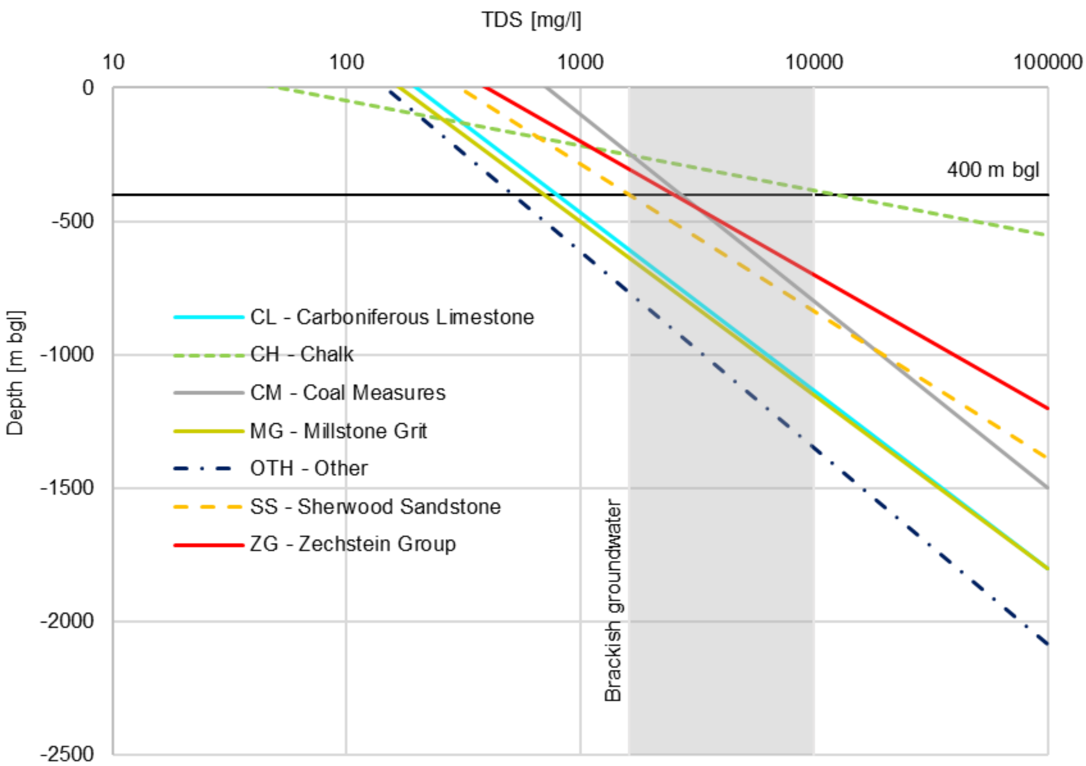
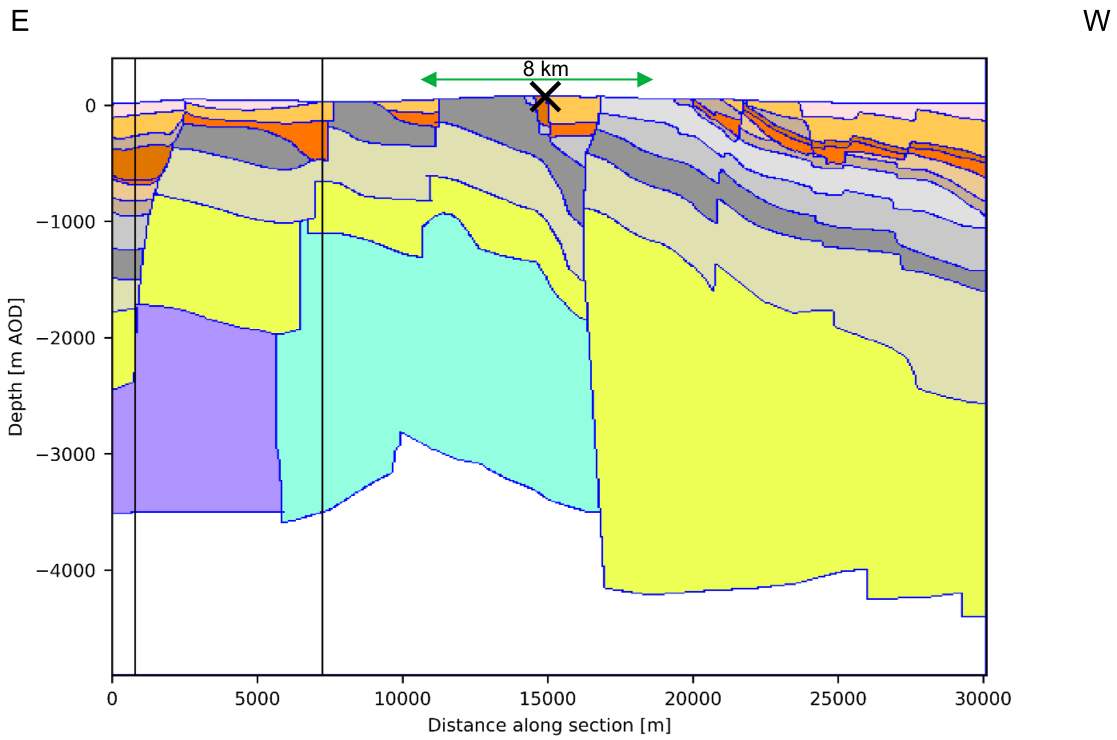


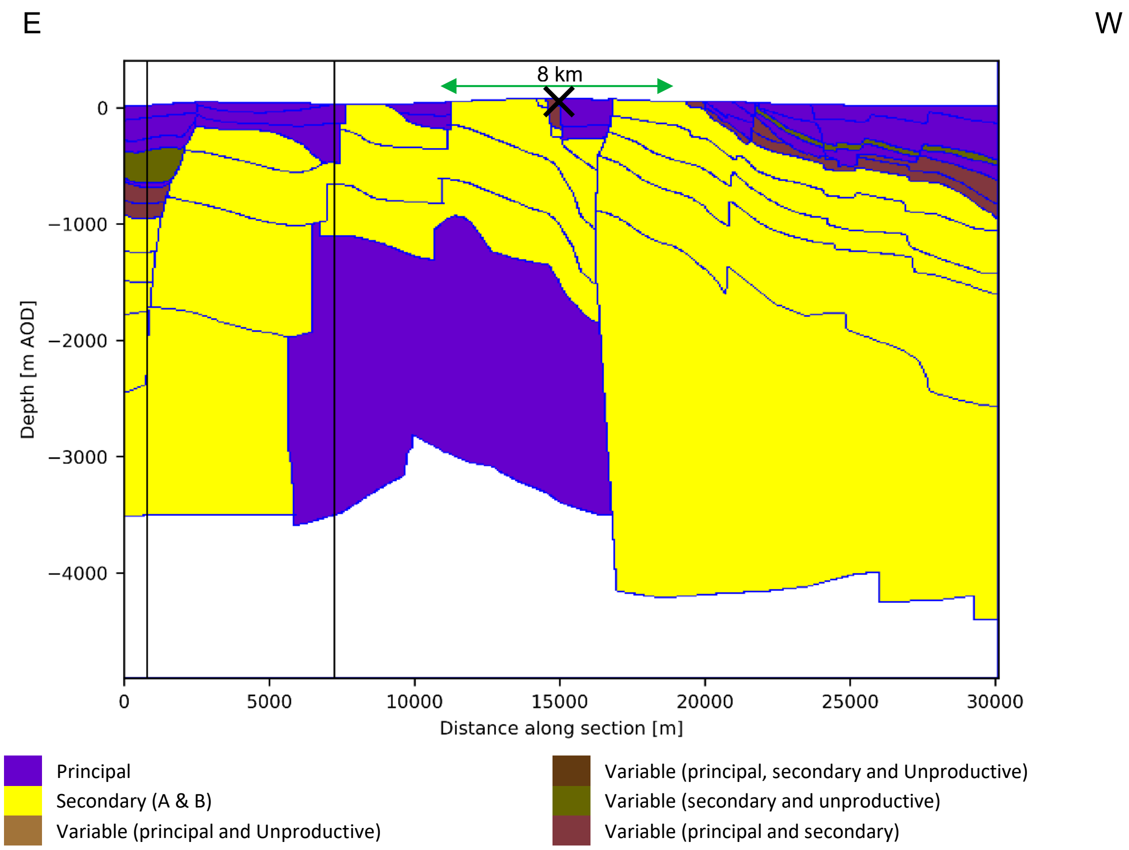
Figure 3.2 TDS/depth relationships

Source: Mott MacDonald



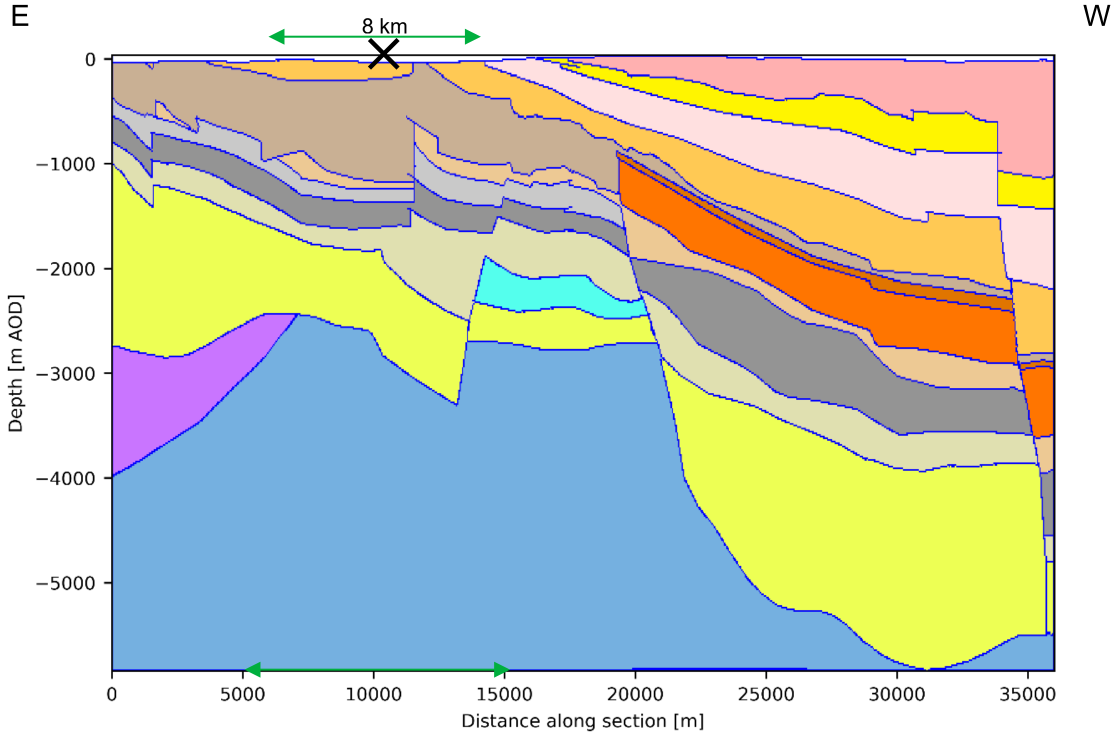
Source: (BGS 2015). See Table 3.1 for the figure legend.

Figure 3.3 Region 8 section 147 bedrock geology. Key to geological units in Table 3.1.



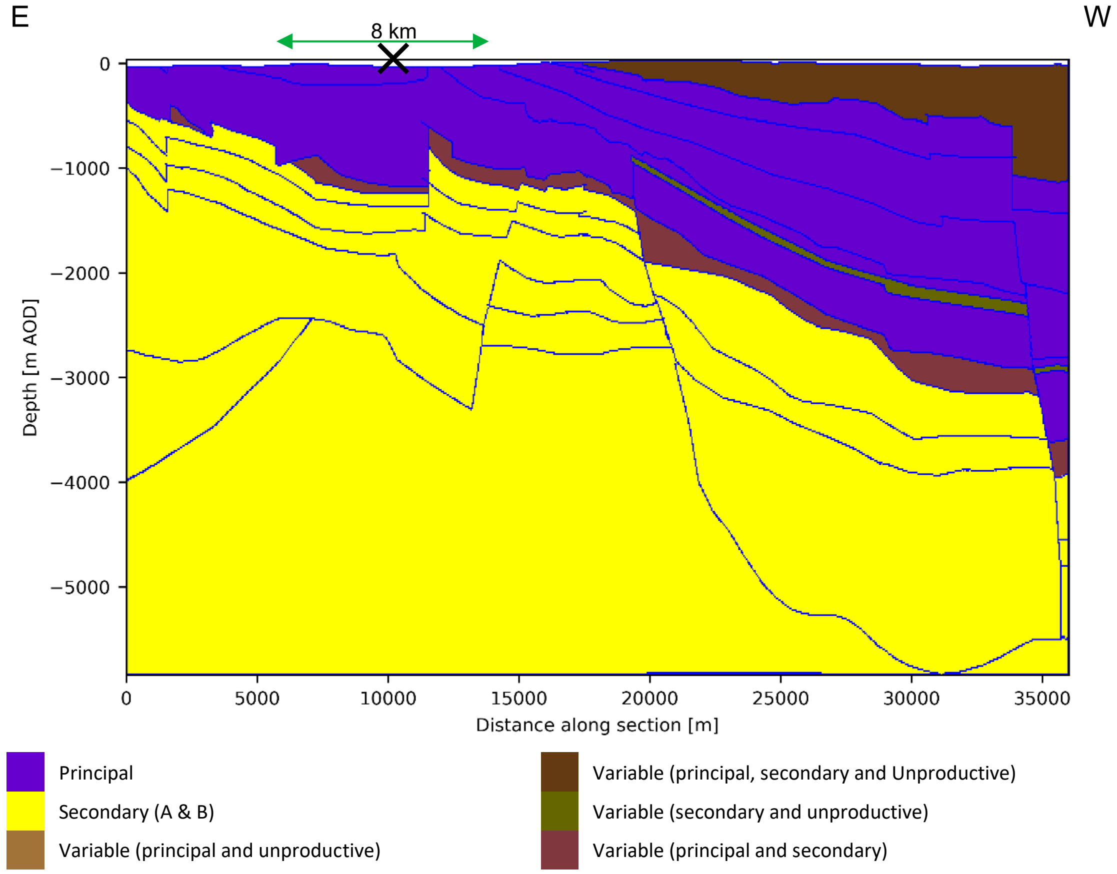
Source: (BGS 2015)

Figure 3.4 Region 8 section 147 aquifer designation



Source: (BGS 2015). See Table 3.1 for the figure legend.

Figure 3.5 Region 8 section 285 bedrock geology



Source: (BGS 2015)

Figure 3.6 Region 8 section 285 aquifer designation

Aquifer permeability

Relationships describing permeability variation with depth have not been developed due to site-specific considerations and, therefore, the time required to perform these studies on a national scale. Instead, to provide an example case study, the aquifer designations have been used. A conservative approach is taken with respect to formation permeability after Loveless and others 2018. Therefore, where the aquifer designation varies, each bed is assigned its most permeable designation.

In cases such as the Mercia Mudstone, designated variable (principal, secondary and unproductive) in 3DGWV and assigned principal aquifer status in this example, it is more appropriate to use local knowledge to assign formation permeability.

Useful brackish groundwater calculation

At each location in the cross sections, a colour denoting brackish groundwater usefulness was assigned based on the aquifer designation and the calculated TDS (Table 3.2). Where the national mapping exercise suggested that groundwater might be classed as fresh, this is highlighted in blue.

3.1.2 Results

The results are shown in Figure 3.7 and Figure 3.8 for sections 147 and 285 respectively. The key for the figures is Table 3.2.

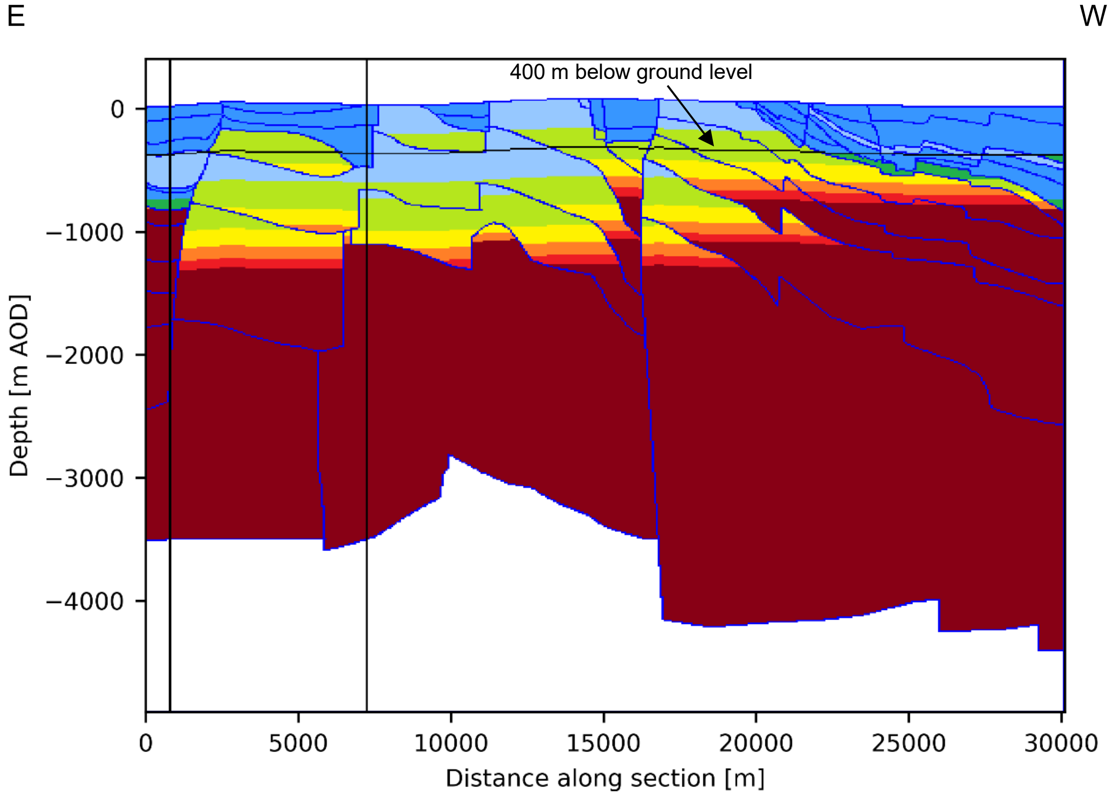
Table 3.2 Brackish groundwater usefulness

		Groundwater TDS					
		<1625 mg/l	1625 – 3500 mg/l	3500 – 5000 mg/l	5000 – 7500 mg/l	7500 – 10,000 mg/l	> 10,000 mg/l
Aquifer designation	Principal	Fresh	High Usefulness brackish GW				Not useful (TDS)
	Secondary	Fresh				Low usefulness brackish GW	Not useful (TDS)
	Unproductive	Not useful (unproductive)					

Source: Mott MacDonald

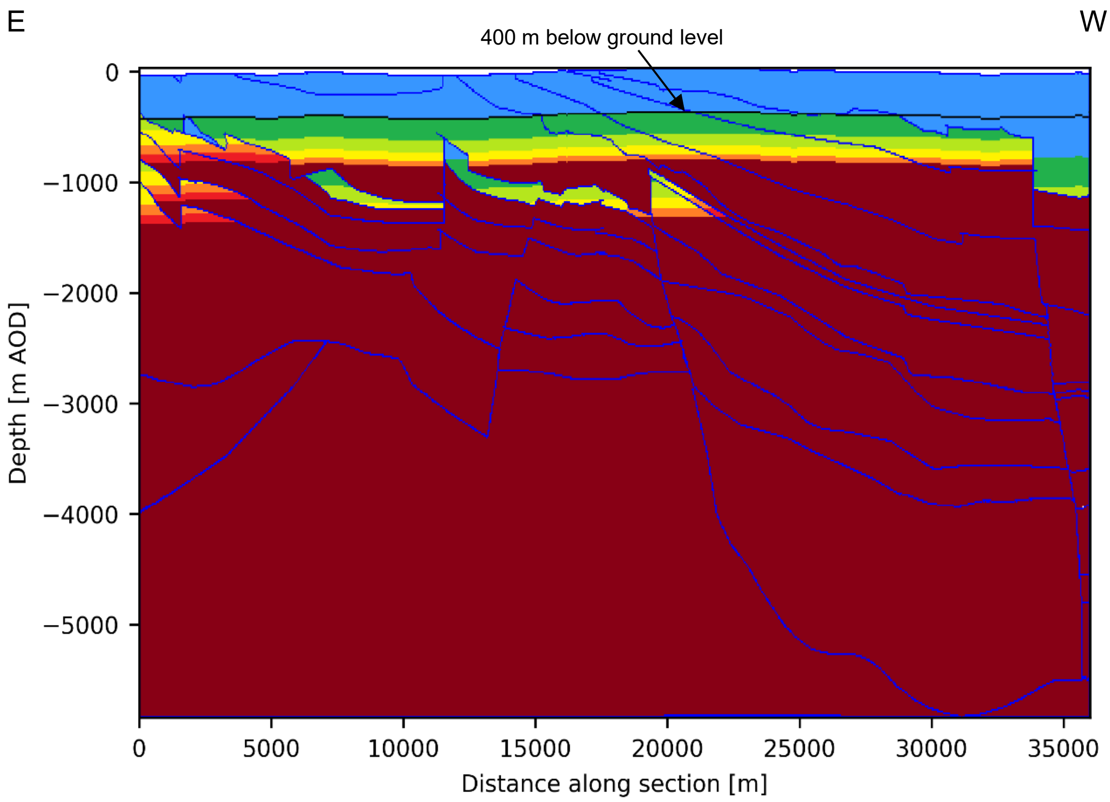
The results indicate, as would be expected given the derived TDS/depth relationships, that brackish groundwater can be expected at depths of between 400 and 1,300mbgl. However, there are differences. For example, the coal measures, which are generally more brackish at shallower depths may have brackish groundwater, albeit useful, above 400mbgl.

Useful brackish groundwater is most closely associated with the Millstone Grit and the Craven Group in section 147. In section 285, useful brackish groundwater is most closely associated with the overlying Permo-Triassic beds as the dip direction means these beds are further below ground to the south of the site area.



Source: Mott MacDonald. See Table 3.2 for the figure legend.

Figure 3.7 Region 8 section 147 useful groundwater distribution



Source: Mott MacDonald. See Table 3.2 for the figure legend.

Figure 3.8 Region 8 section 285 useful groundwater distribution

When considering the implications for the national mapping exercise from this case study, 2 key points arise:

- data to determine TDS/depth relationships is limited. Of the data available, there is a reasonably wide variance in the TDS/depth relationship (high uncertainty). In some cases, the relationship is not strongly log-linear
- large parts of England are designated as secondary aquifers at depth (where data on TDS is likely to be very limited). Therefore, it is likely that large numbers of formations at depth may have TDS assigned from the national average relationship

The results of the initial mapping exercise should be assessed, specifically with respect to the uncertainties raised above. Where there is sufficient data, the next step may be to introduce a more complex regression analysis (compare with the US approach, see Appendix C) if the TDS/depth mapping in some areas of the country remains particularly uncertain.

3.1.3 High-level site risk assessment

Introduction

The high-level risk assessment aims to identify the possible presence of brackish groundwater beneath the hypothetical site and evaluate the confidence in the assessment. A 4km radius of interest (the site area) is considered (Map 1). Here, as an example, three measurements are included in the overall assessment:

- the likely geology beneath the site area
- TDS
- the aquifer designation

Geology of site area

Loveless and others 2018 provide a detailed discussion of the site area. Their conclusions are drawn from the 3D cross sections and data drawn from several deep boreholes north of the site. In summary:

- the site lies within a small graben with units shallower to the west than the east
- the Sherwood Sandstone outcrops over most of the site area, with a small area of outcropping Mercia Mudstone to the south
- formation thickness varies considerably over the wider area. For example, the Sherwood Sandstone varies from less than 50m in the north to more than 1,000m in the south
- several large faults are present that cut all units. Two of these are identified in borehole logs

- confidence is lower in the south of the area of interest as there are no deep boreholes. Estimation of the thickness of lithologies is particularly uncertain as formation thickness varies widely over the area

The geological succession and the possible presence of each lithology underlying the site area are detailed in Table 3.3.

Conceptually, one might combine formations within the Sherwood Sandstone or the coal measures into one unit. However, from a brackish groundwater mapping perspective it is useful to keep these formations separate due to their varying depths and large combined thickness. Therefore, they are considered separately in the risk assessment below.

Table 3.3 Summary of site-specific geology

Formation	Description	Presence local to site	Value	Confidence
Mercia Mudstone Group	Triassic. Mudstone and siltstone, gypsiferous	Not present local to site in the south. Not present in the north. Geological mapping shows small outcrop in site area.	3	2
Bromsgrove Sandstone Formation	Triassic Sherwood Sandstone Group	Not present local to site in the north or south. Underlies Mercia Mudstone in south so may be present.	3	1
Wilmslow Sandstone Formation	Triassic Sherwood Sandstone Group	Present beneath site area in the north. Not present local to site in south.	3	1
Kidderminster Formation	Triassic Sherwood Sandstone Group	Present beneath site area in north and south.	4	1
Kinnerton Sandstone Formation	Triassic Sherwood Sandstone Group	Not present in north. Present beneath site area in south.	3	1
Cumbrian Coast Group	Permian. Comprises the Manchester Marls Formation (mudstone, gypsiferous)	Not present local to site area in south. Present beneath site in north.	3	1
Appleby Group	Permian. Comprises the Collyhurst Sandstone Formation (coarse-grained sandstone)	Not present local to site area in south. Present beneath site in north.	3	1
Warwickshire Group	Carboniferous. Mottled mudstone with common beds of sandstone, and Etruria Marl Formation (fine-grained mudstone)	Present beneath site area in south. Not present local to site area in north.	3	1
Pennine Upper Coal Measures Formation	Carboniferous. Mudstone, sandstone, seat earth and coal	Not present in south. Present local to site area in north.	2	1

Pennine Middle Coal Measures Formation	Carboniferous. Mudstone, sandstone, seat earth and coal	Present beneath site area in north and south.	4	2
Pennine Lower Coal Measures Formation	Carboniferous. Mudstone, sandstone seat earth and coal	Present beneath site area in north and south.	4	2
Millstone Grit Group	Carboniferous. Sandstone with mudstone common throughout	Present beneath site area in north and south.	4	2
Craven Group	Carboniferous. Mudstone and limestone, interbedded	Present beneath site area in north and south.	4	2
Dinantian rocks	Carboniferous. Limestone	Not present in south. Present beneath site in north.	3	1
Dinantian rocks (undifferentiated)	Carboniferous. Limestone with subordinate sandstone and argillaceous rocks	Not present in north. Present beneath site area in south.	3	1
Wenlock Rocks (undifferentiated)	Silurian. Mudstone, siltstone and sandstone	Not present in north. Not present beneath site area in south.	2	1
Ordovician rocks (undifferentiated)	Mudstone, siltstone and sandstone	Not present in north. Present beneath site area in south.	3	1

Source: Loveless and others 2018, Defra 2019, BGS 2019

TDS

Table 3.4 gives a summary of the TDS assessment. There is little local data to support brackish groundwater estimates. Several boreholes to the east of a north-south trending fault (located east of the graben centre) recorded water from very to slightly (approximately 4,000mg/l TDS) saline. A borehole log from a site to the west of the fault records a much lower TDS (316mg/l). However, the formations with which these values are associated are not known. It may be that, as suggested by Loveless and others 2018, the fault provides a barrier to flow. Therefore, it may be appropriate to assess salinity values separately to the east and west of the fault. However, here the formations are treated as single units.

Table 3.4 Summary of TDS assessment

Formation	TDS notes	Value	Confidence
Mercia Mudstone Group	Category 4 in the south (at a distance from the site). Not present in the north.	4	1
Bromsgrove Sandstone Formation	Category 4 in the south. Not present in the north.	4	1
Wilmslow Sandstone Formation	Category 4 in the south. Category 4 in the north.	4	1
Kidderminster Formation	Category 4 in the south. Category 4 in the north.	4	1
Kinnerton Sandstone Formation	Category 4 in the south. Category 4 in the north.	4	1
Cumbrian Coast Group	Category 4 in the south. Category 4 in the north.	4	1
Appleby Group	Category 4 in the south. Category 4 in the north.	4	1
Warwickshire Group	Category 4 in the south. Category 4 in the north (but not present local to the site).	4	1
Pennine Upper Coal Measures Formation	Not present in the south. Category 4 in the north.	4	2
Pennine Middle Coal Measures Formation	Category 4 in the south. Category 4 in the north.	4	2
Pennine Lower Coal Measures Formation	Category 3 in the south. Category 4 in the north.	3.5	1
Millstone Grit Group	Category 4 in the south (at a distance from the site). Category 4 in the north.	4	2
Craven Group	Category 4 in the south (at a distance from the site). Category 4 in the north.	4	2
Dinantian rocks	Not present in the south. Category 1 in the north (small area at a distance from the site).	1	1
Dinantian rocks (undifferentiated)	Category 0 in the south. Not present in the north. Likely to be Category 0 due to depth.	0	3
Wenlock Rocks (undifferentiated)	Category 0 in the south. Not present in the north. Likely to be Category 0 due to depth.	0	3
Ordovician rocks (undifferentiated)	Category 0 in the north. Not present in the south. Likely to be Category 0 due to depth.	0	3

Source: Loveless and others 2018, Defra 2019, BGS 2019

Aquifer designation

Outcrops local to the site allow several units to be reclassified from the conservative estimates of the national mapping exercise. For example, the Mercia Mudstone is downgraded to a secondary B aquifer. The Warwickshire Group and the Cumbrian Coast Group are classified as secondary A aquifers. The aquifer designations are shown in Table 3.5.

Table 3.5 Summary of site-specific aquifer designations

Formation	Aquifer Designation	Value	Confidence	Formation	Aquifer Designation	Value	Confidence
Mercia Mudstone group	Secondary B	2	3	Pennine Upper Coal Measures Formation	Secondary A	3	3
Bromsgrove Sandstone Formation	Principal	4	3	Pennine Middle Coal Measures Formation	Secondary A	3	2
Wilmslow Sandstone Formation	Principal	4	3	Pennine Lower Coal Measures Formation	Secondary A	3	2
Kidderminster Formation	Principal	4	3	Millstone Grit Group	Secondary (undifferentiated)	1	2
Kinnerton Sandstone Formation	Secondary A	3	3	Craven Group	Secondary (undifferentiated)	1	2
Cumbrian Coast Group	Secondary A	3	3	Dinantian rocks	Principal	4	3
Appleby Group	Principal	4	1	Dinantian rocks (undifferentiated)	Principal	4	4
Warwickshire Group	Secondary A	3	3	Wenlock Rocks (undifferentiated)	Secondary B	2	2
				Ordovician rocks (undifferentiated)	Secondary A	3	1

Source: Mott MacDonald, (Defra 2019). Please note, formations with variable 3DGWV designations that outcrop at a distance from the site area have lower confidence.

3.1.4 Overall results

The weights used to calculate the overall usefulness and confidence values are:

- aquifer designation – 20
- TDS – 100
- geology presence – 30

The weighted usefulness and confidence values for each formation are presented in Table 3.6 along with a qualitative assessment of the result.

Table 3.6 Overall assessment results

Formation	Weighted usefulness value	Weighted confidence value	Assessment	Formation	Weighted usefulness value	Weighted confidence value	Assessment
Mercia Mudstone Group	530	220	Very useful brackish groundwater or fresh water likely to be present (low confidence)	Pennine Upper Coal Measures Formation	520	320	Very useful brackish groundwater or fresh water likely to be present (low confidence)
Bromsgrove Sandstone Formation	570	190	Very useful brackish groundwater or fresh water likely to be present (low confidence)	Pennine Middle Coal Measures Formation	580	300	Very useful brackish groundwater or fresh water likely to be present (low confidence)
Wilmslow Sandstone Formation	570	190	Very useful brackish groundwater or fresh water likely to be present (low confidence)	Pennine Lower Coal Measures Formation	530	200	Very useful brackish groundwater or fresh water likely to be present (low confidence)
Kidderminster Formation	600	190	Very useful brackish groundwater or fresh water likely to be present (low confidence)	Millstone Grit Group	540	300	Very useful brackish groundwater or fresh water likely to be present (low confidence)
Kinnerton Sandstone Formation	550	190	Very useful brackish groundwater or fresh water likely to be present (low confidence)	Craven Group	540	270	Very useful brackish groundwater or fresh water likely to be present (low confidence)
Cumbrian Coast Group	550	190	Very useful brackish groundwater or fresh water likely to be present (low confidence)	Dinantian rocks	270	190	Useful brackish groundwater likely to be present (low confidence)

Appleby Group	570	150	Very useful brackish groundwater or fresh water likely to be present (low confidence)	Dinantian rocks (undifferentiated)	170	410	Useful brackish groundwater unlikely to be present (medium confidence)
Warwickshire Group	550	190	Very useful brackish groundwater or fresh water likely to be present (low confidence)	Wenlock Rocks (undifferentiated)	100	370	Useful brackish groundwater unlikely to be present (medium confidence)
				Ordovician rocks (undifferentiated)	150	350	Useful brackish groundwater unlikely to be present (medium confidence)

Source: Mott MacDonald. Please note, weighted usefulness and confidence values can range from 150 – 600 in this example.

Overall confidence in the assessment for all formations is medium or low, which reflects the lack of site-specific data. Freshwater is likely to be found in the Permo-Triassic Sandstones beneath the site. Useful brackish groundwater is most likely to be found in the coal measures beneath the site.

It is not appropriate to give an indicative depth to brackish groundwater at the site due to uncertainty in the geology. The depth to a particular formation varies widely between the two cross sections used.

3.1.5 Interpretation and presentation of data

National map

Cross sections resulting from the national mapping exercise should be regarded as a high-level screening tool to indicate where brackish groundwater might be found. Confidence in the results is mainly based on the confidence in the data used to derive the TDS relationships. The mapping takes a conservative approach. Where there is a variable aquifer designation, the most permeable designation is assumed. TDS is assumed to vary similar to the national average unless there is supporting data to suggest otherwise.

The main outcome from the national mapping will be a 3D geological map, as per the national mapping case study. It would also be possible to construct 2D maps by interpolating between 3D cross sections. These could be used to visualise, for example, the depth to brackish groundwater or predicted TDS at 400mbgl. However, the BGS (Loveless and others 2018) suggests that *it is not appropriate* *to interpolate between cross sections due to uncertainty in geological variation*. Before constructing 2D maps, the following points would need to be addressed:

- consider if the 2D maps would encourage people to use the data inappropriately (however, end users may infer inappropriately between cross sections even without the maps)
- include reference to the uncertainty of the data at a distance from cross sections; include visual indicators (for example, stippling, colour depth) on the map to indicate uncertainty (a function of distance from the nearest cross section)
- develop an appropriate method to interpolate between cross sections Possibilities include:
    - linear interpolation
    - kriging

Site-specific risk assessment

The site-specific risk assessments extend the national mapping and incorporate local, site-specific data, where available. The approach is effectively a tier 1, qualitative assessment that indicates both the likely quality of the brackish groundwater in each geological formation and the confidence in the assessment. It is likely that the results of a site-specific assessment would be presented in a table such as Table 3.6. The site-specific assessment might be used as a tool to determine which, if any of the formations at the site should be treated as possible receptors to a proposed activity or if further investigation and local data gathering is required.

4 Scoping outline guidance – brackish groundwaters

4.1 Introduction

This section details the recommended principles for developing detailed guidance on protecting brackish groundwater. Any protection policies for brackish groundwater should be in line with existing policy. The approach should:

- complement existing guidance on groundwater protection
- help protect brackish groundwater resources under the existing risk-assessment framework

4.2 Outline guidance – brackish groundwater

4.2.1 Delineation

The method for the delineation of brackish groundwater bodies has been developed following the principles discussed in section 2.2. Specifically:

- delineation should initially be based on geology
- brackish groundwater is defined as 1,625 to 10,000mg/l
- the existing principal, secondary and unproductive aquifer designations (Table 8.3) are retained, where appropriate
- maximum or minimum depths should not be prescribed. Instead, the extent of brackish groundwater will depend on relationships that define change in TDS with depth. Initially, these will be developed for the national-scale mapping exercise. A default (other aquifers) relationship will be used where local data is not available (section 2.3.5)
- iterative improvement should be allowed, where required (increasingly sophisticated conceptual model)

4.2.2 Protection under existing risk-assessment framework

The following principles are recommended:

- the possible presence or absence of brackish groundwater should be identified by a site-specific assessment (section 3.1.3)
- brackish groundwater identified during a site-specific assessment should be treated as receptors at risk from a proposed activity
- the risk to the brackish groundwater should be assessed as part of tiered risk assessment (per the current risk-assessment framework)

- the value of each brackish groundwater receptor is determined by its usefulness
- the ‘precautionary principle’ should be observed: where local data is not available and confidence in identifying brackish groundwater receptors is low, useful brackish groundwater should be assumed to be present during a tiered risk-assessment

5 Thermal and other deep-sourced springs

5.1 Criteria for defining known sources and new sources

5.1.1 Introduction

Within the UK, thermal springs arise when hot water from great depth discharges at the surface. The long residence times of deep-sourced springs mean the water is often highly mineralised. Therefore, water temperature and/or mineral content can indicate a deep-sourced spring. However, deep circulating groundwater may mix with cooler near-surface waters or return so slowly to the Earth's surface that they cool naturally before discharging. Similarly, some shallow groundwater may have very long residence times and become highly mineralised before discharge.

The Bath thermal springs have been widely studied (for example, Edmunds and others 2014, R. Gallois 2006, Green 1992) and a reasonable body of literature exists on the thermal springs in the Peak District (for example, Banks 2017, F. C. Brassington 2007, Gunn and others 2006). Naturally occurring saline springs have been studied due to issues with these waters in coal mines and subsequently in relation to geothermal energy (Younger, Boyce and Waring 2015). However, more widely the literature on deep-sourced springs in the UK is limited.

Thermal and mineral springs within Britain were reviewed in the context of the growth and decline of the spa movement within the UK by Banks (in Albu, Banks and Nash 1997) and Mather (J Mather, Wonder-working waters 2016, J Mather 2013). The hydrogeology of 14 'heritage spas' is discussed in detail (J Mather 2013). At one time, there were hundreds of spas in the UK. Spa locations with high mineralisation or thermal properties of the water were typically favoured. Therefore, many deep-sourced springs in the UK are likely to be found at current or former spa locations. Mather (2013) categorises spas into three groups based on their hydrogeology.

1. In the first group, locations are both controlled and constrained by their hydrogeological conditions. Here, flows are reliable, and the waters are generally mineralised because of long groundwater flow paths and residence times. This includes spas at Bath, Buxton, Matlock and Harrogate.
2. Spa locations in the second group are due more to historical entrepreneurial development and the hydrogeology is of secondary importance. This includes saline waters at Droitwich and Leamington Spa and iron-rich waters at Tunbridge Wells. Most of the hundreds of mineral springs promoted as spas in Britain fell into this group. Groundwater supplying these springs generally circulates at shallow depths. These springs are vulnerable to contamination and flow is often unreliable. Many have disappeared.
3. The third group are springs that exist purely because of human disturbance to the groundwater flow path, such as mine workings. Unique ecosystems

may arise due to the geochemistry of these springs. Woodhall Spa in Lincolnshire is an example of a spring in this third group.

The need to protect springs comes from their derived value, for example as a source of drinking water, due to the recreational or therapeutic use of the waters, or their importance to ecosystems. Valuable springs may be found in all three categories discussed above. However, deep-sourced springs are most likely to fall into the first or third categories as these thermal and mineral springs are usually derived from deep, regional groundwater flow.

5.1.2 Definition of deep-sourced springs

Various methods of classifying springs have been proposed (Kresic and Stevanonic 2009), based on different characteristics of springs such as:

- discharge rate and uniformity
- character of hydraulic head creating the discharge (for example, gravity springs, artesian springs)
- geological structures controlling the discharge
- water quality and temperature

With regard to thermal and other deep-sourced springs, several common features may be identified (J. Mather 2013), including:

- high recharge areas providing a driving mechanism for flow
- regional flow that:
    - permits heating of the groundwater at depth
    - provides distinct hydrochemical signatures through increased rock-water interaction
    - allows for longer residence times
- geological structures such as faults that drive regional flow and create a rapid pathway to the surface

Toth 1999 identified several features associated with springs that discharge from regional flow, including:

- reducing conditions
- increase in pH
- increase in TDS
- superhydrostatic hydraulic heads
- positive geothermal temperature and gradient anomalies
- changes in anion facies from HCO_3 to SO_4 to Cl
- discharge points may be characterised by saline springs, soils or wetlands

No specific benchmark depth is proposed here for what constitutes a deep-sourced as opposed to a shallow-sourced spring. Instead, these characteristics of deeper flow are discussed together with other lines of evidence below for the purposes of identifying deep-source springs. The discussion below is not exhaustive, and further detail is included in the referenced literature.

5.2 Lines of evidence for identifying deep-sourced springs

5.2.1 Thermal signature

As discussed above, thermal springs in the UK are likely to have a deep-sourced origin. Meinzer 1923 proposed that thermal springs be defined as those “whose water has a temperature appreciably above the mean annual temperature of the atmosphere in the vicinity of the spring.” Aldwell and Burdon 1980, in Blake and others 2016 suggested that thermal springs are defined as “those natural groundwater springs where the mean annual temperature is appreciably warmer than average groundwater temperatures.” Edmunds 1971 and Albu, Banks and Nash 1997 also define thermal groundwaters in a qualitative sense, as being ‘significantly’ higher than the mean air temperature.

Abesser and Smedley 2008, in discussing Carboniferous limestone springs in the UK, define thermal waters as those with a temperature more than 5°C above the local mean annual temperature (of 10.3°C), and consider groundwater with a temperature of more than 2°C above the annual average to contain at least a thermal component. However, local water temperature can vary. Albu, Banks and Nash 1997 indicate typical non-thermal waters in the White Peak are around 6-9°C. This is at least a quantitative definition that is likely to allow for a degree of noise in temperature measurements and we recommend adopting either this or a similar quantitative basis.

Thermal springs in the UK identified from literature (Albu, Banks and Nash 1997, Smith 2017, Green 1992) include:

Table 5.1 Thermal springs in England

Location	Spring	Temperature
Bath, Somerset	Unspecified	40°C
	Cross Bath	41°C
	The Hetling Spring	47°C
	The King’s Bath	45°C
Bristol	Hotwells	24°C
Bakewell, Derbyshire	British Legion	11.6°C
	Recreation Ground	13.3°C
Bradwell, Derbyshire	Bradwell Spring	12.4°C

Buxton, Derbyshire	St. Anne's Well	27°C
Crich, Derbyshire	Meerbrook Sough[3], Leashaw Farm	17°C
	Ridgeway Sough, Whatstandwell	14.1°C
Dove Valley, Derbyshire	Beresford Dale	13.8°C
Dimin Dale, Derbyshire	Lower Dimindale	11.5°C
Matlock, Derbyshire	-	20°C
Stoney Middleton, Derbyshire	Stoke Sough, Grindleford	14°C
	Stoney Middleton Spring	18°C

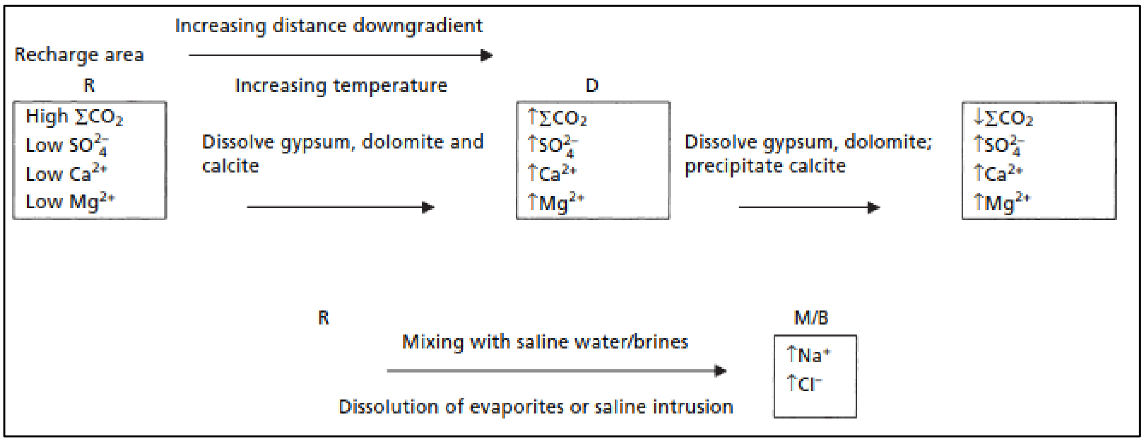
There is a suggestion in the popular press (Daily Mirror 2007) that thermal springs may arise at Droitwich Spa. However, we found no further literature to support this.

5.2.2 Groundwater mineralisation and water quality

As discussed above, highly mineralised spring water may have a deep-sourced origin. This is due to longer residence times allowing increased water-rock interaction and, therefore, an increase in minerals within the water. Please note that the definition of 'mineral springs' as associated with the practice of bottling spring waters in the UK (Appendix E) is not a function of residence time.

The chemical composition of groundwater may also give clues to its age. For example, a schematic model of the chemical evolution of groundwater in carbonate aquifers is shown in Figure 5.1.

Figure 5.1Schematic model showing the evolution of the chemical character of groundwater in carbonate aquifers



[3] A sough is an underground channel to drain water from a mine. Therefore, these waters would fall into Mather's Group III category.

Source: Hiscock and Bense (2014). R= recharge, D=downgradient and M/B=mixing with saltwater/brines

However, the generalised water quality evolution presented in Figure 5.1 may not be reflected at an individual source. The Taff Well spring (water more than 5,000 years old) near Cardiff is thought to arise from outcropping Carboniferous Limestone in the Brecon Beacons (Farr and Bottrell 2013). Here, the spring has lower calcium and similar or slightly lower sulphate concentrations than the mean of other local groundwater abstractions and baseline Welsh limestone aquifer water quality data. However, dissolved oxygen concentrations, indicative of reducing conditions, are much lower in the spring water than in the oxygen-rich local groundwater.

The chemical composition of deep-sourced springs depends on the rock encountered by groundwater along its flowpath from recharge to discharge points, as well as the formation from which the spring issues. For example, the limestone springs of the Peak District show two distinct groups. Buxton-type waters are higher in Mg, Mn and $^{87}Sr/^{86}Sr$ and lower in Ca and SO_4, indicating flow from deep sandstone aquifers via a high permeability pathway in the limestone. Matlock-type waters have elevated SO_4 due to dissolution of buried evaporites, with no chemical evidence for flow below the limestone (Gunn and others 2006).

TDS alone is unlikely to indicate the age of the water and it is noted that some young springs such as the saline springs at Droitwich (312,257mg/l TDS) and Cheltenham (6,625 mg/l TDS)) may have elevated TDS.

Mixing with younger water can also impact the composition of deep-sourced spring water. For example, at Harrogate, 88 springs arise within a small area and adjacent springs can have widely different composition (J Mather 2013) due to mixing with surface waters.

Concentrations of trace elements such as bromine, reducing conditions (indicated by the presence of sulphide and ammonium) and iron and aluminium concentrations (at chalybeate spas) were found to be most indicative of aged groundwater at the 14 heritage spas reviewed by Mather (J Mather 2013).

Groundwater quality components including dissolved oxygen, pH, the anion facies and the TDS can give clues to the age of groundwater and its pathways through the subsurface. However, water quality data such as that discussed above is unlikely to categorically prove or disprove the deep-sourced origin of groundwater.

5.2.3 Age dating groundwater

Deeper flow paths associated with longer residence times may be identified using a variety of groundwater age dating methods, based mainly on analysing radionuclides (**Table 5.2**). CFCs and SF_6 or tritium age dating can be combined to assess the degree of mixing with young waters in deep-sourced springs (Farr and Bottrell 2013).

Table 5.2 Methods of age dating groundwater

Tracer	Age range
Radionuclides	
Argon 37	Days to months
Sulphur 35	Several years
Krypton 85	Decades
Tritium	Decades
Silicon 32	100s to 1000s of years
Argon 39	100s to 1000s of years
Carbon 14	100s to 10,000s of years
Krypton 81	>100,000 years
Chlorine 36	Several 100,000 years
Iodine 129	>1,000,000 years
Others	
Chlorofluorocarbons (CFCs)	Decades
Sulphur Hexafluoride (SF_6)	Decades
Tritium	Decades

Source: Phillips and Castor2003, Farr and Bottrell 2013 and Edmunds and others. 2014

Stable-isotope compositions can be used to indicate if a source has a meteoric origin. Noble gas compositions can indicate the climate and topographical elevation under which recharge occurred (RW Gallois 2006, Farr and Bottrell 2013).

Geothermometry, which uses solute geothermometers – classically silica or cations, can be used to estimate the maximum temperature to which thermal spring water has been heated (Younger, Boyce and Waring 2015). This temperature estimate can be combined with estimates of regional geothermal gradient to estimate the maximum depth to which spring water has descended. For example, geothermometric analysis suggests that the Bath spring waters have travelled to a depth of at least 2,500m (R. Gallois 2006).

It should be noted that these age dating tools are highly specialised and not routinely applied in hydrogeological investigations. Not only are very specific sampling and laboratory methods required to analyse these elements and compounds, but interpreting the results also requires a degree of specialism.

5.2.4 Geological structures and topography

Regional groundwater flows are likely to be associated with the major sedimentary basins of the UK. Flows are gravity-driven, with a topographically high recharge area required to provide energy (hydraulic head) to drive water through the deep system. Springs driven by regional groundwater flow gradients are typically ascending springs, that is, they ascend from depth, as opposed to gravity drainage springs, which are typically much shallower.

Geological structures are an important part in determining the depths a groundwater flow path will attain, as well as determining where and how rapidly groundwater is discharged at the surface. Structural settings could involve folding, tilting, faulting and fracturing. For example, many of the thermal springs discussed here and further springs in Wales and Ireland (Farr and Bottrell 2013, J Mather 2013) lie in or adjacent to relatively deep basinal fold structures with a bedrock succession dominated by Carboniferous limestone. The Harrogate springs (J Mather 2013) are located along the axis of an asymmetrical anticline and are more common where faults occur. They arise from a sequence of interbedded sandstones and shales near the base of the Carboniferous Millstone Grit Series.

The importance in hydrogeological conceptual understanding in determining the origin of and pathways taken by deep-sourced springs cannot be overstated. However, the significance of faulting, fractures, fissures and karstic features in deep-sourced spring water transport and discharge (Farr and Bottrell 2013, R Gallois 2006, J Mather 2013, Albu, Banks and Nash 1997) means that water origin and pathways are likely to remain uncertain. Competing conceptual models may exist. Despite significant focus, the origin of some of the most widely studied deep-sourced springs in the UK remains uncertain. For example, R Gallois 2006 identifies several competing conceptual models for the Bath hot springs, with no consensus regarding the deeper spring-controlling structures, recharge areas or flow paths.

5.2.5 Uniformity of spring discharge

Discharge from deep-sourced springs is likely to be relatively constant, with little or no seasonal variation in flow rate or geochemistry (J Mather 2013). Records of spring flow or local knowledge regarding spring constancy may be used to identify deep-sourced springs.

5.3 Catalogue of known springs

A high-level literature review was carried out to identify and catalogue, where possible, known deep-sourced springs. Those springs are given in Table 5.3. The location of many of these springs are shown in Figure 8.5.

Table 5.3 Catalogue of deep-sourced springs in England

Spring	Geographical area	Sedimentary basin (or other)	Potential depth	Geological formation	Issuing formation	Hydrochemistry	Flow (l/s)	Temperature	Age dating	Use	WFD water body receiving spring flow	Other associated WFD waterbodies	Refs
Bath	Bath, Somerset, England	Bristol-Bath sedimentary basin	2,700 to 4,300 m	Carboniferous Limestone	Emerges through Lower Lias Shale	Major component having a Ca-Na-Mg, SO_4-Cl-HCO_3 chemistry. Saline.	15	45°C at issue Max 69-99°C within subsurface	1,000 years minimum residence time	Drinking fountain and local spa complex.	River Avon	Severn Lower (downstream-status moderate)	(BGS 2018, GA Kellaway 1993, Albu, Banks and Nash 1997, R

Spring	Geographical area	Sedimentary basin (or other)	Potential depth	Geological formation	Issuing formation	Hydrochemistry	Flow (l/s)	Temperature	Age dating	Use	WFD water body receiving spring flow	Other associated WFD waterbodies	Refs
													Gallois 2006)
Bristol (Hotwells /Clifton)	Avon Gorge, Bristol, England	Bristol-Bath sedimentary basin	2,700 to 4,300 m	Carboniferous Limestone. Thought to have same source as Bath hot springs.	Avon Gorge, within Carboniferous limestone.	Mixture of thermal water, like Bath, and normal cold groundwater from the limestone, in proportions 1:2.3	2.7	24°C at issue Max 49-72°C within subsurface	1,000 years minimum residence time	Historically, Georgian pump room and hot baths. Now diminished in flow and unused.	River Avon	Severn Lower (downstream-status moderate)	(BGS 2018, Avon RIGS Group 2013, GA Kellaway 1993)
Buxton (Derbyshire)	Derbyshire, England	Derbyshire Dome Carboniferous limestone aquifer	950m	Carboniferous Limestone	Limestone-shale boundary	Ca-Mg-HCO_3	10.5	27.5°C	3,900 to 6,400 years	Bottled water; recreational and therapeutic use.	River Wye		(Albu, Banks and Nash 1997, FC Brassington 2007)
Bakewell (Derbyshire)	Derbyshire, England	Derbyshire Dome Carboniferous limestone aquifer	200m	Carboniferous Limestone	Limestone-shale boundary	Ca-SO_4-HCO_3	0.2 to 9.3	11.6 to 13.3°C		Recreational use.	River Wye		(Albu, Banks and Nash 1997, FC Brassington 2007)
Matlock (Derbyshire)	Derbyshire, England	Derbyshire Dome Carboniferous limestone aquifer	500m	Carboniferous Limestone	Limestone-shale boundary	Ca-Mg - HCO_3— SO_4	0.5 to 11.83	17.4 to 19.8°C			River Derwent		(Albu, Banks and Nash 1997, FC Brassington 2007)
Beresford Dale	Derbyshire, England	Derbyshire Dome Carboniferous limestone aquifer		Carboniferous Limestone	Limestone-shale boundary	Ca-HCO_3	1.67	13.8°C			River Dove		(Albu, Banks and Nash 1997, FC Brassington 2007)
Stoney Middleton	Derbyshire, England	Derbyshire Dome Carboniferous limestone aquifer		Carboniferous Limestone		Na-Ca-Cl-SO_4	1.33	17.7°C		Not currently used. Possible future recreational use.	River Derwent		(Albu, Banks and Nash 1997, FC Brassington 2007, Smith 2017)
Bradwell	Derbyshire, England	Derbyshire Dome Carboniferous limesto		Carboniferous Limestone		Na-Ca-Cl-SO_4	0.67	12.4°C			River Derwent		(Albu, Banks and Nash 1997, FC Brassin

Spring	Geographical area	Sedimentary basin (or other)	Potential depth	Geological formation	Issuing formation	Hydrochemistry	Flow (l/s)	Temperature	Age dating	Use	WFD water body receiving spring flow	Other associated WFD waterbodies	Refs
		ne aquifer											gton 2007)
Crich	Derbyshire, England	Derbyshire Dome Carboniferous limestone aquifer		Carboniferous Limestone				14.1°C – 17°C			River Derwent		(Albu, Banks and Nash 1997)
Harrogate	Harrogate, Yorkshire, England	Carboniferous sedimentary basin	255m	Sequence of interbedded sandstones and shales near the base of the Carboniferous Millstone Grit Series. Springs do not all originate from same source.	Eighty-eight springs, mainly central Harrogate and Valley Gardens area	Highly mineralised and dominated by sodium chloride with low sulphate and little to no iron. Mg:Ca ratios of 0.49 and 0.59.		14°C		Recreational and therapeutic use (bathing and to take the water in the Royal Pump room).	Oak Beck (tributary of River Nidd)	River Nidd	(UK Groundwater Forum 2019, Albu, Banks and Nash 1997, J Mather 2013)
Droitwich[4]	Northern Worcestershire, England		30-130m	Triassic (undifferentiated-mudstone, siltstone and sandstone)		Saline spring waters resulting from dissolution of halite deposits				Brine swimming baths; salt extraction.	Salwarpe River	Severn (River Basin District)	(Albu, Banks and Nash 1997, J Mather 2013)
Shap Spa	Cumbria[5]					Sulphurous waters; brackish; Na-Ca-Cl dominant facies.	Still flowing	11.6°C		Historical spa.			(J Mather 1997, J Mather 2013, Younger, Boyce and Waring 2015)
Manesty	Cumbria					Brackish; Na-Ca-Cl dominant facies. Dilution via modern-	Still flowing	12.3°C					(Younger, Boyce and Waring 2015)

[4] Conflicting evidence as to whether Droitwich has a deep-sourced origin

[5] Saline springs similar to those observed in rural Cumbria were also historically found in the north-east of England, including urban Tyneside. However, these have been disrupted by large-scale coal mining and are no longer flowing (Younger, Boyce and Waring 2015).

Spring	Geographical area	Sedimentary basin (or other)	Potential depth	Geological formation	Issuing formation	Hydrochemistry	Flow (l/s)	Temperature	Age dating	Use	WFD water body receiving spring flow	Other associated WFD waterbodies	Refs
						day recharge via old mine workings expected.							
Lorton (Stanger)	Cumbria					Saline; Na-(Ca)-Cl dominant facies.	Still flowing	14.2°C					(Younger, Boyce and Waring 2015)
Gilcrux	Cumbria					Brackish	Still flowing	20.1°C					(Younger, Boyce and Waring 2015)
Brandlehow Mine	Near Keswick, Cumbria					Saline	Still flowing						(Younger, Boyce and Waring 2015, Feather 1966)
	East Midlands	East Midlands Triassic Sandstone				Saline	Still flowing						(Younger, Boyce and Waring 2015, Andrew and Kay 1983)
Nottington Spa[6]	Dorset			Limestones of the Cornbrash Formation. Found at nose of Weymouth anticline	Junction of alluvium/Cornbrash	Reduced (sulphide). Dominant anion bicarbonate. Weakly mineralised.				Not currently used.	River Wey		(J Mather 2013, Mather and Prudden 2007)
Woodhall Spa	Lincolnshire		Originates from a shaft 366m deep	Sands of the Upper Jurassic Kellaways Formation confined beneath the Oxford Clays	Arises because of previous coal mining activity.					Currently unused. Possible future recreational use.	River Witham		(J Mather 2013, BBC 2014)

Note: List of springs in table is not exhaustive

[6] Mather and Prudden (2007) suggest a long flow path and/or confining clays as explanation for groundwater chemistry

5.4 Method for identifying and mapping the origin of deep-sourced springs

5.4.1 Introduction

Further to the discussion presented in sections 5.1 and 5.2, it is apparent that thermal and deep-sourced springs are controlled by specific hydrogeological circumstances. Even where they have been well-studied there is a possible lack of consensus regarding geological controls. It is also probable that, for many deep-sourced springs, there is little data to determine their origin. A bespoke approach for each spring is likely to be required.

In line with the scope of allowing findings of earlier elements of the project to inform methodological strategies, no wide-scale mapping exercise has been carried out for thermal and deep-sourced springs. Instead, a suggested method is presented below. The suggested method takes a desk-study approach and would initially be applied to the deep-sourced springs identified in section 5.3.

Three items are required for each deep-sourced spring:

- the location of the spring or springs
- origin of the spring - a conceptual model of the hydrogeology of the spring, detailing:
  - the location of recharge area
  - pathway(s) from the recharge area to spring discharge point
  - confidence in the recharge area and pathways
  - the value of the spring derived from its use

It is anticipated that the outcome would be a 2D map of England, ideally indicating for each spring:

- its location
- its possible catchment area (or areas if competing conceptual models exist); shading or colour depth could be used to indicate certainty in the suggested area
- a cross section of the pathway to the spring
- its value, displayed by colour or symbol

The 2D map would be supported by documentation for each spring, describing in detail its conceptualisation and value judgement and the lines of evidence used in determining these.

Data to support the location of each deep-sourced spring is likely to be easily available and self-evident. The other two required items are discussed below.

5.4.2 Deep-sourced spring value

Deep-sourced springs will be assigned a value (very high to very low) based on their use. High value springs are those of historic and current importance, for example, Bath, Buxton, Harrogate. Very low value springs, such as Bristol Hotwells are those which are not currently used, are likely to provide minimal thermal resource, minimal baseflow to rivers and are unlikely to support ecosystems.

5.4.3 Origin of deep-sourced springs

The amount and type of data available for each spring may vary widely. The aim is to build a conceptual model of the recharge areas and flow pathways to each deep-sourced spring, and therefore, estimate the likely extent of the catchment area. The following steps are suggested:

1. collate historical literature
2. collate geographic information:

- topography (specifically the location of topographic highs)
- surface geology (bedrock and superficial)
- 3D geology
- location of geological structures (folding, faults)
- regional hydraulic gradient (for example, from local boreholes, hydrogeological mapping)

3. collate geochemical data to support deep-origin, to inform the estimation of the age of spring water and the depth to which it has travelled

- geochemistry of spring water (compare with water from other local sources or similar geologies). In particular:
    - major/minor ions
    - TDS
    - dissolved oxygen
    - nutrients (nitrate, nitrite, orthophosphate)
    - pH
    - trace elements such as bromine
    - metals (for example, iron or aluminium concentration
    - temperature
- age dating
- water quality of surrounding area:
        - nearby rivers
        - borehole sampling

4. build qualitative conceptual model of flow and transport to spring:

- draw together the multiple lines of evidence collated above
- bring in studies from literature, where appropriate

It should be noted that there may be more than one conceptual model that may explain the observed spring discharge, as noted by (R Gallois 2006) for the Bath springs). Here, the models should be critically assessed with respect to their varying catchment areas.

5. assess confidence:

- low to very low: little or conflicting data, competing conceptual models, complex (fractured/fissured) geology
- medium to high: much good quality data, a single conceptual model

It is likely that most springs will be assigned low to very low confidence.

5.4.4 Identifying new deep-sourced springs

It is likely that other deep-sourced springs exist that have not been identified in this report. This is either because they are not reported in the reviewed literature or they are not known to be deep-sourced springs.

The springs identified in Table 5.3 fall into four main categories:

- saline springs in rural Cumbria and possibly the north-east, although evidence suggests these have stopped flowing
- thermal springs in the White Peak, Derbyshire
- thermal springs at Bath/Bristol
- thermal springs at Harrogate

It is possible that, in these areas, there are other deep-sourced springs with a similar origin.

Despite the conceptual discussion of regional flows presented by J Toth 1999, the identified deep-sourced springs are not associated with all the major sedimentary basins in England. It may be that here the hydrogeology is not favourable; spring discharges, which may not have raised temperatures due to a slow return to surface, have not been identified as having a deep-sourced origin; or discharges may be direct to surface water. A review of the hydrogeology of the major sedimentary basins of England, including the Wessex, Weald, Cheshire, Cleveland and West Lancashire basins may suggest areas where deep-sourced springs might occur.

If a spring is newly identified as having a possibly deep-sourced origin, the geochemistry and hydrogeological setting should be screened (see section 5.2) to determine if a deep-sourced origin is supported.

5.4.5 Review of difficulties in identifying and mapping deep-sourced springs

Two main difficulties are identified:

- **lack of data to support deep-sourced spring conceptualisation**: Identified catchment areas may be very large with low certainty. Additional data collection (for example, water quality sampling, age dating and/or geological investigation may help constrain the estimated catchment area. If necessary, focus should be placed on high value springs first. However, even with significant effort, it may not be possible to reach a consensus regarding the deeper spring-controlling structures, recharge areas or flow paths
- **lack of understanding of the specific hydrogeological conditions that drive deep-sourced springs**: Identifying additional deep-sourced springs is difficult. However, general areas where other deep-sourced springs might be expected to be found can be identified (section 5.3). Unidentified deep-sourced springs with a similar origin to those identified may be protected by association. Additionally, it seems unlikely, given the historical focus on spa development in England and on holy wells before that (J Mather 2016), that significant deep-sourced springs have not been identified

It is suggested that these issues are reviewed following the mapping exercise described above.

6 Outline guidance – deep-sourced springs

Like the brackish groundwater review (Section 2), the discussion of deep-sourced springs presented above suggests there is groundwater at depth that must be protected due to its connection to deep-sourced springs. Therefore, it is suggested that protecting deep-sourced springs should fall under the existing risk assessment framework.

6.1 Protection under existing risk assessment framework

The following principles are recommended:

- the possible presence or absence of deep-sourced springs or recharge zones or formations that supply water to deep-sourced springs should be identified by a site-specific risk assessment; this would be informed by the outcomes of section 5.4
- deep-sourced springs or recharge zones or formations that supply water to deep-sourced springs identified during a site-specific assessment should be treated as receptors at risk from a proposed activity
- the risk to these receptors should be assessed as part of tiered risk assessment within the current risk-assessment framework
- the value of the springs should be derived from their use in supporting baseflow to rivers, in supporting ecosystems or their recreational or therapeutic use
- a ‘precautionary principle’ should be adopted: it is the responsibility of the author of the risk assessment to demonstrate that deep-sourced springs or recharge zones or formations that supply water to deep-sourced springs are not present and that they are not at risk from a proposed activity. Where there is uncertainty, further investigation and/or monitoring are required.

7 Conclusions and recommendations

7.1 Introduction

There is currently very little known about the location of deeper aquifers in England that contain brackish groundwater and their potential usefulness. There is also limited understanding of the origin of thermal and other 'deep-sourced' spring waters, some of which have reputed health benefits and have been used as spa waters. Consequently, there is little current guidance on the level of groundwater protection that may be suitably applied to these resources.

This report attempts to address this shortcoming by:

- reviewing where these resources occur
- providing methods to identify and map these resources
- producing outline guidance to protect these resources

The main objective is to help us develop our position on protecting brackish groundwaters and deep-sourced springs in England.

7.2 Brackish groundwater

7.2.1 Sources of brackish groundwater in England

The most important sources of brackish groundwater in England are likely to be:

- dissolution of naturally occurring mineral salts, most significantly in confined aquifers such as beneath areas of thick till deposits in the Vale of York or at depth in the Chalk (beneath the zone of active circulation)
- historical or recent seawater intrusion in coastal areas, for example in the Permo-Triassic sandstones of Liverpool or Manchester
- connate groundwater, for example at depth in the Cheshire Basin

7.2.2 Definition

Brackish groundwater is defined as groundwater with TDS concentrations between 1,625mg/l to 10,000mg/l. This covers groundwater defined as slightly to moderately saline.

7.2.3 Mapping method

Complementary methods are proposed for:

- developing a national map to show the possible presence of 'useful' brackish groundwater throughout England

- carrying out a high-level site-specific assessment to determine if 'useful' brackish groundwater is likely to be present (and the confidence in this assessment)

The focus of the mapping is on bedrock geology, as the proposed method uses the BGS 3D geology cross sections.

It is not possible to map brackish groundwater in superficial deposits using the proposed technique. This source of brackish groundwater should be assessed as part of a site-specific risk assessment.

At the national scale, useful brackish groundwater is defined as a function of aquifer permeability and the TDS concentration. Here, the geothermal data catalogue (Appendix A) is used to provide estimates of TDS variation with depth. Aquifer designation is used to quantify aquifer permeability. Aquifers designated as unproductive are marked as not useful. To improve confidence in the results, it is suggested that more local and regional data is used if the proposed method is taken forward.

The site-specific assessment extends the definition of useful groundwater as used for the national mapping. Six measures are proposed to assess the usefulness of brackish groundwater in each geological formation local to a site:

- TDS concentration
- aquifer hydrogeological properties
    - aquifer designation and
    - aquifer permeability/storage);
- extent of the formation beneath the site
- water quality (other contaminants)
- the volume of water available and/or renewability of resource

Overall usefulness of the brackish groundwater in each formation at the site is the sum of the values from each measure multiplied by weights that define the relative importance of the different measures. Each measure is also given a confidence value, which is also multiplied by the weight of the measure. The sum of these make up the overall confidence score for the brackish groundwater risk assessment.

The outcome of the high-level national mapping exercise is a series of 3D cross sections displaying the presence of useful brackish groundwater at depth.

The outcome of a site-specific brackish groundwater assessment is a qualitative assessment showing, for each formation:

- whether brackish groundwater is likely to be present and, if so, if it likely to be useful
- the confidence in this qualitative assessment

A case study for a site in the Cheshire Basin demonstrates both mapping methods.

7.2.4 Degree of protection

Protecting brackish groundwater should align with existing groundwater protection policy. The approach should:

- complement existing guidance on groundwater protection
- help protect brackish groundwater resources under the existing risk-assessment framework

For protection under the existing risk-assessment framework, the following principles are recommended:

- the possible presence or absence of brackish groundwater should be identified by a site-specific assessment (section 3.1.3)
- brackish groundwater identified during a site-specific assessment should be treated as receptors at risk from a proposed activity
- the risk to the brackish groundwater should be assessed as part of tiered risk assessment in line with the current risk-assessment framework
- the value of each brackish groundwater receptor is determined by its usefulness value
- a 'precautionary approach' should be taken: where local data is not available and there is little confidence in identifying brackish groundwater receptors, useful brackish groundwater should be assumed to be present during a tiered risk-assessment

7.3 Deep-sourced springs

7.3.1 Definition

The need to protect springs comes from their value, for example as a source of drinking water, their recreational or therapeutic use or their importance to ecosystems. It is difficult to define deep-sourced springs because of the many and often site-specific features associated with springs discharging water from depth. The following are lines of evidence to support a deep-sourced origin:

1. water quality parameters. In particular:
    - raised temperature
    - groundwater mineralisation
    - increased TDS
    - presence of trace elements, for example bromine
    - presence of raised metal concentrations, for example iron or aluminium
    - reducing conditions

- raised pH

However, mixing with recent water can disguise the presence of deep-sourced groundwater. Deep-sourced spring water quality should be compared with local groundwater quality, and groundwater drawn from other similar geology but with a modern origin.

2. age dating. Age dating can strongly constrain groundwater age but is highly specialised and not routinely applied in hydrogeological investigations
3. uniformity of spring discharge. Deep-sourced springs are likely to be relatively constant, with little or no seasonal variation in flow rate or geochemistry
4. geological structures. Geological structures are an important part in determining the depths a groundwater flow path will attain, as well as determining where and how rapidly groundwater is discharged at the surface. Structural settings could involve folding, tilting, faulting and fracturing. For example, many of the thermal springs discussed here lie in or adjacent to relatively deep basinal fold structures with a bedrock succession dominated by Carboniferous limestone

The importance of hydrogeological conceptual understanding in determining the origin of pathways taken by deep-sourced springs cannot be overstated. However, despite significant investigative effort competing conceptual models may exist. Even with significant focus, the origin of some of the most widely studied deep-sourced springs in the UK remains uncertain.

7.3.2 Catalogue of known deep-sourced springs

A literature review was carried out to identify and catalogue, where possible, known deep-sourced springs in England. The springs identified fell into four main categories:

1. saline springs in rural Cumbria and possibly the north-east, although evidence suggests these have stopped flowing
2. thermal springs in the White Peak, Derbyshire
3. thermal springs at Bath and Bristol
4. Harrogate

7.3.3 Mapping method

Deep-sourced springs are usually controlled by specific hydrogeological circumstances. Additionally, for many deep-sourced springs, there is little data with which to determine their origin. However, broadly speaking three items are needed to map the source of each known spring:

1. its location
2. its origin - a conceptual model of the hydrogeology of the spring detailing

   a. the location of recharge area

   b. pathways from the recharge area to spring discharge point

   c. confidence in the recharge area and pathways

   A bespoke approach for each spring to determine its source is likely to be needed

3. its value (measured by its usefulness)

Spring value

Deep-sourced springs will be assigned a value from very high to very low based on their use. High value springs are those of historic and current importance. Very low value springs are those which are not currently used, are likely to provide minimal baseflow to rivers and are unlikely to support other ecosystems.

Origin of deep-sourced springs

Five steps are suggested:

1: collate historical literature

2: gather geographic information

3: collate geochemical data to support deep-origin, to inform the estimation of the age of spring water and the depth to which it has travelled

4: build qualitative conceptual model of flow and transport to spring

5: assess confidence

The outcome of the mapping exercise would be a 2D map of England showing for each spring its location, value, estimated catchment area and the confidence in the catchment area. The 2D map would be supported by documentation for each spring, describing in detail its conceptualisation and value judgement and the evidence used to determine this).

The main obstacles in identifying and mapping deep-source springs are due to the relative lack of data available.

7.3.4 Degree of protection

Like the brackish groundwater review (Section 2), the discussion of deep-sourced springs presented above suggests there is groundwater at depth that must be protected due to its connection to deep-sourced springs. Therefore, it is suggested that the protection of deep-sourced springs should fall under the existing risk assessment framework.

To establish protection under the existing risk assessment framework the following principles are recommended:

- the possible presence or absence of deep-sourced springs or recharge zones or formations that supply water to deep-sourced springs should be identified by a site-specific risk assessment
- deep-sourced springs or recharge zones or formations that supply water to deep-sourced springs identified during a site-specific assessment should be treated as receptors at risk from a proposed activity
- the risk to these receptors should be assessed as part of tiered risk assessment in line with the current risk-assessment framework
- the value of the springs should be based on their use, for example in supporting baseflow to rivers, supporting ecosystems or their recreational or therapeutic use
- the 'precautionary principle' should be adopted: it is the responsibility of the author of the risk assessment to demonstrate that deep-sourced springs or recharge zones or formations that supply water to deep-sourced springs are not present and that they are not at risk from a proposed activity. Where this is uncertain, further investigation or monitoring is needed.

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Appendix A Summary of TDS distributions from geothermal data catalogue

The geothermal data catalogue is ‘A comprehensive catalogue of underground temperature, heat flow and geochemical data…’ first produced by the Institute of Geological Sciences in 1977 and later updated by the British Geological Survey (BGS) in 1984 and 1987.

Figure 8.1 shows the distribution of TDS with depth of data from the catalogue. Table 8.1 summarises the information in terms of formations from which water samples were obtained, the number of locations from which the data is derived, depth range, and the range in TDS concentrations.

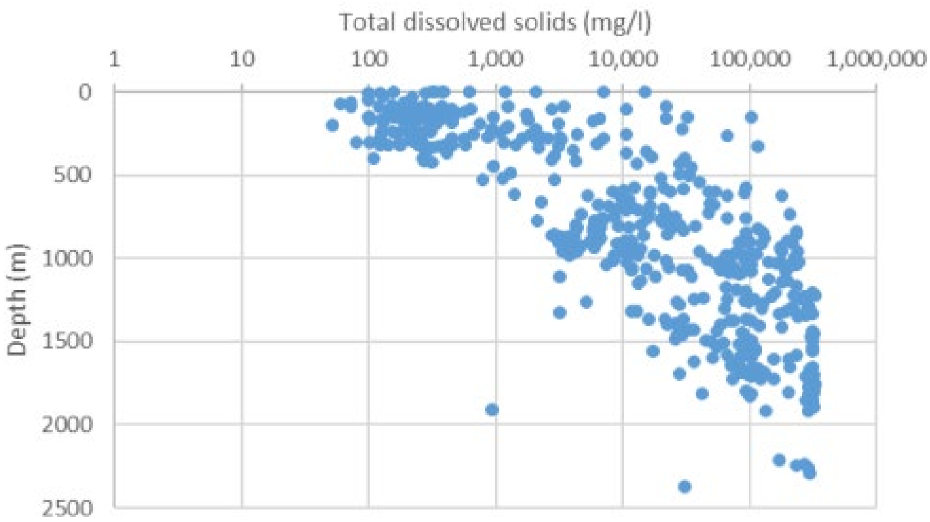

Figure 8.1 TDS as a function of depth for England, based on data from the geothermal data catalogue reproduced from Loveless and others (2018)

Table 8.1 Water quality analyses by formation, based on data from the geothermal data catalogue reproduced from Loveless and others (2018)

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

Appendix B Review of groundwater protection in England

The following summary (sections B.1 to B.4) is reproduced exactly from Loveless and others (2018). This puts into context and informs the discussion in the main body of the report regarding the appropriate degree of protection to be given to brackish groundwater.

B.1 Overview of EU directives and guidance*:* The Water Framework Directive and Groundwater Daughter Directive

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

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

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

The WFD sets out steps and a timeframe for achieving good quantitative and chemical status of European waters, including groundwater. As part of this process, the WFD requires member states to define and identify groundwater bodies within river basin districts and to report to the European Commission (the Commission) on the status of these bodies. The following groundwater-related definitions are set out in the WFD.

Groundwater is defined in the WFD in Article 2.2 as:

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

In Article 2.11 an aquifer is defined as:

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

In Article 2.12 a body of groundwater or groundwater body is defined as a:

> “distinct volume of groundwater within an aquifer or aquifers”

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

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

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

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

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

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

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

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

After the WFD was adopted, a Common Implementation Strategy (CIS) (European Commission 2001) was developed and agreed in May 2001. This sets out a common understanding of approaches to, and implementation of, the WFD, and provides a series of examples of best practice.

B.2 Implementation in England

Allen and others 2002 describe the interpretation of the WFD and outline procedures we used to carry out the initial delineation and characterisation of the groundwater bodies to meet the requirements of the WFD. The principles set out in Allen and others 2002 included the following key observations, that:

> ‘the delineation and characterisation of groundwater bodies [should be] … iterative. Thus, for example, only simple conceptual models are required at first in order to delineate the groundwater bodies, becoming, where required, more sophisticated (and expensive) as the

characterisation process proceeds. Iteration also allows for the refining of boundaries or the subdivision or aggregation of groundwater bodies'

> 'groundwater systems in aquifers should be subdivided or aggregated to form groundwater bodies of a suitable size for management (generally at least tens of square kilometres in area), which will reflect the pressures and impacts on groundwater; and that: 'Groundwater body boundaries should generally be chosen initially on the basis of geology, using WFD aquifer boundaries. If necessary, subsequent subdivision is performed using groundwater divides and finally using flowlines. The groundwater body as delineated will remain constant during a River Basin Management Plan, but may be subdivided or amalgamated with adjacent bodies in subsequent RBMP cycles, dependent on management needs'

The report concluded with two final principles, that:

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

Allen and others (2002) also noted that:

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

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

B.3 UKTAG guidance on implementation of the WFD

The UK Technical Advisory Group (UKTAG), the advisory group on implementation of the WFD and Groundwater Directive in the UK, published a paper setting out guidance on the delineation and characterisation of groundwater bodies in the UK in response to the requirements of the WFD (UKTAG 2012). The report refines the definitions of groundwater, aquifer and groundwater bodies, sets out the principles of how groundwater bodies should be delineated, provides guidance on groundwater body depth and the definition of groundwater body horizons and reporting to the Commission. The following is a summary of UKTAG definitions and guidance relevant to groundwater body delineation.

UKTAG definitions related to groundwater

In addition to the definitions in the WFD, (UKTAG 2012) introduces two new concepts of pore water, as:

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

and of groundwater at extreme depth, as:

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

These are then related to interpretations of the WFD definitions of groundwater based on their respective roles in environmental management (see Table 8.2 below).

Table 8.2 Roles of sub-surface water in environmental management

Zone	Terminology	Role
Water in unsaturated zone	Porewater	Porewater above the water table. Protect as a vertical pathway to groundwater.
Water in the saturated zone		Porewater in low permeability deposits. The concept of the zone of saturation is not relevant in these deposits as it is usually not feasible to define a water table where lateral percolation is impeded. The main role of these strata is as a protecting layer for groundwater.
	Groundwater in strata overlying or underlying groundwater bodies	Groundwater has a value as a lateral or vertical pathway to other receptors. May be usable but only for local supplies <10m3/day.
	Groundwater in a groundwater body	Groundwater is part of an aquifer and is a receptor as a long-term resource that can be exploited for human activities or support surface flows and ecosystems.
	Groundwater that is permanently unsuitable for use	Groundwater which has neither pathway nor resources value. For example, where salinity is greater than seawater.

B.3.1 Groundwater body depth

(UKTAG 2012) extends the Common Implementation Strategy (CIS) guidance (European Commission 2003) related to groundwater lateral boundaries and groundwater body depth. UKTAG (2012) notes that:

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

UKTAG (2012) states that:

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

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

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

UKTAG (2012) states that the default maximum thickness of groundwater bodies in the UK should be 400m, apart from porous superficial aquifers, such as sand and gravel aquifers, and low transmissivity bedrock, such as the Dalradian, which should have an assumed maximum thickness of 40m and 100m, respectively (UKTAG 2012). Measurement of the thickness should be from the upper extent of the groundwater body downward, where:

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

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

B.4 Summary of groundwater protection in England

We published a revised approach to groundwater protection in in 2018 (current version Environment Agency 2018). The principles and definitions set out in that report and associated documentation are consistent with the previous, more detailed Groundwater protection: principles and practice (GP3) report (Environment Agency 2013).

We currently define principal aquifers, secondary aquifers (secondary A, B and undifferentiated), and unproductive strata (Table 8.3) based on their geological characteristics, the quantity and ease with which groundwater can be obtained from the aquifers, and the extent to which they support flow in rivers and habitats.

Table 8.3 Aquifer types in England

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

Our approach to groundwater protection uses a risk-based framework, where the technical framework for groundwater risk assessment includes:

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

B.5 3D groundwater vulnerability mapping

The 3D groundwater vulnerability screening method for England (3DGWV) (Loveless and others 2018) is targeted specifically at onshore oil and gas activities. The approach is designed to assess the vulnerability of potential receptors to a particular activity. Therefore, it aligns with our risk-based approach to groundwater protection (section B.4). The stages of the assessment process are outlined below.

- **Classification of the importance of potential receptors**: Carried out for all units within the geological sequence, according to our aquifer designations and evidence for groundwater quality. These are classified as A to D, representing progressively lower value groundwater, detailed within Table 8.4.
- **Calculation of intrinsic vulnerability**: Characteristics of the intervening units between the potential receptor and hydrocarbon source rock, such as separation distance, thickness of mudstones and clays and geological pathways, which may influence potential receptor vulnerability.
- **Calculation of specific vulnerability**: Intrinsic vulnerability factored by the nature of the hydrocarbon exploitation activity (and associated processes impacting the subsurface) factored again by the nature of the hydraulic head in the system.
- **Assignment of risk group**: Specific vulnerability and receptor classification (that is, perceived importance of the rock unit for groundwater).

Table 8.4 Receptor classification (Loveless and others 2018)

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

Appendix C Summary of US approach to brackish groundwater mapping

Recent work in the US (J Stanton and others 2017) produced maps of brackish groundwater occurrence across the contiguous United States. This work was driven by a need to better understand the occurrence and characteristics of brackish groundwater as a potential water resource.

The mapping used a multi-regression analysis approach, considering whether a wide variety of variables may be correlated with salinity in groundwater. This approach extended previous mapping exercises carried out in the US going back to the 1960s.

Parameters were used for the regression if they were available in digital form across the whole area. Significant variables included in the model were: (natural log transformed) depth below land surface; bedrock geology; subsurface evaporite deposits; principal aquifer; ecoregion[7]; baseflow index; percentage irrigated lands; soil characteristics; topographic wetness index; regional water table; proximity to the coast; land cover; superficial geology; hydrologic landscape region; groundwater region and generalised geology.

The single strongest predictor associated with TDS was the natural logarithm of depth. The second strongest predictor was the presence of evaporites (halite, gypsum and anhydrite, or both). Geological unit (mapped at outcrop) was also a dominant predictor in the model. Groundwater base-flow index (indicating groundwater flushing to surface water) was a strong negative predictor and associated with lower TDS.

Observed data (336,000 samples which when assigned to a coarse grid represented over 50% of the total land area) were limited to readily-available, typically national data sets and were biased towards shallow, freshwater resources. Data from below 1,500 ft (457 m) was particularly limited. Observed brackish groundwater occurrence (and hydrogeological properties) were assigned to coarse grid cells at one of four depth intervals (< 50ft (15 m) bgl, 50 – 500ft (15 – 152 m) bgl, 500 – 1,500ft (152 – 457 m) bgl and 1,500 – 3,000ft (457 – 914 m) bgl). The statistical model was calibrated by comparing with the gridded observed data.

The calibrated statistical model was used to produce maps of brackish groundwater distribution across the US at depths of 500, 1,500 and 3,000ft (152, 457 and 914 m) bgl. The model did not predict brackish groundwater occurrence at shallow depths.

Uncertainty in the produced maps was not represented explicitly. However, uncertainty clearly exists both from the depth and spatial distribution of brackish groundwater samples and from the interpolation required to construct the

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[7] Regions that have similar climate, geology and soils.

spatially contiguous data sets used in the regression. Uncertainty in the results is briefly touched on (with respect to estimating the volumes of brackish groundwater) but not addressed in detail.

In addition to mapping brackish groundwater occurrence, the project also attempted to:

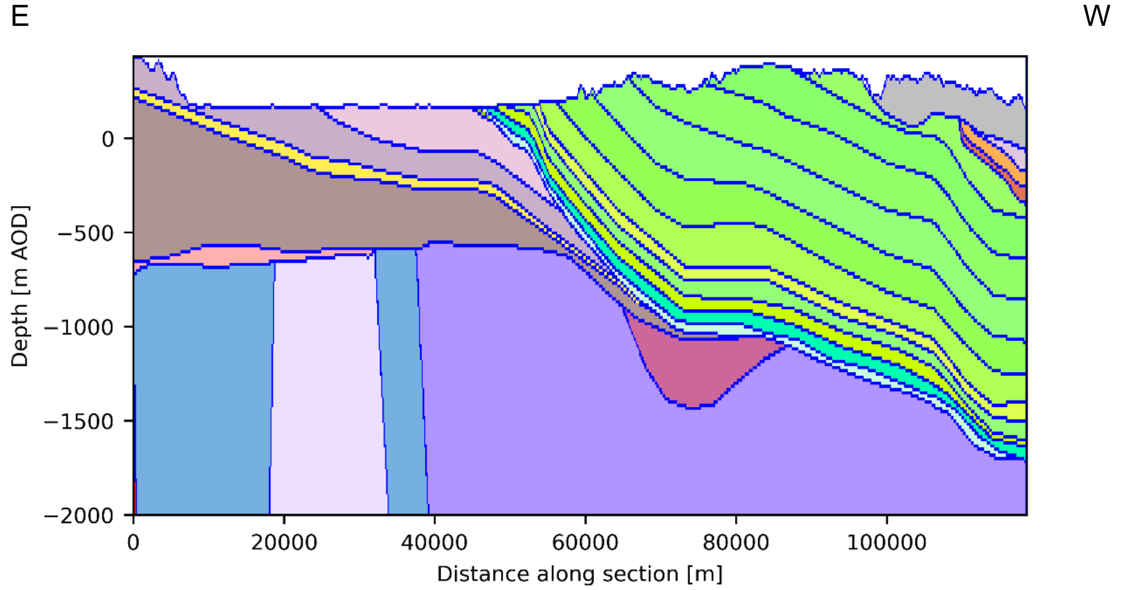
- estimate current saline groundwater use for the principal aquifers
- map the usefulness of brackish groundwater with respect to chemical characteristics which might limit its use

Appendix D Chalk brackish groundwater mapping example

The section used is Region 12 – section 181 (an E-W section through North East Anglia). Please see (BGS 2015) for more details on the section location.

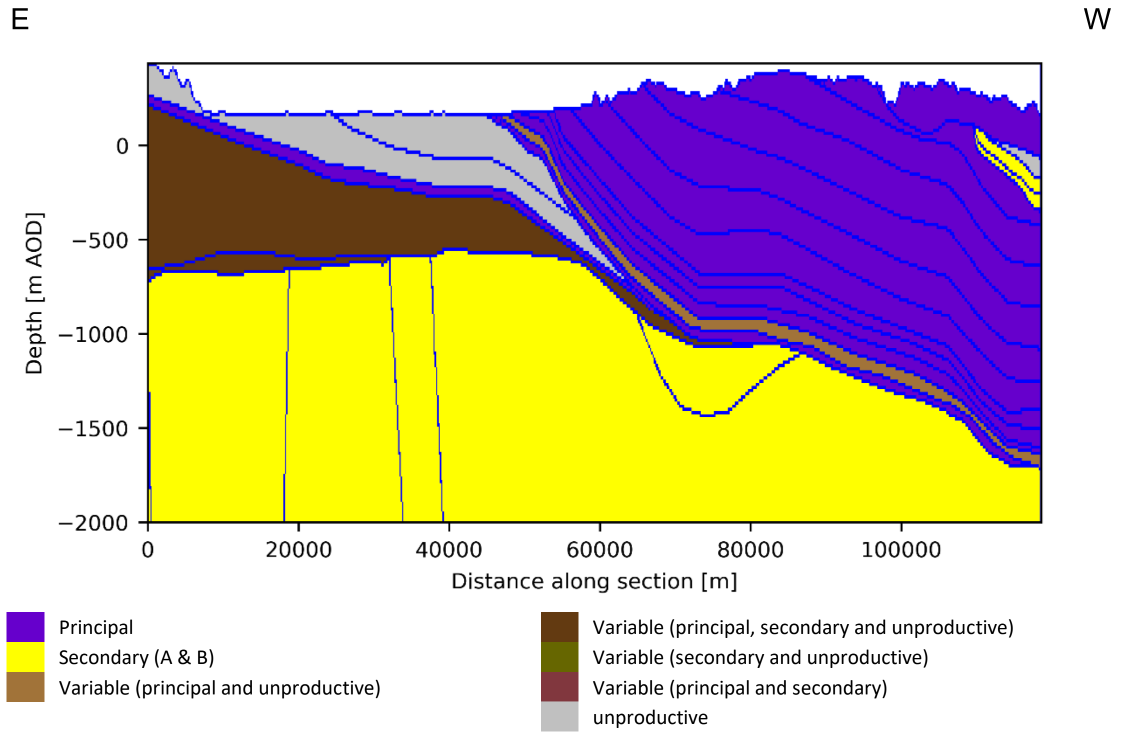
Table 8.5 Geology key

Crag Group - pebbly sands
Thames Group - clay, silt, sand and gravel
Lambeth Group - clay, silt, sand and gravel
Thanet Formation - sand, silt and clay
Portsdown Chalk Formation
Culver Chalk Formation
Newhaven Chalk Formation
Seaford Chalk Formation
Lewes Nodular Chalk Formation
Newpit Chalk Formation
White Chalk Subgroup (undifferentiated)
ZigZag Chalk Formation
Grey Chalk Subgroup (undifferentiated)
Gault Formation and Upper Greensand Formation (undifferentiated) - mudstone, sandstone and limestone
Lower Greensand Group - sandstone and mudstone
Wealdon Group - mudstone, siltstone and sandstone
West Walton Formation, Ampthill clay formation and Kimmeridge clay formation (undifferentiated) - mudstone, siltstone and sandstone
Kellaways Formation and Oxford Clay Formation (undifferentiated) - mudstone, siltstone and sandstone
Inferior Oolite Group and Great Oolite Group (undifferentiated) - limestone, sandstone and mudstone
Lias Group - mudstone, siltstone, limestone and sandstone
Mercia Mudstone Group - mudstone, siltstone and sandstone
Lower Devonian rocks (undifferentiated) - mudstone, siltstone and sandstone
Intrusive Igneous rocks - granite, foliated
Ordovician rocks (undifferentiated) - mudstone, siltstone and sandstone
Cambrian rocks (undifferentiated) - mudstone, siltstone and sandstone
Silurian rocks - undifferentiated - mudstone, siltstone and sandstone



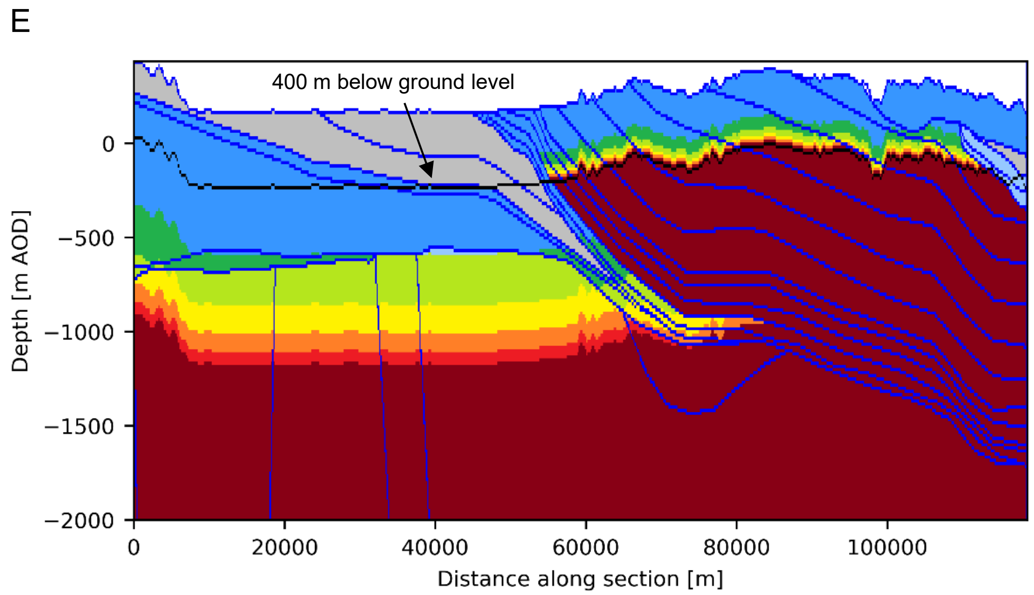
Source: (BGS 2015). See Table 8.5 for the figure legend.

Figure 8.2 Region 12 section 181 bedrock geology, key in Table 8.5



Source: (BGS 2015)

Figure 8.3 Region 12 section 181 aquifer designation



Source: Mott MacDonald. Note:
Table 8.6 provides the key.

Figure 8.4 Region 12 section 181 useful groundwater distribution

Table 8.6 Key to Figure 8.4

		Groundwater TDS					
		<1,625 mg/l	1,625 – 3,500 mg/l	3,500 – 5,000 mg/l	5,000 – 7,500 mg/l	7,500 – 10,000 mg/l	> 10,000 mg/l
Aquifer designation	Principal	Fresh	High Usefulness brackish GW				Not useful (TDS)
	Secondary	Fresh				Low usefulness brackish GW	Not useful (TDS)
	Unproductive	Not useful (unproductive)					

Source: Mott MacDonald

Appendix E Bottled mineral water and spring water in the UK

Within the UK, bottled waters labelled as natural mineral water must be (Smedley 2010):

- abstracted from a recognised groundwater source
- protected from known risks of pollution
- bottled at source
- fulfil the requirements for physical, chemical and microbiological quality
- have a consistent composition
- not be subject to treatment other than for limited purposes by recognised methods

Waters labelled as ‘spring water’ must also be from a groundwater source and must be bottled at source. However, there is no formal requirement for source protection from pollutants and the spring waters may undergo additional treatments to those allowed for mineral waters. They must also comply with regulations on physical, chemical and microbiological quality, but do not require a consistent composition (Smedley 2010).

The location of bottled mineral water sources in the UK is shown in Figure 8.5.

Figure 8.5 Location of known thermal and mineral springs in the UK, after Banks, 1997 (Albu, Banks and Nash 1997).

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