Environment Agency

Perspectives on protection of deep groundwater

Chief Scientist's Group report

October 2020

Version: SC180015

We are the Environment Agency. We protect and improve the environment.

We help people and wildlife adapt to climate change and reduce its impacts, including flooding, drought, sea level rise and coastal erosion.

We improve the quality of our water, land and air by tackling pollution. We work with businesses to help them comply with environmental regulations. A healthy and diverse environment enhances people's lives and contributes to economic growth.

We can’t do this alone. We work as part of the Defra group (Department for Environment, Food & Rural Affairs), with the rest of government, local councils, businesses, civil society groups and local communities to create a better place for people and wildlife.

Published by:
Environment Agency,
Horizon House, Deanery Road,
Bristol, BS1 5AH

www.gov.uk/environment-agency

ISBN: 978-1-84911-466-0

Further copies of this report are available from our publications catalogue: www.gov.uk/government/publications or our National Customer Contact Centre: 03708 506 506

Email: research@environment-agency.gov.uk

Author(s):
Stephen Buss, Alan Herbert, Mike Rivett, Nick Rukin

Keywords:
Deep groundwater, brackish groundwater, deep sourced springs, oil and gas, groundwater value, groundwater protection

Research contractor:
Stephen Buss, Environmental Consulting Ltd,
32 Port Hill Road, Shrewsbury SY3 8SA
01743 239064

Environment Agency’s Project Manager:
Ian Davey

Collaborator(s):
Tim Besien, Sarah Scott, Lucy Snape, Jenny Thomas

Project number:
SC180015

Citation:
Environment Agency (2020) Perspectives on protection of deep groundwater. Environment Agency, Bristol.

Research at the Environment Agency

Scientific research and analysis underpins everything the Environment Agency does. It helps us to understand and manage the environment effectively. Our own experts work with leading scientific organisations, universities and other parts of the Defra group to bring the best knowledge to bear on the environmental problems that we face now and in the future. Our scientific work is published as summaries and reports, freely available to all.

This report is the result of research commissioned by the Environment Agency's Chief Scientist's Group.

You can find out more about our current science programmes at https://www.gov.uk/government/organisations/environment-agency/about/research

If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact research@environment-agency.gov.uk.

Professor Doug Wilson
Chief Scientist

Executive summary

This report was commissioned by the Environment Agency to capture ideas associated with the exploitation of deep and/or brackish groundwater, and the risks associated with this, particularly with respect to deep springs. It is particularly relevant to the exploration for, and exploitation of, onshore oil and gas (including shale gas). The report is based on an approach that included conducting a literature review and holding a half-day workshop.

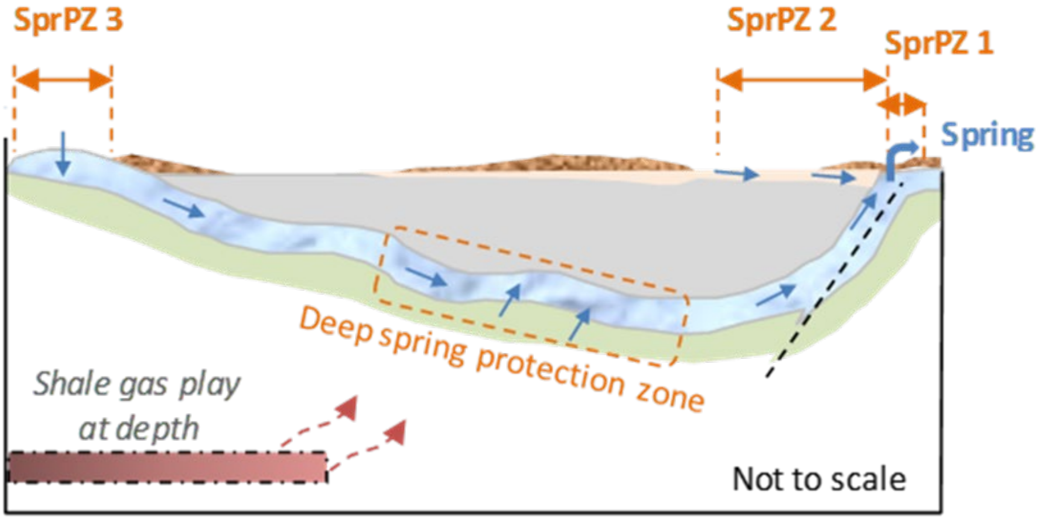
Exploitation of deep groundwater (that is, groundwater from deeper than 400m) can lead to impacts on near surface groundwater resources and groundwater quality. The abstraction of groundwater – from any depth – is likely to lead to an eventual reduction in water resource in the near surface fresh groundwater. Temporary withdrawal of a finite volume of water from depth could lead to a small but persistent impact at the near surface. Groundwater at depth may also be affected as water is removed from the base of shallow aquifers. Impacts may include the increased flushing of salinity from aquifers, the introduction of oxidising groundwater to previously anaerobic environments, and the loss of deeper fresh groundwater as a resource that has not yet been affected by anthropogenic activities (that is, pollution).

The study assessed the frequency of monitoring data in the Environment Agency's Water Management Information System from 2017 that indicated the occurrence of brackish groundwater and groundwater quality data; 16.5% of sample locations yielded brackish groundwater (that is, with a total dissolved solids content >600mg per litre). Most of the brackish groundwater sampled would be suitable for livestock watering and the irrigation of crops without treatment or blending. It would also be suitable for drinking after blending or treatment. The constraints on treatment are explored in the report, but England's water distribution infrastructure is so well-connected that blending is likely to be the most suitable and economic option for creating potable water from brackish.

The report discusses the hydrogeological settings of deep springs (that is, springs fed by groundwater from deeper than 400m), and the Bath Springs in particular, with the aim of illustrating how best to assess their provenance. Two studies in the literature offer a range of forensic geochemical techniques that might be employed in understanding deep spring provenance. These methods can tie in with the three-dimensional (3D) geological mapping approach of the earlier 3D groundwater vulnerability project undertaken jointly by the British Geological Survey and the Environment Agency.

It is expected that provenance mapping will be an important part of any risk assessment for activities within the 3D catchment of a deep spring. The report reviews the English approach to groundwater source protection in the light of deep spring protection and identifies some European examples of protecting deep springs. This led to the recommendation for a tiered methodology for characterising and delineating deep spring protection zones (SprPZs in the figure below). This process should be implemented if activities in deep groundwater might have an impact on deep springs.

It is recognised that, if available in sufficient and sustainable amounts, deep and/or brackish groundwater could be used to compensate for increased demand for fresh water. The brackish resource is currently unquantified. A comprehensive study should therefore be commissioned to quantify the amount of available brackish water in England that is not already accounted for in existing catchment water balances. This should include an assessment of existing hydrochemical data and sampling of Environment Agency monitoring boreholes to provide an understanding of the vertical distribution of brackish water through aquifers.



Schematic illustration of the potential application of Spring Protection Zones (SprPZs) to a deep spring and its subsurface pathway that is potentially vulnerable to a proposed shale gas play at significant depth

The definition of SprPZs and the constraints on development within them need to be explored. While operators of any proposed deep scheme that could affect groundwater will be required to complete impact assessments, there needs to be a method to flag up that such an assessment is required. Indicative SprPZs therefore need to be defined by the Environment Agency in advance and a methodology for defining them developed. Although the majority of spring flows may originate from the deep system, protection of the near spring shallow subsurface cannot be ignored and is recommended for discussion when defining SprPZs. For instance, the water flowing from the Bath Springs includes a component of modern leakage into the spring flow system.

It is also recommended that a more comprehensive literature review of European approaches to spring protection is made. Recognising that carbonate aquifers constitute the most important thermal water resources outside volcanic areas, this review should focus on countries where carbonate rock (for example, limestone) karst aquifer systems that typically support deep spring spa/mineral/thermal waters are more prevalent.

Contents

List of tables and figures

1 Background

1.1 ‘A capturing of ideas’

This report was commissioned by the Environment Agency to capture ideas associated with the exploitation of deep and/or brackish groundwater, and the risks associated with this, particularly with respect to deep springs.

The report reflects a brief consideration (68 hours) by the authors through work elements including:

- design of approach and development of ideas
- a half-day workshop
- a literature review
- preparation of this report

It should therefore be read as it was intended – as a capturing of ideas rather than a polished guidance document.

1.2 Terms of reference

To help steer the project, the following objectives were proposed.

1. Define criteria that may be used for ‘usable brackish groundwater’. This should include consideration as to how brackish groundwater might be used (noting constraints), including for fracking, other industries, agriculture and desalination to augment drinking water supplies. An economic approach to the assessment of usability should also be considered.
2. Comment on how and, if possible, where and with what effect the impact of the abstraction of deep groundwater may have on shallow aquifer systems through downwards leakage.
3. Comment on the potential for impacts on deep aquifers of temperature change as a result of open and closed loop geothermal schemes with, for example, loss of heating/cooling potential.
4. Indicate how a total dissolved solids (TDS)/transmissivity/borehole depth relationship might be used to develop a map of the presence or absence of usable groundwater. A ‘worked example’ and how methodology could be made practicable should be provided.
5. Set out a method for mapping the provenance of deep springs – indicate how the Environment Agency might go about delineating the source waters of deep-sourced springs. This should include a summary of how other European countries delineate deep groundwater bodies for the Water Framework Directive (for example, for spa waters). Is it appropriate to map ‘source protection zones’ and, if so, how might a methodology be defined?

6. Comment on whether other deep-sourced springs may exist in addition to those that are well-documented. Give consideration to where deep groundwaters contribute to near surface groundwaters, without necessarily appearing as springs.
7. Set out the data gaps and other limitations identified, and provide a concise report of the project findings using the Environment Agency report template.

1.3 Structure of this report

This report sets out a discussion of the tasks listed above. It is not sequenced in the same order as the listed tasks. Instead it aims to provide a narrative structure that starts by considering deep activities and potential impacts on groundwater (Section 2). It then describes one such activity, that is, the use of brackish water (Section 3) before considering the provenance of deep springs and their protection (Sections 4 and 5 respectively).

2 Conceptualisation of impacts from activities in deep groundwater

2.1 Definition of deep groundwater

For context it is important to have a clear definition of what is meant by ‘deep’ groundwater. Working jointing with the British Geological Survey (BGS), the Environment Agency has already conducted a study on three-dimensional groundwater vulnerability (Loveless et al. 2018). Drawing on work by the UK Technical Working Group on the Water Framework Directive (UKTAG), the Environment Agency identifies a depth of 400m above which the use, and hence protection, of groundwater is prioritised.

A depth of 400m is commensurate with the somewhat deeper (as to be expected) maximum depth of 600m to which groundwater protection is assured under the Usable Groundwater Base of Groundwater Protection (BGWP) used in Alberta, Canada (AER Environment Group 2019). The BGWP depth value varies with locality and equates to the best estimate of the elevation of the base of the formation in which non-saline groundwater (<4,000mg per litre TDS) occurs at the assessed location (Lemay 2009).

The joint BGS/Environment Agency study recognised that deeper groundwater may be of increasing interest associated with exploitation of deep resources such as shale gas and/or a demand for disposal of large volumes of water where near surface resources are already stressed (Loveless et al. 2018). It also recognised the importance of deep (>400m) groundwater as a pathway and as a potential resource, and hence its need for certain defined protections. It is therefore appropriate to use the definition of deep groundwater as groundwater at a depth >400m below surface in the discussion that follows.

It might also be appropriate to identify a depth beyond which consideration of protection of groundwater is not required.

UKTAG guidance suggests that, at some depth, groundwater has no value – either as a resource or as a pathway – and that such permanently unsuitable groundwater might correspond to groundwater at extreme depth and with salinity greater than sea water (UKTAG 2012). Loveless et al. (2018) show that, in England, there are very few sampled groundwaters with salinity less than sea water at depths >1,750m.

When developing guidance, care should be taken to avoid unnecessary complexity of regulation for groundwater bodies at depths where other rights and restrictions are defined. For example, The Infrastructure Act 2015 gives rights for the exploitation of petroleum resources at depths >300m and, in the case of hydraulic fracturing,[1] at depths of >1,000m below the surface (1,200m below defined protected areas).

---

[1] The Onshore Hydraulic Fracturing (Protected Areas) Regulations 2016 (SI 2016 No. 384)

Similarly, care would be needed when developing guidance for groundwater protection that might be applied to the host formation for a facility for deep geological disposal of radioactive waste in a geological disposal facility (GDF). For example in considering the suitability of Central England Subregion 1 for hosting a GDF, a report by Radioactive Waste Management (RWM 2019) citing UKTAG 2012 noted that:

- the aquifers are within 400m of the surface and groundwater deeper than this is unlikely to be suitable for drinking water
- solution mining of brines extended to no more than 500m
- the absence of thermal springs suggests very little movement of groundwater deeper than these depths

The depth range considered for hosting a deep GDF is given as between 200m and 1,000m. The lower limit was chosen to ensure geological stability and to avoid disruptive events such as associated with glaciation, related to site-specific conceptual understanding.

2.2 Types of impact

This section considers those activities related to deep groundwater that might result in impacts elsewhere such as:

- a change in the quantity or quality of protected water bodies
- changes that affect the use of groundwater
- impacts on human health, habitats, buildings or cultural assets (for example, spa springs)

In order to determine how activities related to exploitation of deep groundwater should be regulated, it is useful to consider an analogy of the source–pathway–receptor paradigm as used elsewhere in regulation of the environment.

The receptors are those environmental assets or activities associated with these. The pathways are the mechanisms by which changes in deep groundwater conditions lead to changes in the environment or restriction in the future use or enjoyment of the environment. And finally, the source for this linkage is the action that affects the condition of the deep groundwater.

2.3 Activities that might cause an impact

2.3.1 Regulatory context

The Water Framework Directive defines aquifers and groundwater bodies (distinct volumes of groundwater within an aquifer) and sets out the requirement for groundwater bodies to be characterised and their uses assessed. It recognises that some groundwater bodies may have lower objectives.

The Water Framework Directive requires Member States to review the impact of changes in groundwater levels or the water quality. This should include an assessment of the effect of such groundwater bodies on:

- surface water and associated terrestrial ecosystems
- water regulation, flood protection and land drainage
- human development

This review would form the basis for identifying those bodies of groundwater for which lower objectives could be set in accordance with Annex 2 section 2.4 of the Water Framework Directive.

Groundwater bodies have been defined in the main groundwater aquifers (principal and secondary).

Based on the definition of deep groundwater given in Section 2, it would be appropriate to investigate whether these provisions would apply when considering groundwaters below 400m in depth. Accordingly, such deep groundwaters should be characterised and assessed to identify whether there is a need for the same level of protection, or whether, given the effect of their status and its impact on protected resources, lower objectives – and hence protection criteria – are appropriate.

The Water Framework Directive does not address the question of how to establish the depth to which a groundwater body should be defined. In developing advice on the implementation of the directive, however, UKTAG (2012) separately discusses water in strata above or below groundwater bodies that has limited direct value as a resource, but which has value as a lateral or vertical pathway to other receptors. It also suggests that groundwater at extreme depth, and where it is highly mineralised or saline, may be considered permanently unsuitable for use.

This section of the report identifies those issues that should be considered in the characterisation and assessment of groundwater at depths >400m, from which objectives for a groundwater body might be defined and appropriate regulation and protection applied.

2.3.2 Use of deep groundwater for potable or commercial water supply

Some deep groundwater is used directly as a resource for potable public water supply or commercial water supply in some settings. Loveless et al. (2018) identified 13 public water supplies that were between 400m and 500m deep. Such groundwater forms part of a groundwater body that requires protection under the Water Framework Directive, with objectives defined similarly to shallow groundwater bodies in aquifers.

2.3.3 Deep groundwater as a pathway supplying shallow groundwater, surface water or springs

Deep groundwater that is not in itself a currently viable resource may nevertheless form a conduit for water to recharge a shallower aquifer, supply a surface water body as baseflow, or supply a deep-sourced spring. In these cases, changes in the condition of the deep groundwater will directly affect protected water bodies and abstraction of deep groundwater might derogate the supply to these shallow or surface resources.

The identification of the role of deep strata in providing groundwater to springs or providing inter-aquifer flow is not straightforward. Even in the case of deep mineral and thermal springs with long established cultural importance for English spa towns, the provenance of their source waters is generally still not well understood, as evidenced by ongoing research discussed in Section 4.3.

These groundwater resources might be affected by abstraction of deep groundwater interrupting the pathway, or activities at depth leading to mobilisation of contaminants, or by reinjection of abstracted water as a waste. For example, hydraulic fracturing (‘fracking’) of shale horizons at depth requires large volumes of water. It might prove commercially advantageous to abstract deep groundwater locally where the relatively poor water quality is acceptable for fracking fluids, and then to reinject to depth the waste fracking fluids produced back at surface.

Protection of such groundwater resources or assets would require the development of a site-specific conceptual model to determine the likely impact of exploitation of deep groundwater that might be connected. This model would be based on the deep geological setting and would require consideration of the groundwater water balance and geochemistry of deep groundwaters where possible (for example, by following the proposals for risk assessment set out in Sections 4.5 and 5.3). Abstraction or injection would potentially change head gradients and flow directions.

2.3.4 Deep groundwater as a pathway connected to shallow groundwater, surface water or springs

Even where the deep groundwater adjacent to shallow groundwater bodies or sources does not provide a substantive contribution to a protected groundwater resource, pathways from deep groundwater may nevertheless lead to impacts on the quality of shallower groundwater bodies and springs.

Such impacts might arise if the deep water quality is distinct from the shallow water or becomes contaminated. In such circumstances, changes in deep groundwater conditions may have an impact on the water quality of the protected water body. For example, deep groundwater containing 2,000mg per litre of chloride may only provide a 2% flow contribution to a shallow spring but it might still give a significant contribution to the mineral content of the spring of 40mg per litre of chloride.

Impacts associated with deep groundwater quality are discussed in more detail in Section 2.5. However, changes in the movement of deep groundwater may lead to significant impacts on adjoining water bodies. A risk based approach based on a sound conceptual model would again be required to justify use of the deep groundwater where there is the possibility of adverse impacts.

2.3.5 Poor quality deep groundwater that may yet have commercial value as a resource

Fracking of shale formations to extract shale gas will take place at depths >1,000m, or >1,200m below defined protected areas. The rights to use deep ground for the purpose of exploiting petroleum resources are addressed in the Infrastructure Act 2015. The shale formations targeted for fracking in their natural state are of low permeability and would not be considered a deep groundwater body. However, it is possible that groundwater in adjacent formations at these depths could be considered permanently unsuitable for use.

However, as noted in Section 2.3.3, fracking operations might require significant volumes of water in locations where conventional supplies are stressed and lead to significant volumes of waste water being produced at surface. It might be commercially advantageous to abstract water from a depth local to the operations and to reinject waste water to deep permeable formations, subject to legal requirements. Such activities would require management to ensure that the resources are used sustainably. They would also be associated with a risk of contamination of shallower resources should the fracking process itself be poorly controlled, or if well completion integrity were breached. Impacts on the quality of deep groundwater and the extent of changes to deep groundwater flow and quality should be considered.

2.3.6 Deep brines

Deep brines have been a valuable resource over long periods of history. Salt is now mined in dry mines, and also by the injection and circulation of water followed by abstraction of brines. Salt is a valuable commodity and the presence of deep halite formations provides a potentially valuable mineral and storage resource. Activities affecting deep groundwater in contact with halite bearing formations may have an impact on the accessibility or value of these resources.

2.3.7 Deep groundwater as a thermal resource

In the UK, geothermal energy for electricity generation is only feasible at depths of the order of kilometres and in quite well-defined spatial areas (for example, on the south-west England batholith). Hence there is no feasible consequence of the use of groundwater at depths from say 400m to 1,200m from the utilisation of deep geothermal heat.

However, low enthalpy geothermal energy (ground source energy) is routinely obtained using open and closed loop heat exchange boreholes. Such geothermal heat exchangers are routinely drilled to depths of over 200m and may in the future be deeper. The thermal resource is not managed directly except where excess heat poses a risk of causing undesired environmental consequences. Closed loop shallow geothermal energy is not regulated.

Although these ground source energy uses of deep geological systems are shallower than considered here for ‘deep groundwater’, some schemes in small land footprints may seek to extend to a greater depth. In addition, the efficiency of the schemes depends on saturated aquifer conditions. The need for large numbers of relatively deep boreholes provides the potential for connections between deep groundwater and shallow aquifers. This means the geothermal resource could be affected by changes in groundwater levels and additional risks could be created if deep groundwater quality is poor.

2.3.8 Deep groundwater connected to other deep resources

As discussed above, other resources at depth are in contact with deep groundwater. Activities where deep groundwater quality is affected or changes in deep groundwater flows induced might have impacts on other activities at depth. For example, contamination of deep groundwater in the vicinity of deep mine workings might make dewatering from deep mines less viable. Dewatering of a deep system could also dry out previously flooded mine workings, leading to renewed aeration of mine walls and the release of contaminants on re-flooding of the mine.

2.4 Potential impacts on water resource availability

Activities in deep groundwater bodies may affect:

- flows from springs sourced from the aquifer under consideration, or (vertically) adjacent aquifers (see Section 4),
- other activities at depth such as the dewatering of deep mines or deep waste disposal sites

The removal of any amount of groundwater from a deep aquifer horizon must also, eventually, be compensated for by flow from a near surface groundwater body. This could lead to:

- derogation of shallow groundwater uses
- baseflow discharge to rivers, the coast or dependent aquatic ecosystems

This would pose a risk in areas of severe water stress (particularly south-east England).

Any activity involving the permanent abstraction of water from a water-stressed catchment – even from deep groundwater – should not be permitted unless there is flow compensation at the surface.

However, temporary activities could be considered. Abstraction of a volume of water from depth may not be realised in the near surface for many years and, crucially, is likely to be drawn out over a much longer timescale than the initial withdrawal. Hence the impact on flows near the surface might be very small but would continue for a considerable duration.

2.5 Potential impacts on groundwater quality

2.5.1 Variations in groundwater quality with depth and spatial manifestation

Some of the changes in groundwater quality that can occur in aquifers with depth and spatially using images are illustrated in Figures 2.1 and 2.2. Generic hydrogeological settings for deep groundwater sourced springs and discharges are also presented in Section 4.2; these note the different ages of groundwater on different flow paths within aquifers.

Different ages and flow paths mean:

- Different influences during the time of recharge such as:
  - Climate[2] – for example, warmer temperatures and more organic-rich soils in wetter periods (for example, from about 5,000–8,000 years before present (BP)) lead to greater carbon dioxide in the soil zone and so greater potential for dissolution of carbonate minerals
  - Land use – in agricultural areas, water recharged before World War II typically has lower nitrate concentrations than more recent waters due to post WWII intensification of agriculture
- Interaction with different strata and minerals such as:
  - Evaporite minerals (halite, gypsum) that might be present in strata overlying or underlying the aquifer of interest, or indeed might be present in layers within that aquifer
  - Clay-bearing formations and minerals that can lead to ion exchange of calcium for sodium where the clays are of marine origin; this exchange process can lead to further carbonate mineral dissolution and an increase in alkalinity
  - Sulphide-bearing strata (typically the Coal Measures and marine clays such as those of the Jurassic period) in which reaction between dissolved oxygen in the fresh recharge waters can oxidise the sulphide minerals to leave lower dissolved oxygen concentrations, higher sulphate and sometimes elevated dissolved metal concentrations – this effect can be strong where groundwater interacts with strata in mine workings
- Bacterially mediated oxidation of organic carbon in overlying or underlying strata or within the aquifer itself which can lead to the following effects:
  - decrease in dissolved oxygen (aerobic decomposition)

---

[2] Deep water in the Chalk of south-east England can be 20,000 years old, having originally fallen as rain towards the end of the last Ice Age (Downing 1998).

  - decrease in nitrate (denitrification)
  - an increase in dissolved iron and manganese where iron and manganese oxides in the strata are reduced; other trace metals such as arsenic respond to redox changes and may be released
  - a decrease in sulphate and an increase in sulphide (including hydrogen sulphide gas where groundwaters are more acidic)
  - generation of methane gas
  - an increase in dissolved carbon dioxide, and potential changes in pH and alkalinity depending on the nature of the strata
- Different rates of flushing of old waters (for example, depositional water)
- Different depths for the freshwater–seawater interface in aquifers

The degree of effect of these processes will depend on:

- the geochemical nature of the aquifer and adjacent strata
- the flux of fresh groundwater through the aquifer
- artificial influences such as the oxidation of sulphide-bearing strata in mine workings

Thus there is the potential for deep groundwater systems and associated springs to have very different groundwater quality to other deep systems and to shallower groundwater. Desk-based studies can anticipate the likely variability of deep groundwater quality, but careful groundwater sampling from known depths will usually be required to fully characterise this variability.

As some aquifers move from unconfined hill terrain to confined depths and synclinal basins, the depth variations are expressed as spatial variations in groundwater quality in an aquifer; see Figure 2.2 for changes in Chalk groundwater quality as the aquifer becomes confined beneath the Paleogene deposits.

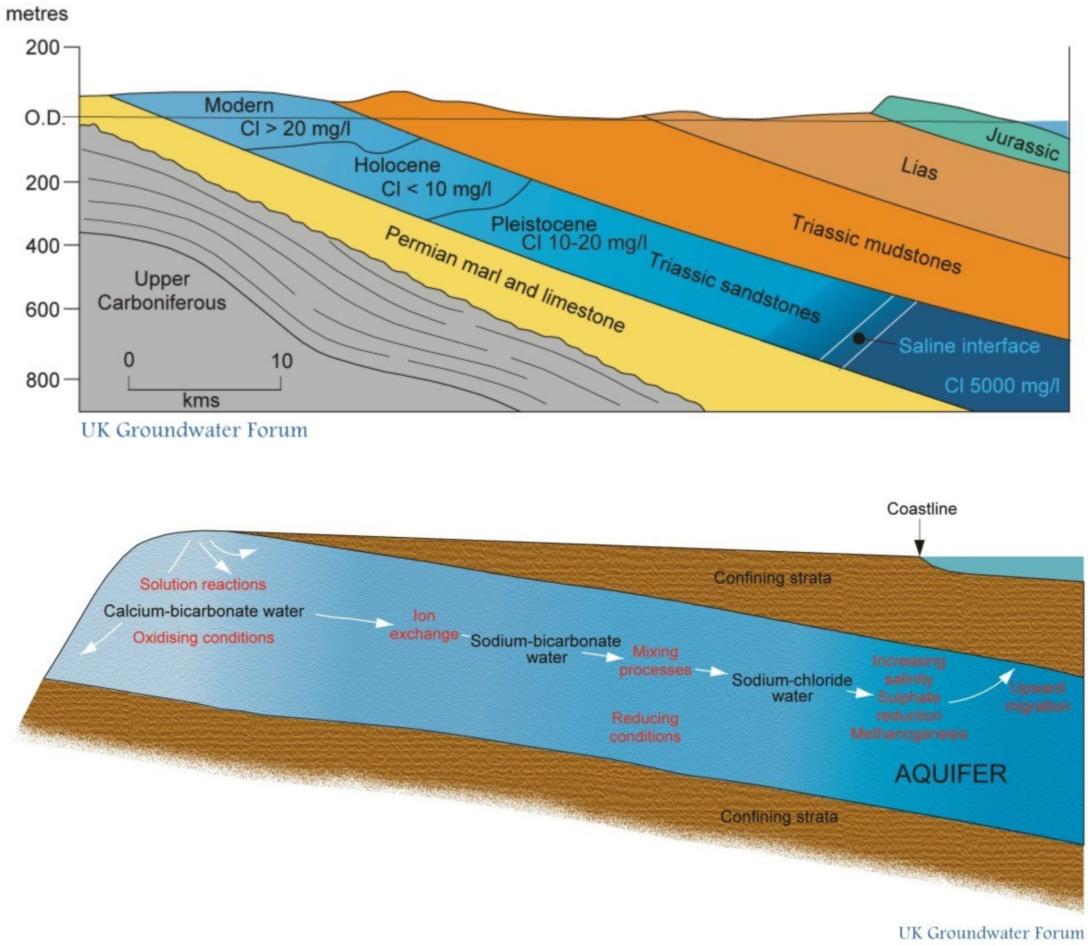


Figure 2.1 Two examples of down-dip changes in groundwater quality

Source: Image gwf014 ‘Stratification of groundwaters of different ages in the Triassic sandstones of the East Midlands of England’, ‘Schematic diagram of downgradient chemical changes in groundwater’ from © UK Groundwater Forum, 2011. All Rights Reserved.

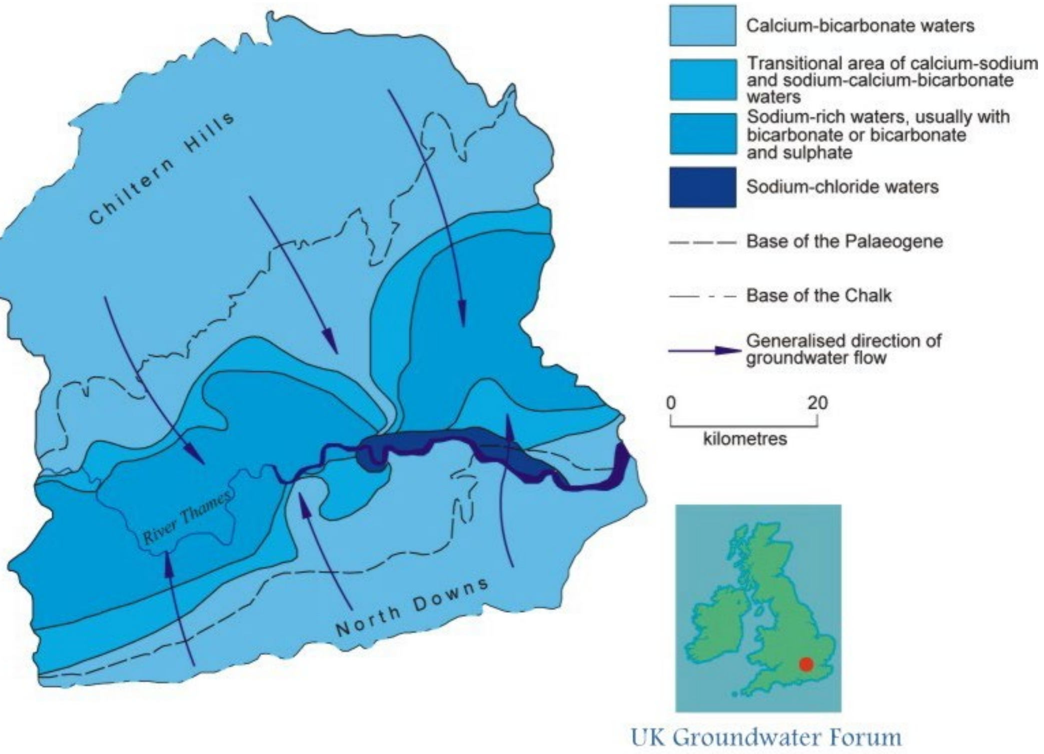


Figure 2.2 Example of spatial changes in groundwater quality

Source: Image gwf016 ‘The chemical composition of groundwater in the Chalk of the London Basin’ from © UK Groundwater Forum, 2011. All Rights Reserved

2.5.2 Uses of groundwater from intermediate depths

Most groundwater is abstracted from shallower (less than about 200m) rather than deeper aquifer horizons due to:

- lower drilling and pumping costs
- typically lower salinity or better quality
- higher transmissivity in the case of Chalk aquifers

One notable exception is that deeper groundwater (greater than about 200m) in the Sherwood Sandstone aquifer typically has lower nitrate concentrations due to its age (and perhaps some denitrification). Hence this deeper water can be used to blend (often within the same borehole) with shallower groundwater to provide acceptable nitrate concentrations for potable use.

2.5.3 Potential impacts on groundwater quality

The following effects are considered to be plausible impacts on groundwater when abstracting from deep aquifers.

Effects that are considered positive and negative with regard to the quality of groundwater at depths shallower than 400m include the following.

- Increased circulation of recharge to depth leading to:

  - decrease in salinity where the salinity is related to poorly flushed connate waters[3] rather than reaction with evaporite minerals (positive effect)
  - a move towards more oxidising conditions and with that perhaps precipitation of previously dissolved metals (positive effect, unless that leads to clogging of wells) or oxidation of sulphide minerals with related increases in sulphate and dissolved metals (negative effect)
  - possible solution enhancement of permeability and perhaps a change in major ion chemistry as a result of that dissolution (positive or negative)
  - likely increase in nitrate and other anthropogenic contaminants at depths (for example, pesticides, chlorinated solvents) (negative effect)
- Increased (or newly started) leakage from overlying aquifers through lower permeability layers leading to:
  - a possible change in major ion composition of the deeper groundwater as a result of water rock interaction (for example, ion exchange, sulphide weathering) by the leaking water in the intervening layer, which could increase the hardness and sulphate concentration of deeper groundwater
  - denitrification (positive effect) of the shallower groundwater, drawn downwards, if intervening layers contain biodegradable organic matter or reduced constituents (dissolved iron and manganese, sulphide or methane)
- Loss of groundwater at depths not affected by near surface activities, as a source of water unaffected by anthropogenic contaminants as these become more commonly found in shallow UK groundwaters (see BGS 2011); similarly, a loss of such groundwater as a possible record of former climate (for example, change in oxygen, hydrogen and carbon isotope ratios)

---

[3] Waters are that were trapped in the pores of sedimentary rocks as they were deposited

3 Characterisation and mapping of usable brackish groundwater

This section attempts to provide a workable definition of brackish water (Section 3.1) and then considers brackish groundwater uses (with and without treatment) (Section 3.2). Information readily available to the authors of this report is then briefly reviewed to understand better the distribution of brackish groundwater in the UK (Section 3.3). Section 3.4 illustrates how usable brackish water might be mapped. Section 3.5 examines a proposed framework for establishing whether theoretically usable brackish water would actually be viable based on consideration of a range of factors.

3.1 Definition of brackish groundwater

Simply put, brackish groundwater is groundwater that is not potable but where the concentration of TDS is not high enough to be considered saline. There is inconsistency in the identification of lower and upper concentration thresholds between potable and brackish, and between brackish and saline.

Brackish water is typically defined with reference to either TDS or salinity. Both are normally measured in mg per litre (gram per litre for very high values) or parts per million (ppm). In unpolluted water, these are essentially the same measures. In polluted waters, however, TDS might include dissolved hydrocarbons, for example, while salinity does not. Laboratory measurement of TDS causes some loss of carbon dioxide during the drying process and so measured TDS values of unpolluted waters can be lower than the sum of major ion concentrations.

There is no UK drinking water standard for TDS or salinity. The standard for conductivity of 2,500µS per cm at 20°C equates to a TDS value of about 1,625mg per litre, but this limit is based on aggressiveness to pipework. WHO (2011) describes water with TDS values <600mg per litre as of ‘good palatability’ but values >1,000mg per litre as ‘increasingly unpalatable’.

The lower threshold of what constitutes brackish groundwater in international surveys of brackish waters varies. For instance:

- A limit of 300mg per litre chloride was used when mapping brackish groundwater in the Netherlands (Stuyfzand and Raat 2010). If the composition was purely sodium chloride, this equates to a TDS of 494mg per litre.
- The joint BGS/Environment Agency three-dimensional groundwater vulnerability (3DGWV) project used a TDS value of 1,000mg per litre as the upper limit of potability (Loveless et al. 2018).
- A recent survey of brackish groundwater in the USA also used a value of 1,000mg per litre (Stanton et al. 2017).

Similarly, an upper concentration threshold of brackish water may be cited in literature as 10,000mg per litre or 30,000mg per litre. In the literature the upper limit of brackishness often seems to encompass a usability criterion rather than a water quality threshold. For instance:

- Corrosion-resistant stainless steel (type 316L) ought not be used for boreholes in groundwater exceeding a TDS of 10,000mg per litre (Turnbull 2010).
- Above 10,000mg per litre chloride (or 20,000mg per litre TDS) membrane filtration for treatment to potable quality is uneconomic (Stuyfzand and Raat 2010).
- In the USA, groundwaters are protected if they have a TDS <10,000mg per litre (Stanton et al. 2017).

Seawater typically has TDS of around 35,000mg per litre and a chloride concentration of 19,000mg per litre.

However, the most important aspect for this project is whether any particular brackish groundwater is ‘usable’. Its usability should be related to a feasibility assessment and/or a cost–benefit balance (that is, how much is the water worth versus how much does it cost to extract, treat to an appropriate standard, convey to its place of use, and dispose of it).

3.2 Potential uses of brackish groundwater

3.2.1 Use for potable water

Brackish groundwater is increasingly being used around the world for drinking, irrigation or industry, though mostly in arid and semi-arid countries. In 2010, the USA had the capacity to desalinate 1,520 million litres (Ml) per day of brackish water (USGS undated); of this, 67% was for drinking water, 18% for industry, 9% for power and the remaining 6% for other uses. Most of the facilities for the production of drinking water were in Florida, California and Texas; most were inland. A substantial component of the potable water resource for the Netherlands is also derived from treated brackish groundwater (Stuyfzand and Raat 2010).

There appears to have been limited use of brackish water in the UK to date. Thames Water operates a brackish water desalination plant on the River Thames at Beckton in east London (Water Technology Net, undated). The Thames Gateway Water Treatment Works can provide 150Ml per day of drinking water by pumping from the river during the last 3 hours of an ebb tide. It is not operated continuously and it is anticipated that it will only be used during droughts (Thames Water, undated). The scheme benefits from:

- the economies of scale of operating a very large treatment works
- being adjacent to the source of brackish water with a negligible head difference from the water body
- an excellent connection to water users

Despite this, it is apparent that desalination for potable water use in England is only economical in the most severe conditions of water stress.

On the other hand, Smith et al. (2001) reported that treatment of brackish groundwater from the Chalk aquifer beneath the Millennium Dome provided a component of grey water use in the facility.

3.2.2 Constraints on treatment of brackish groundwater

Chemical limitations on the intake water quality for brackish groundwater reverse osmosis (BWRO) systems to prevent scaling of membranes were listed by Stuyfzand and Raat (2010). These include the following issues; the paper also helpfully provides advice on geochemical modelling to highlight these issues on a case-by-case basis.

- 'The salinity must be favourable for optimum membrane purification at reduced costs: preferably chloride less than 10,000mg/l or total dissolved solids (TDS) less than 20,000mg/l. BWRO systems normally operate between 1,000 and 7,000mg/l Cl'.
- 'The concentration of ions less soluble than Na, K, and Cl should be low enough to prevent scaling of membranes … with, for instance, silicate ($SiO_2.nH_2O$, $MgSi_2(OH)_6$), sulphate ($BaSO_4$, $CaSO_4.2H_2O$), carbonate ($CaCO_3$, $CaMg(CO_3)_2$, $FeCO_3$), or phosphate ($Ca_5(PO_4)_3OH$; $NH_4MgPO_4{\cdot}6H_2O$) minerals'.
- 'The abstraction of brackish feed water should not result in salinisation or freshening of the aquifer, well clogging or corrosion of well and transport mains'.

To reinforce this, barite (barium sulphate) is known to cause particular problems with clogging of reverse osmosis membranes; Stanton et al. (2017) found that a considerable percentage of brackish water samples (48–74%) from US wells had potentially problematic concentrations of barium.

3.2.3 Agriculture

Livestock has a much greater tolerance to brackish water than humans and, apart from dairy cattle and pigs, are content with drinking water at TDS values up to 4,000mg per litre (dairy cattle can drink water at 2,400mg per litre and pigs up to 1,000mg per litre) (Government of Western Australia 2019). Sheep can adapt to concentrations up to 10,000mg per litre without this affecting their yield.

Crops tend to be less tolerant to brackish water, but can adapt to TDS values of up to 2,000mg per litre (assuming that the brackish water contains acceptable concentrations of boron) (Ayers and Westcot 1994).

3.2.4 Industry

Despite requiring corrosion-resistant material, brackish groundwater with concentrations >10,000mg per litre can still be used for cooling during power generation, aquaculture and a variety of uses in the oil and gas industry (that is, drilling and fracking).

3.3 Occurrence of brackish groundwater in England

Water quality data from deep boreholes in English bedrock aquifers (mostly principal aquifers) are summarised in the joint BGS/Environment Agency report (Loveless et al. 2018, Section 3.3.1). Brackish groundwater was identified in almost all of the aquifers examined and at depths from the ground surface to about 1,500m. This is not, however, exclusively the domain of brackish waters, as saline and hypersaline waters have also been identified from boreholes across this depth interval.

The datasets reviewed by Loveless et al. (2018) were created as a result of geothermal exploration programmes that presumably targeted deeper aquifer formations. These probably do not provide a spatial picture of the extent of brackish groundwater in bedrock.

To scope out the potential for spatially extensive brackish groundwater resources in bedrock aquifers, the baseline reports for Chalk aquifers and Sherwood Sandstone aquifers were reviewed. Reports for other aquifers have been published but were not reviewed due to time constraints. TDS values are not generally given in the baseline reports and so have been estimated from specific electrical conductivity (SEC) using the conversion:

$$1{,}000\text{mg per litre TDS} = 1{,}560\mu\text{S per cm}$$

Qualitative findings are provided in Table 3.1. Broadly speaking, in these principal aquifers, brackish groundwater is most often associated with saline intrusion and, in the Sherwood Sandstone, dissolution of evaporites at the edge of the Mercia Mudstone. These are not spatially extensive regions of the aquifers and so would not typically be considered a resource. Furthermore, where depth sampling through the saline interface has been undertaken, the transition from fresh to saline is very rapid, and the occurrence of brackish water samples in these environments is related to the effects of mixing in the pumped boreholes. However, some samples from confined aquifers (Staffordshire and Worcestershire, and Vale of York) suggest that more extensive brackish water bodies might be present here.

Table 3.1 Brackish groundwater in important aquifers in England

Aquifer	Area	Comments
Permo-Triassic sandstones	Staffordshire and Worcestershire	1/35 samples gave an SEC >1,560µS per cm. Water with an SEC of 2,510µS per cm was obtained from the confined zone of the aquifer, south of Birmingham, about 10 km from the nearest sandstone outcrop.
	Shropshire	1/90 samples gave an SEC of >1,560µS per cm. Water with an SEC of 2,023µS per cm was obtained from the outcrop area.

Aquifer	Area	Comments
		The literature suggests an influence (on other samples) from Coal Measures inflows.
	Vale of York	Perhaps 10/41 samples gave an SEC of >1,560µS per cm. Many were from the area confined by Till, as well as beneath the Mercia Mudstone.
		The maximum SEC was 3,170µS per cm.
	West Cheshire and Wirral	Extensive brackish and saline groundwater samples were taken from the aquifer, adjacent to the Dee and Mersey estuaries, and in the Cheshire brinefields.
		Median SEC was 562µS per cm but the mean was 2,079µS per cm (maximum 23,900µS per cm).
		The saline interface is at 50–200m below ground level in the Lower Mersey Basin.
	Manchester and east Cheshire	Some brackish groundwater samples from the aquifer, with a 95th percentile value from 91 samples of 2,605µS per cm.
		Sampling of the Chat Moss borehole revealed that the water quality went from fresh to brackish over a depth interval of about 10m between around 190. and 200m depth.
	Liverpool and Rufford	Some brackish groundwater samples from the aquifer, with a 95th percentile value from 48 samples of 3,275µS per cm.
		Some brackish groundwater is associated with saline intrusion, some with gypsum dissolution.
	Devon and Somerset	None of 28 samples yielded brackish groundwater.
Chalk	Dorset	None of 31 samples yielded brackish groundwater.
	Hampshire	None of 37 samples yielded brackish groundwater.
	North Downs, Kent and east Surrey	Only 1/123 samples from the unconfined aquifer yielded brackish groundwater (at 2,030µS per cm).
		3/10 samples from the confined aquifer yielded brackish or saline groundwater (median 1,310µS per cm, maximum 26,800µS per cm). Higher concentrations are related to saline intrusion.
	Chilterns (Colne and Lee catchments)	None of 61 samples from the unconfined aquifer yielded brackish groundwater, but 2/20 samples from the confined aquifer yielded brackish groundwater (maximum 4,410µS per cm) from beneath central London.

Aquifer	Area	Comments
	Great Ouse catchment (East Anglia)	None of 77 samples yielded brackish groundwater.
	Yorkshire and north Humberside	None of 115 samples from the unconfined aquifer yielded brackish groundwater, but more than half of 21 samples from the confined aquifer yielded brackish groundwater (maximum 17,200µS per cm) from beneath Hull. These were related to mixing with sea water.

Brackish groundwater is present in superficial aquifers such as estuarine deposits. For instance, Stuyfzand and Raat (2010) were able to map extensive brackish groundwater bodies beneath the Netherlands, as were many US studies (Stanton et al. 2017). Such datasets are not available for the much less spatially extensive English superficial aquifers. It might be expected that there are near surface bodies of brackish water in superficial deposits adjacent to major estuaries, perhaps also in the Wash and the Somerset Levels.

The Environment Agency's Water Management Information System (WIMS) database for 2017 was available from a previous project. There were no values stored for TDS, but conductivity values were recorded. A cumulative frequency curve of the mean values from each point where there were conductivity data is shown in Figure 3.1.

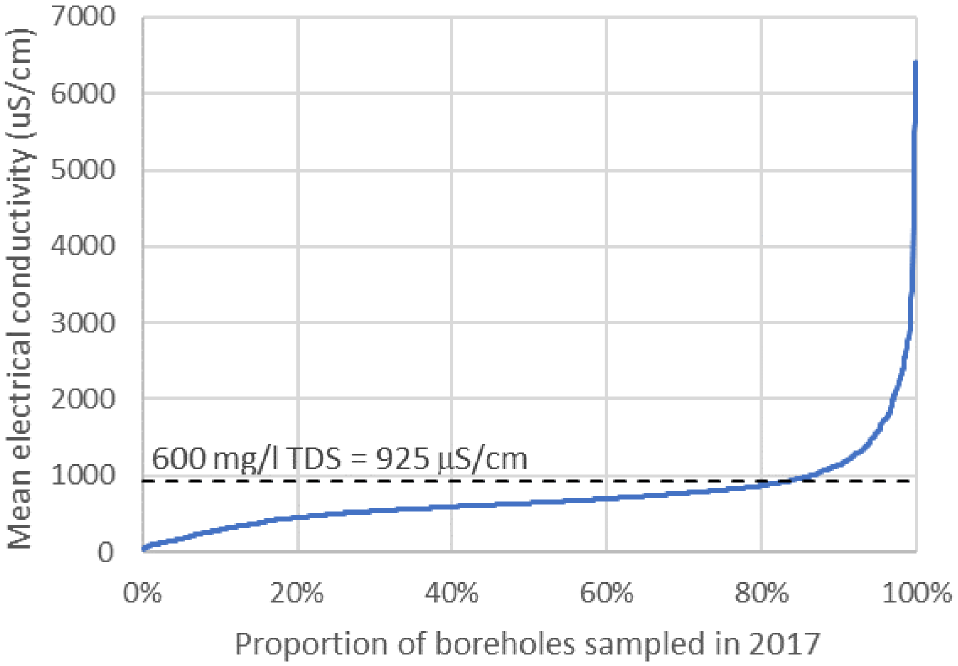


Figure 3.1 Mean conductivity values from all groundwater samples (excluding landfills) stored in WIMS for 2017

The following observations can be made.

- Of the 1,989 unique, non-landfill groundwater monitoring points, 329 (16.5%) conductivity values were indicative of brackish water (a TDS value that is the maximum limit of ‘good palatability’ of 600mg per litre equates to a conductivity of about 925µS per cm). This relatively large proportion indicates that 600mg per litre is an unexceptional value and that the presence of brackish water at this concentration is not a rare occurrence.
- Since most of the boreholes on the Environment Agency’s monitoring network are, or were, abstraction boreholes, the prevalence of brackish water indicates a high degree of tolerance to that water quality on the part of the historical borehole operators.
- The incidence of monitoring boreholes yielding significantly higher TDS values than 600mg per litre falls off quickly as TDS rises. These lower rates of incidence probably represent the lack of available historical abstraction boreholes to monitor, or a lack of interest in monitoring non-potable water, rather than a reduced spatial distribution of brackish groundwater with this water quality.

The locations of boreholes where the mean water quality during 2017 was brackish are shown in Figure 3.2; not all the 1,989 borehole locations are marked as several of the points are not in England.

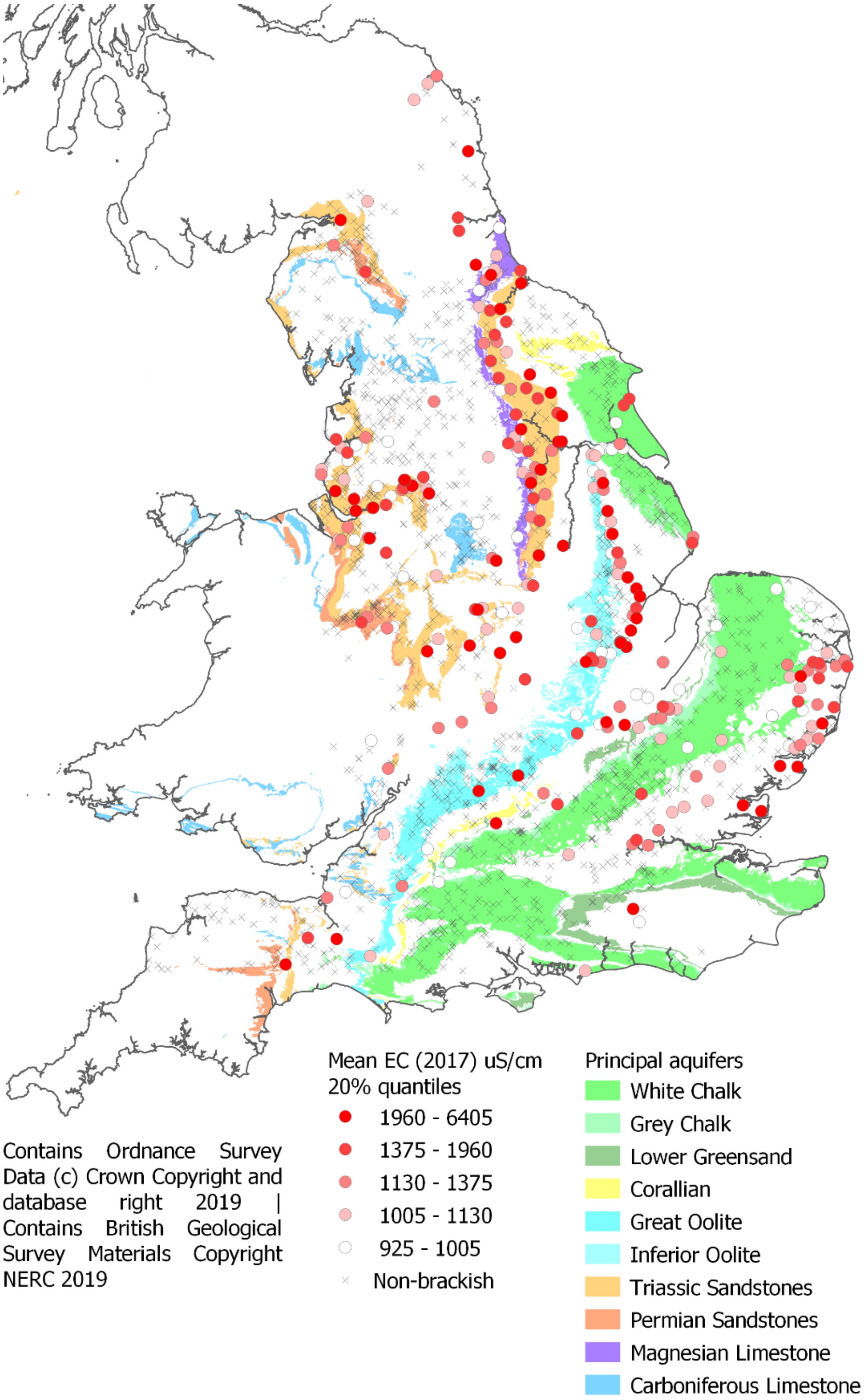


Figure 3.2 Mean conductivity values from all geo-located groundwater samples (excluding landfills) stored in WIMS for 2017

The following observations can be made.

- Brackish groundwaters are widespread across England and occur in all the principal aquifers. The genesis of the brackish waters in particular locations is varied, but is likely to include:

    - saline intrusion around the Mersey Estuary, the Humber Estuary and the Orwell Estuary in particular
    - evaporite (gypsum and/or halite) dissolution in the vicinity of the edge of the Mercia Mudstone
    - higher concentrations down-dip where major aquifers become confined (the Permian Magnesian Limestone, Lincolnshire Limestone, the Chalk beneath Suffolk and London)

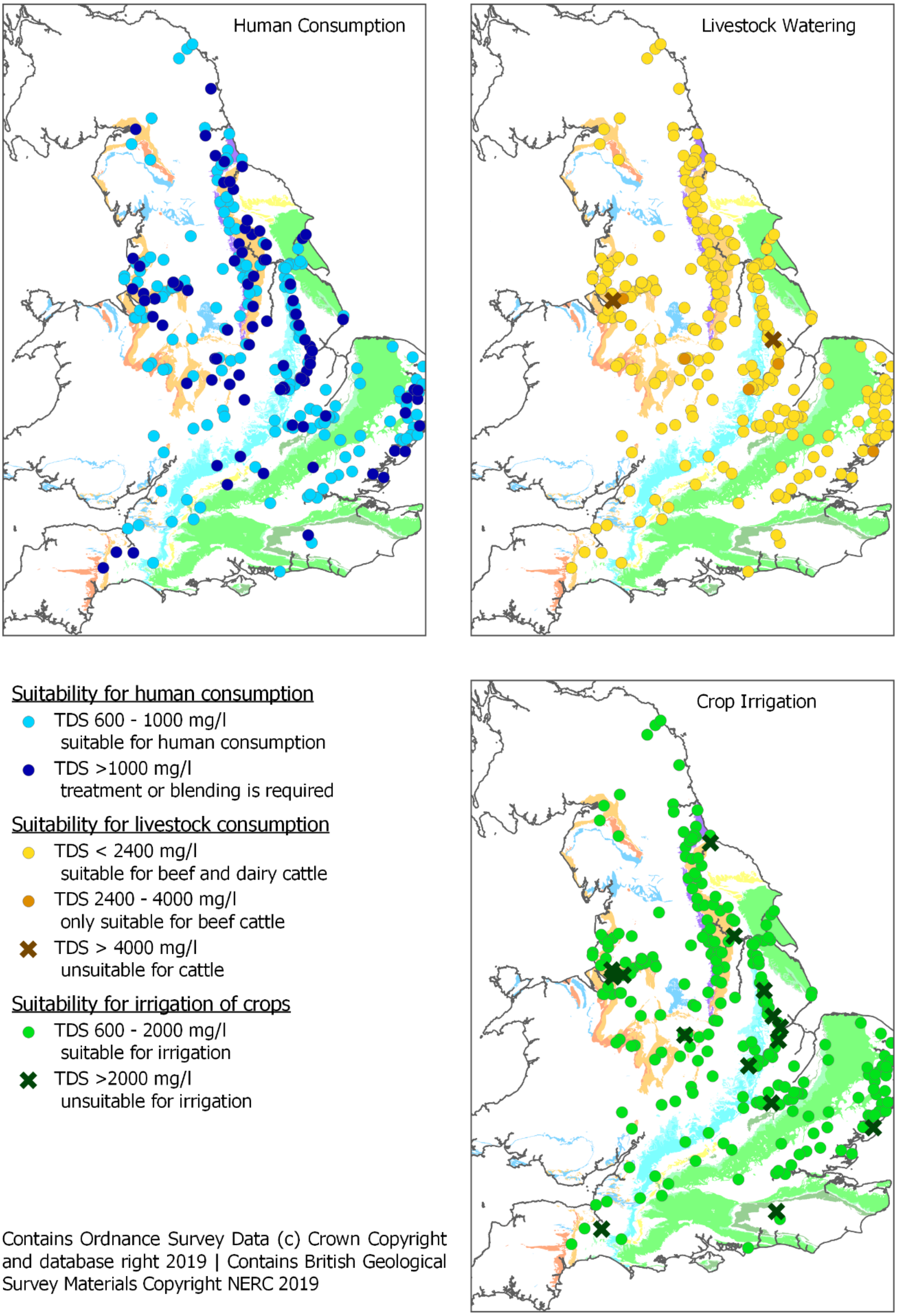
- A higher proportion of boreholes in the north of England seem to have brackish groundwaters relative to those in the south of England. As well as differences in bedrock geology and a legacy of mining, this may also be in relation to widespread cover of confining glacial till in the north (with lower recharge through the till restricting flushing of original saline waters) and/or a more faulted and blocky geological structure, leading to smaller scale flow systems and, again, less flushing.
- In the unconfined aquifers, those locations with brackish water are scattered within areas of dominantly non-brackish waters. The boreholes might have been contaminated with, for example, road salt. This makes it difficult to say with any certainty that certain areas of unconfined aquifer might yield brackish water.

3.4 Mapping usable groundwater

Figure 3.3 shows the water quality data from Section 3.3 plotted against the water quality thresholds for human consumption, livestock watering and crop irrigation identified in Section 3.2. It shows that the potential for direct use of brackish groundwater is widespread, assuming that water is available from these aquifer units. However, Environment Agency monitoring sites are mostly in the near surface aquifers which are currently subject to sustainability assessment.

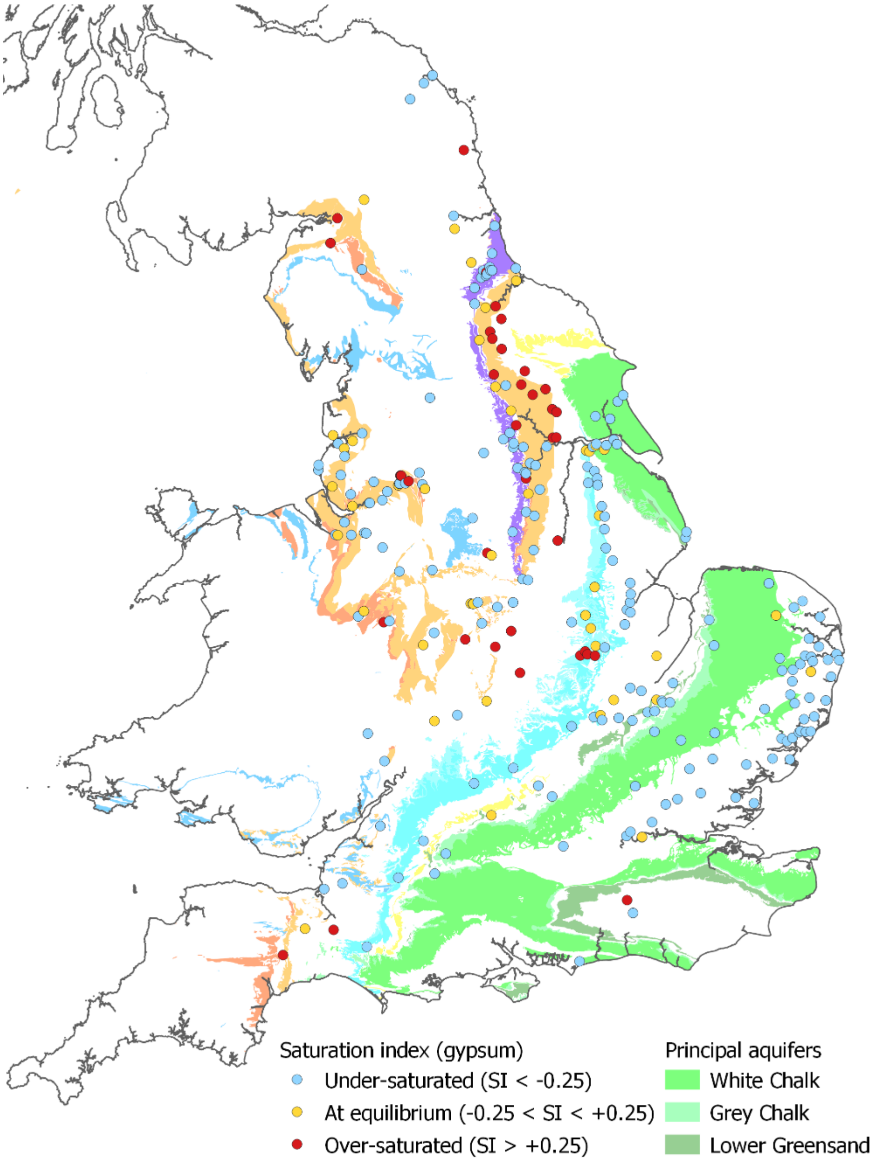
As noted In Section 3.2.2, the feasibility of whether brackish water can be converted to potable water by reverse osmosis depends on water quality parameters other than TDS. As an example, the mean saturation index of gypsum at locations in the WIMS database where there were coincident conductivity, calcium and sulphate measurements, is plotted in Figure 3.4. This shows that there may be some risk of scaling the membranes if, for example, groundwater from the confined zone of the Nottinghamshire–Doncaster Triassic Sandstone aquifer was to be considered for potable use.

The saturation index of barite was considered when creating Figure 3.4, but all samples that had coincident conductivity, barium and sulphate measurements showed oversaturation of barite; the mean saturation index was +3.3. Further analysis of the choice of samples for barium measurement would be helpful before determining that barite scaling is a widespread risk.



Contains Ordnance Survey Data (c) Crown Copyright and database right 2019 | Contains British Geological Survey Materials Copyright NERC 2019

Figure 3.3 Suitability of brackish water for direct uses



Contains Ordnance Survey Data (c) Crown Copyright and database right 2019 | Contains British Geological Survey Materials Copyright NERC 2019

Figure 3.4 **Mean gypsum saturation index for groundwater samples (excluding landfills) for 2017**

Notes: Saturation index was simply calculated using molar concentrations, not activities.

3.5 Framework for economic appraisal of usability

The most important element of this project was to assess whether any particular brackish groundwater is ‘usable’. Usability should also be related to a feasibility assessment and/or a cost–benefit balance.

3.5.1 Value of groundwater

Potable groundwater is valued in the Environment Agency's Groundwater Appraisal Guidance (2018, unpublished): the central value is £0.50 per m^3 except in areas of serious water stress where it is £1.25 per m^3. These 'areas of severe water stress' are defined according to water company boundaries and all are in south-east England. The Groundwater Appraisal Guidance also values water for irrigation of selected crops, for energy production and for ground source heat schemes.

For uses such as hydraulic fracturing, instead of valuing the groundwater against its use as fracking water (which is not quantified) it may be valued as the same as the potable water that is kept in the environment because this is not being used in fracking.

Water that has not been abstracted from the environment may also be valued in terms of its wider environmental benefits. The Environment Agency's National Water Environment Benefit Survey (NWEBS) provides a valuation per km reach for water bodies. Given a particular catchment that the abstraction is operated in, which has a known flow, the NWEBS valuation could be turned into a 'per m^3' value.

3.5.2 Cost of abstraction and treatment

For a brackish water to be 'usable', the cost of abstraction, treatment and disposal needs to balance favourably against the value of the fresh water – for drinking water, and other uses, and/or for the environment.

A considerable number of variables are involved in the calculation and include the following.

- Cost of development of the borehole and headworks. A typical cost for development of a public water supply borehole in the UK is considered to be between £1 million to £2 million per Ml per day. The cost of borehole construction, the pump and headworks will be greater for higher TDS water as corrosion-resistant type 316L stainless steel is approximately 50% more expensive than standard type 304 stainless steel (MEPS International 2019). The threshold TDS above which type 316L stainless steel should be used is 2,000mg per litre (Turnbull 2010).
- The density of brackish water with TDS of 10,000mg per litre is 1.007kg per m^3. Hence the energy requirement for pumping is<1% greater than for fresh water.
- It is important to understand the properties (especially transmissivity) of the aquifer being exploited as they control drawdown in the borehole. Excessive drawdowns in low transmissivity aquifers would increase pumping costs considerably.
- The average cost of desalination by reverse osmosis of brackish groundwater in Jordan (including plant construction), for example, is given as £0.29 per m^3 (Qtaishat et al. 2017). In a global survey, the

WateReuse Association put the range of costs[4] for brackish water desalination at between £0.06 per m^3 and £0.58 per m^3 (WateReuse Association 2012).

- For the sake of simplicity, it is assumed that:
  - any dissolved 'contamination' from the brackish waters (for example, trace metals, natural radioactivity) will not be a concern
  - if these substances are present, they could be either safely disposed of in reverse osmosis concentrate or put back down the oil/gas well

  This would need to be considered on a site-by-site basis with data on in situ water quality.
- In addition to the direct cost of treatment, there is a potential loss of water resource, though for brackish waters the recovery can be 90% compared with only 50% for seawater (the rest becoming concentrate).
- At locations where treatment is required (rather than, say, blending), the power consumption of reverse osmosis plants is high and the location of a treatment plant relative to a power supply is crucial. Likewise the site needs to be close to a means of water distribution and a location for disposal of the reverse osmosis concentrate.
- Disposal of brackish water reverse osmosis concentrate is likely to be acceptable to UK sewerage undertakers and trade effluent disposal costs are published online (see, for example, Southern Water, 2014).

It was originally proposed that, by using a combination of these variables, the annual cost of abstraction might be related to TDS (that is, need for treatment) and transmissivity, or abstraction rate. In this way, the cost might be compared to the value of groundwater (Section 3.5.1). But the following uncertainties mean that any generic estimates will be wildly inaccurate.

- The cost of any installation will be site-specific as it will be strongly correlated with distance to water distribution, power and waste disposal facilities.
- References in the literature tend to cite treatment costs only by comparing brackish water and sea water, but there is no apparent linear relationship between TDS and cost. Qtaishat et al. (2017) attempted to illustrate a cost–TDS relationship for the Jordan Valley but found that there was no correlation. Instead, the cost of a facility – once proximity to infrastructure is taken into account – is mostly related to economies of scale: larger facilities provide cheaper water.
- Given that the distribution of brackish water in England is patchy (on the scale of water company boundaries) and the water distribution network in England is very well-connected, blending brackish water

---

[4] Using a 2019 exchange rate of £1 to $1.30

with fresh water is likely to be the preferred option for potable water supply rather than treatment.

4 Provenance of deep springs

Before the impacts of deep groundwater use can be evaluated, it is important to define deep springs and then understand or visualise the settings in which deep groundwater sourced springs might occur and how their provenance (or origins) may be delineated.

This section begins by setting out the contextual drivers for deep spring study (Section 4.1). It then suggests a definition for deep springs (Section 4.2), illustrates some generic settings (Section 4.3) and provides an outline review of the existing literature delineating the provenance (origins) of English deep springs, exemplified in particular by the much studied Bath spring system (Section 4.4). This review underpins the tiered methodology to delineate deep spring provenance presented in Section 4.5.

4.1 Study drivers

A spring is a natural discharge point of subterranean water (groundwater) at the surface of the ground, or directly into the bed of a stream, lake or sea.

Deep-sourced springs, or ‘deep springs’ contain a proportion of, or possibly solely, groundwater originating from depth. Their occurrence has potentially significant implications for the exploitation of the deep subsurface for shale gas or its use for geological disposal of radioactive waste. Although there can be connections via old boreholes and mine shafts, the occurrence of a deep spring usually infers that natural (possibly rapid) flow pathways connect to the ground surface from depth. Any such connection will heighten the risks of stray methane gas, contaminants from hydraulic fracturing or disposed radionuclide migration derogating the spring and perhaps affecting other receptors at or near the surface.

The most well-known deep springs typically have a significant commercial value as spas or as spring/mineral water supplies. It is therefore important to be able to:

- identify and map the location of deep-sourced springs
- delineate the provenance of deep springs, aiming to establish the origins of the spring water, its age and the spring’s subsurface circulation history

Once the provenance of a deep spring system becomes reasonably proven, suitable protection measures can be implemented to safeguard the spring and other receptors.

4.2 Definition of deep springs

The Environment Agency does not currently have a definition of ‘deep springs’ (or deep-sourced springs). A number of related definitions do exist including, for example, legal definitions relating to bottled spring water and mineral water. Similarly, the recent joint work by the BGS and the Environment Agency –

which was innovative on the international stage – produced a three-dimensional approach to groundwater protection (3DGWV approach) that differentiates between shallow groundwater and groundwater at depths >400m (Loveless et al. 2018).

This report proposes a definition of deep springs that retains consistency with these approaches and identifies springs where there is evidence of a groundwater provenance from depths below 400m. Specifically, the water should be inferred to have travelled through geological formations of a depth >400m at some point between recharge and discharge. This would represent a reasonable first approach to a working definition and may be tested, to some extent, by whether that definition reliably includes the well-documented thermal springs in England that are believed to be deep springs and priority resources to be protected. It is recognised that:

- there should be some latitude in the 400m value
- it should be treated as a nominal approximation in that the flow paths at depth are estimates

4.3 Generic hydrogeological settings of deep springs

This section uses images downloaded from the UK Groundwater Forum website image gallery[5] to help visualise the 3 common hydrogeological settings of deep springs.

- Setting A: thick isotropic aquifers in hilly terrain
- Setting B: dipping confined aquifer with fault pathway to surface
- Setting C: syncline of layered strata in hilly terrain

4.3.1 Setting A: thick isotropic aquifers in hilly terrain

Figure 4.1 shows the simplest hydrogeological setting: a deep relatively isotropic, structurally undeformed aquifer. The locally capping clay need not be present.

Three types of spring are shown in Figure 4.1. On the left of the section, a **spring** is shown discharging relatively recent groundwater at the toe of a slope and junction with underlying clay. There is also an **intermittent spring line** in the centre left of the section discharging under similar localised controls.

On the right of centre, there is a **major perennial discharge area** where recharge from the higher ground has opportunity to discharge more easily where the clay cover is absent. In this example the discharging water is up to decades in age, but in some settings or aquifers, the water could be younger or older.

---

[5] www.groundwateruk.org/Image-Gallery.aspx

An **artesian discharge area** is shown on the right of the section. Here discharge may be diffuse and take place at low rates up through the confining clay, or be localised and rapid if that clay is punctured by a borehole or mine shaft to produce an artificial deep spring. Due to the inhibition in outflow under natural conditions, the section's example suggests the travel time from recharge area to discharge is of the order of centuries or millennia.

Saline groundwater is also shown on the right of the section. In some settings this could be seawater, and in others it could be insufficiently flushed basin or connate water or water that has interacted with evaporite deposits.

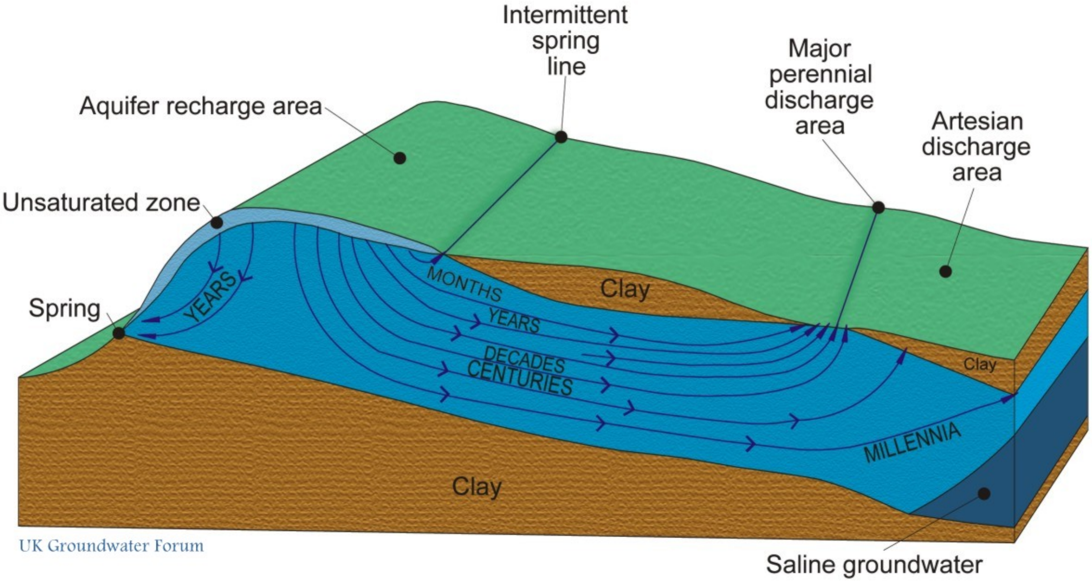


Figure 4.1 Setting A: deep isotropic, structurally undeformed aquifer

Source: Image gwf013 'Age of groundwater' from © UK Groundwater Forum, 2011. All Rights Reserved.

4.3.2 Setting B: dipping confined aquifer with fault pathway to surface

Figure 4.2 shows the next simplest hydrogeological setting: hilly (non-flat) terrain with a dipping aquifer confined by a lower permeability dipping layer to depth, but with a natural pathway to the surface via a permeable fault. In this example, the confining cover is important in preventing discharge of groundwater to the hillslope under natural conditions.

Three types of spring are shown in Figure 4.2. On the left of the section, a **spring** is shown discharging with the topographic/permeability break setting as discussed above for Setting A. On the right of centre, there is an **artesian borehole (flowing)** where recharge from the higher ground has opportunity to discharge via a borehole (or mine shaft) or is limited to slow upward seepage through the confining layer. A **fault line spring** occurs where discharge from depth is via the permeable zone of a geological fault.

Depending on the scale of the hydrogeological system, the topographic relief, the degree of recharge and the hydraulic properties of the aquifer, the water discharging at the fault line spring could be centuries or millennia old. It could be brackish if there has been insufficient flushing.

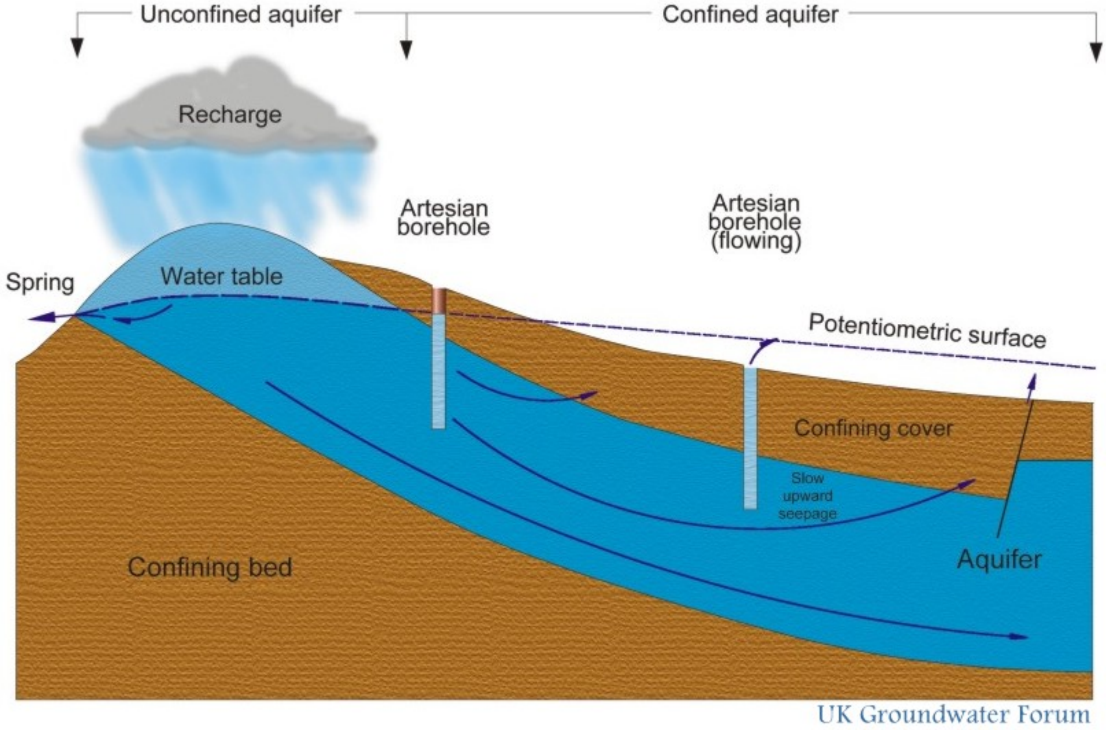


Figure 4.2 Setting B - Dipping Confined Aquifer with Fault Pathway to Surface

Source: Image gwf011 ‘Unconfined and confined aquifers’ from © UK Groundwater Forum, 2011. All Rights Reserved.

4.3.3 Setting C: syncline of layered strata in hilly terrain

Figure 4.3 shows a more complex hydrogeological setting: layered strata in a geological syncline with recharge in the hills finding its way to springs by deep circulation through more permeable strata confined by overlying lower permeability strata. The example shown, a conceptual model for the Bath Springs, also has flow to the surface from the deepest strata enhanced by a fault. This allows deeper warmer waters to reach the surface before they cool.

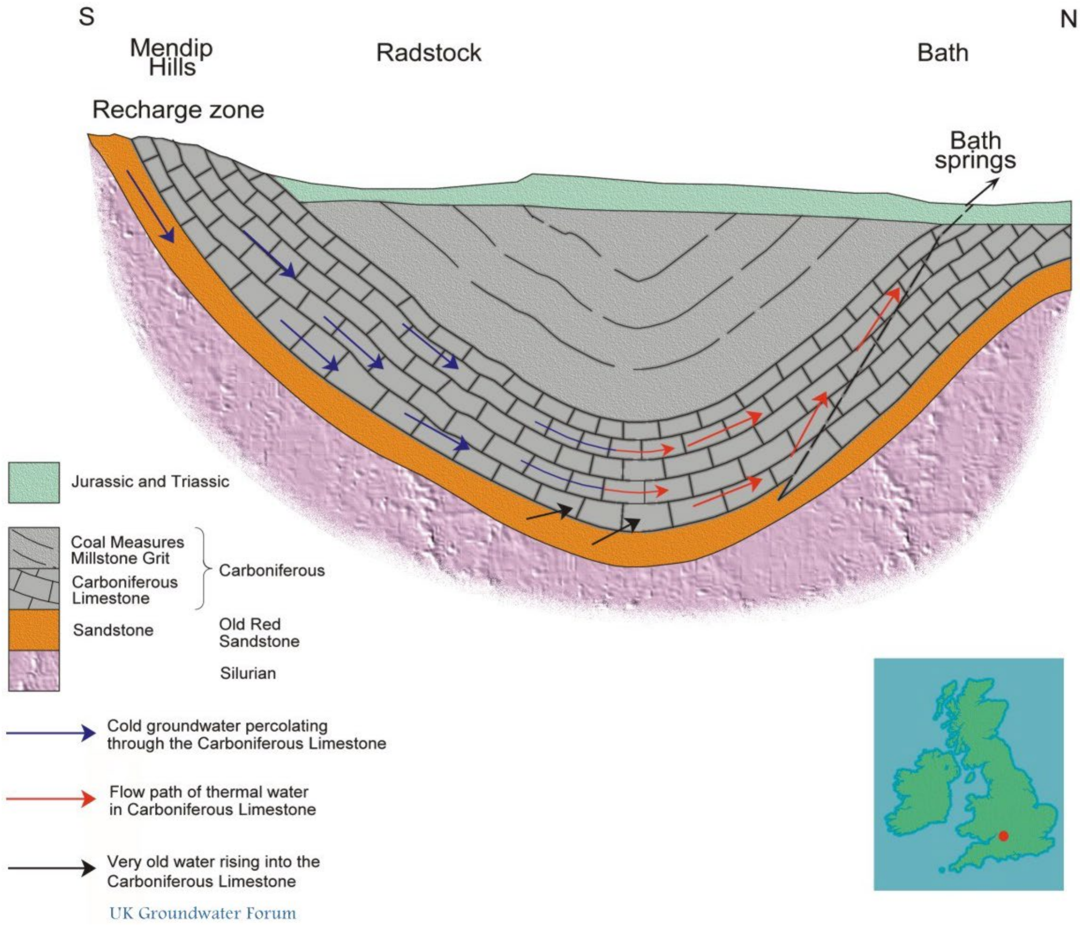


Figure 4.3 Setting C: syncline of layered strata in hilly terrain

Source: Image gwf022 'The origin of the thermal springs at Bath' from © UK Groundwater Forum, 2011. All Rights Reserved.

4.4 Review of deep springs provenance literature

The most well-known deep springs in England are reviewed in outline below with the aim of providing insights on methodologies that have been used to discern deep spring provenance.

Detailed reference is made to studies of the Bath Springs and the range of predominantly geochemical 'forensic' techniques used to assess the provenance of those deep springs. As the most studied deep spring site in the UK, the detail within the Bath Springs exemplar serves to guide methodologies that could be (and in some cases have been) used elsewhere to discern deep spring provenance. Note that the coverage of deep springs in England and the Bath case in this report aims to be illustrative rather than comprehensive.

4.4.1 Overview of English deep springs

Deep-sourced springs in England (and elsewhere) are typically characterised – and primarily identified – by their elevated temperatures (Albu et al. 1997, Barker et al. 2000) relative to shallow groundwater temperatures that are typically around 10–11°C in the UK (Jackson et al. 2013).

According to Gallois (2007):

> ‘There are only five known occurrences of thermal springs in the UK, of which only that at Bath Spa exceeds the 30°C defined by White (1957) as the lowest temperature at which a spring should be called hot’.

This statement is telling and indicative that higher temperature thermal springs are rare in the UK, as is confirmed by Edmunds et al. (1969). Of the 5 occurrences of thermal springs referred to by Gallois (2007), 4 of these well-known sites are in England:

- Bath Springs – comprising 3 spring sites that are the UK’s hottest at around 47°C
- Hotwells Spring in Bristol at 24°C
- Derbyshire Peak District springs:
    - St Anne’s Well, Buxton at 28°C
    - Matlock Spa (2 sites) at 20°C

The fifth thermal spring is Taff's Well at Cardiff in Wales.

These sites are extremely important commercially either as spa towns founded in the 19th century on the reputed health benefits (Banks1997, Robins and Smedley 2013) and/or their bottled mineral/spring water industry (Smedley 2010).

All of these thermal springs are sourced from the Carboniferous Limestone within broadly comparable geological structure settings; see Figures 4.3 and 4.4 for examples. These permit meteoric water to descend to sufficient depth for it to be heated by the geothermal gradient and return to the surface without a significant fall in temperature, thereby generating a deep-sourced geothermal spring. Similar mechanisms account for thermal springs in sedimentary basins across the world (Gallois 2007, Goldscheider et al. 2010).

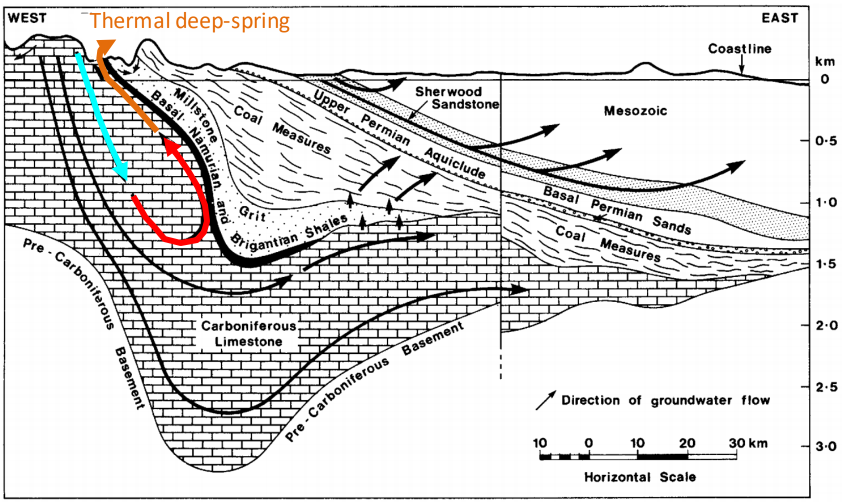


Figure 4.4 Schematic cross-section through the East Midlands highlighting the conceptualisation of thermal deep spring discharge occurring from the Derbyshire Carboniferous Limestone in the west

Notes: Modified from Downing et al. (1987)

Although spring temperatures above 20°C allow ready identification of thermal springs from depth, marginal to somewhat increased temperatures over ambient in the approximately >11°C to 20°C range may still be significant and evidence of some deep spring provenance. Temperatures in such springs (much below their maximum achieved at depth) may arise from a combination of slow upward flow, contorted pathways and dilution by shallow system, low temperature groundwater. Extending the definition of thermal springs to include these slightly elevated temperatures gives a total of 10 identified springs in Derbyshire, including the 3 springs at Buxton and Matlock noted above). The additional 7 springs, spanning a temperature range of 11.5–17.7°C, occur around the periphery of the Peak District Carboniferous Limestone (Edmunds 1971, Brassington 2007). Notably, 5 of these Derbyshire springs, at 11.5–13.3°C, are only marginally above shallow groundwater background temperatures. For further details on the Buxton–Derbyshire system and its provenance assessment research, see Stephens (1929), Edmunds et al. (1969), Edmunds (1971), Gunn et al. (2006), Brassington (2007), Bottrell et al. (2008) and the summary within the international review by Goldscheider et al. (2010). Conceptualisation of the spring system is illustrated in Figure 4.4.

Some of the suspected deep-sourced saline springs in the Lake District in west Cumbria (their salinity suggesting deep sources) can sometimes display quite modest temperatures (11.6–14.2°C), again requiring the corroborative use of hydrogeological and hydrochemical lines of evidence (Cooper 2011, Younger et al. 2015).

The challenge in such cases in Cumbria, Derbyshire and elsewhere is to be able to recognise the deep-sourced spring provenance contribution where the deep source temperature and geochemical water signature has become ‘diluted down’ at the point of spring emergence. To be able to recognise groundwater pathways from depth, it is critical to be able to forensically assess springs where the geothermal/deep signature has become low and any deep provenance less apparent. Unique water quality and temperature stability in some deep spring discharges may offer critical support to dependent ecosystems.

Deep springs that were historically present may sometimes no longer exist, but this does not negate groundwater pathways from depth to shallow systems remaining, nor the return of former spring flows following changes in environmental conditions and anthropogenic influence.

The historical disappearance of several surface brine springs in England’s north-east Coalfield documented by Anderson (1945) is attributed to the progressive dewatering and fracturing of the Coal Measures during 3 centuries of deep mining (Banks et al. 1996, Younger et al. 2015). Permeability induced by mining permitted greater infiltration and circulation of meteoric water, causing brines to reside at depth, or become diluted upon any upward migration.

Saline, deep-sourced springs appear to be no longer present in the north-east. However, it is instructive how Younger et al. (2015) compared the nature of salinity found in the deep springs of north-west Cumbria and the deep borehole data at Sellafield (Bath et al. 2006) to evaluate related groundwater provenances. Comparisons of the major ions and stable isotopes (δ^2H, δ^{18}O and δ^{34}S) of these saline groundwaters allowed their differentiation from offshore oilfield formation waters and brines within the former subsea workings of coastal collieries.

4.4.2 Bath Springs: delineation of provenance

The City of Bath Springs represent Britain's hottest thermal springs at around 47°C and host a spa facility dating back to Roman times, with evidence of human occupation through the Iron Age and Mesolithic periods to about 7,000 years BP (Kellaway 1994).

The occurrence and conceptualisation of the Bath spring system are shown in Figure 4.5. The system is dominated by the Bath/Bristol district complex synclinal structure, formed between 3 intersecting fold axes (Andrews et al. 1982). The Carboniferous Limestone is the most important aquifer, contributing the main flow of thermal water. The King's Spring, surrounded by a Roman reservoir, emerges through Lower Lias shales and accounts for the main flow with a sizeable discharge at around 13 litres per second, with 2 smaller springs nearby that display similar water quality (Andrews et al. 1982). The temperature of the King's Spring of 46.5°C has been constant (within ±0.5°C) since 1754 and represents a thermal yield of 2MW (above a non-thermal groundwater temperature of 10°C) (Andrews et al. 1982).

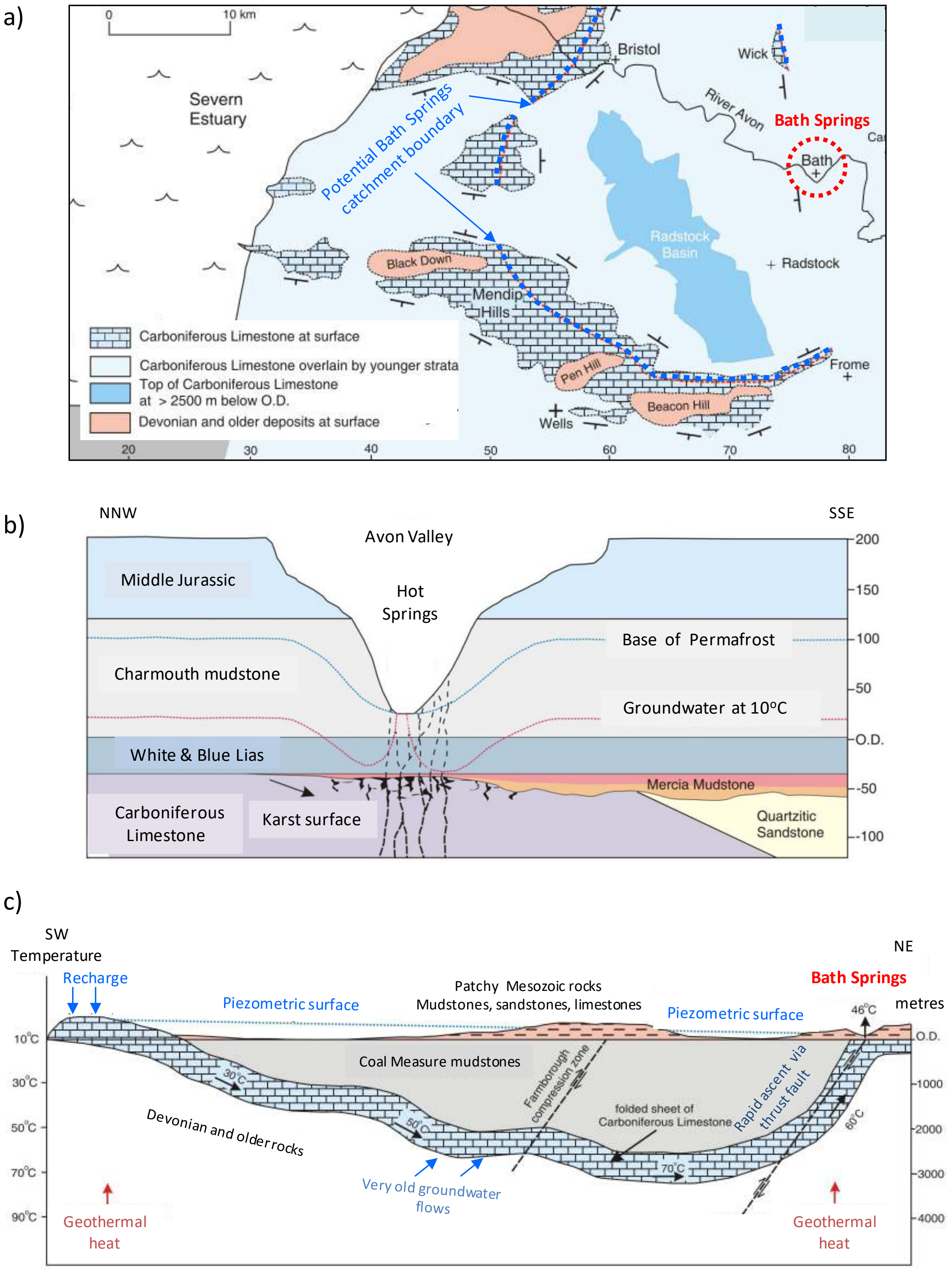


Figure 4.5 The City of Bath spring system and its conceptualisation

Notes: After Gallois (2007) and previously based on Andrews et al. (1982) and Kellaway and Welch (1998)

Scientific investigations date back some 200 years. Work developing the geological conceptualisation by William Smith occurred between 1799 and 1813 (Kellaway 1991a) and hydrochemical analyses on spring waters being conducted since 1823. Speculation about spring origins dates back even further, with Glanvill (1669) being the earliest publication on provenance

(Edmunds et al. 2014). Table 4.1 lists, in chronological order, important examples of more recent research.

Table 4.1 Key recent research on the Bath spring system

Reference	Topic
Burgess et al. (1980)	Hydrogeology and hydrochemistry of the wider Bath–Bristol Basin
Andrews et al. (1982)	Pivotal study using geochemical techniques to deduce the circulation history of the geothermal waters
Andrews (1991)	Radioactivity and dissolved gas tracers
Edmunds and Miles (1991)	Geochemistry
Kellaway (1991b)	Bath City Council report on 'The Hot Springs of Bath: Investigations of the Thermal Waters of the Avon Valley', which draws together a wide range of system understanding
Kellaway (1994)	Geological conceptualisation and environmental protection of the springs
McCann et al. (2002)	Geophysical assessment
Edmunds (2004)	Review of the 400-year history of hydrogeological and geochemical investigation
Gallois (2006, 2007)	Review of geological formation of the spring system
McCann et al. (2013)	Provides geophysical seismic reflection data to evidence the deep pathway
Edmunds et al. (2014)	Use of noble gas, chlorofluorocarbon (CFC) and other geochemical evidence to further constrain the age and provenance of the thermal waters

Much of the finer tuning of provenance detail, system circulation history and resolution of groundwater ages in the Bath system (and indeed studied springs globally) has been achieved through the use of geochemical techniques. The fine tuning also recognises the substantial contributions from geological, geophysical and hydrogeological investigations that help to increase understanding, particularly of the deep spring geological framework and possible flow regimes. With the development of analytical instruments and science, these techniques have continued to advance and offer greater insight. The papers of Andrews et al. (1982) published in *Nature* and more recently Edmunds et al. (2014) in *Applied Geochemistry* are leading papers of their time, each using cutting edge geochemical techniques to constrain the provenance of the Bath Springs including their circulation history, temperature at depth and groundwater age profile. Box 4.1 highlights aspects of the approach adopted by Andrews et al. (1982) that may continue to inform modern-day assessments.

Box 4.1: Geochemical characterisation methods used by Andrews et al. (1982)

Inorganic major ion (and trace element) hydrochemistry demonstrated a stable chemical composition of thermal water. Geochemical modelling showed it to be in equilibrium with calcite, dolomite, gypsum, fluorite and barite minerals. Regional aquifer sampling revealed no other groundwaters with comparable composition to the Bath thermal spring water other than the Triassic aquifer. It was observed the nearby Bristol Hotwells spring had a composition equivalent to a 1 to 2.3 ratio of Bath-type thermal water to Carboniferous Limestone water.

Dissolved radio-elements (isotopes). For example, Bath thermal water was distinguished from other groundwaters by a very low uranium content, but an elevated ^{234}U to ^{238}U activity ratio (a ratio found in the Old Red Sandstone). Elevated radioactivity in the spring was ascribed to ^{222}Rn, with the increasing concentrations observed ascribed to delayed recovery of groundwater levels following the 1976 drought event. ^{222}Rn to ^{220}Rn activities, the uranium to thorium ratio, and uranium geochemistry pointed to uranium deposition in the flow system.

Exsolved gas composition and dissolved noble gas tracer content were used to propose the exsolved gas composition. This composition was explained by the exsolution of atmospheric gases dissolved at recharge, modified by the geochemical reaction of oxygen in the aquifer, by the addition of radiogenic ^{4}He due to radioelement decay and by the addition of hydrocarbon gases. Dissolved inert gases suggested a recharge temperature around 9°C.

Stable isotope δ^{2}H/δ^{18}O data were used to demonstrate that the thermal water was of meteoric origin with a ratio comparable to modern shallow groundwater in the region (and distinct from late Pleistocene groundwaters). Combined with the inert gas data, climatic conditions at recharge were indicated to be similar to present day.

Drawing on hydrogeological head data (historical and modern), the primary recharge area – the Mendip Hills on the basin margin about 15km south-west – was identified. This basis for this was that it was the only area with sufficient head to exceed the heads measured in a borehole sampling of thermal water in 1836 at 10m above the spring elevation and hence drive flows.

A **geothermometer approach** (see Box 4.2

The lines of geochemical evidence in Box 4.1, combined with the geological and hydrogeological understanding of the time, enabled Andrews et al. (1982) to provide the conceptualisation of the provenance of the Bath Springs depicted in Figure 4.5 with reasonable quantification, albeit with some uncertainties that workers since have sought to address. The geochemical evidence appears consistent with and, indeed, reinforces the inference of hydraulic controls anticipated on the system. Provisional, Darcy's Law estimates of flows over the approximately 15km Mendip–Bath travel distance gave travel times of 4,000 years. At Bath, thermal water under pressure was projected to rise relatively rapidly, via a southerly dipping east–west thrust fault in the vicinity, recharging a low storage Triassic sequence, probably by way of the Palaeozoic unconformity, with consequent discharge at the springs.

) was used to estimate maximum temperatures (and hence circulation depths) based on a silica geothermometer. Maximum rock equilibration temperatures of 64°C (for chalcedony control) and 96°C (for quartz control) were calculated; the maximum temperature reached at depth was perceived to lie within this range. Similar geothermometer calculations inferred that the thermal component of the Hotwells Bristol source was equilibrated at depth in the range 49°C to 72°C, before mixing with shallow Carboniferous Limestone groundwater and lowering of the spring discharge temperature to 24°C.

Circulation depth estimates were made from the geothermometer maximum temperatures and regional geothermal gradients assumed of 26°C per km* to give circulation depths of the Bath thermal water at 2,700–4,300m to attain a temperature of between 64°C and 96°C; such depths implied the Carboniferous Limestone and/or the Old Red Sandstone to be the principal storage aquifer(s).

Stable isotope $\delta^{13}C$ data, specifically the slightly negative $\delta^{13}C$ of the dissolved bicarbonate, provided the evidence that the thermal water had equilibrated chemically with the marine Carboniferous Limestone rather than with the largely non-marine Old Red Sandstone. The conclusion was that most recent storage was in the former, though a proportion of the thermal water may previously have been transmitted in the latter.

Thermal water age evidential data included trace tritium and nitrate contents, and variations in dissolved oxygen, Eh and $^{234}U/^{238}U$ activity ratio. They suggested some limited mixing of the thermal water with very small quantities of ‘recent’ waters from shallow aquifers. Age dating based on the ^{14}C activity in the water was not conclusive as assumptions were poorly constrained. It was concluded from the observed ^{4}He content (from uranium and thorium decay) that at least a proportion of the thermal water must be much older than 10,000 years and may be derived from long residence in the Old Red Sandstone. The bulk of the thermal water was thought, albeit not conclusively proven, to be <10,000 years.

* Bath is in an area of low heat flow (Downing and Gray 1986, Edmunds et al. 2014). Its geothermal gradient compares to a UK average of around 30°C per km.

Box 4.2: Solute geothermometers

Solute geothermometers are an important geochemical methodology. They are used to derive the maximum temperature that a groundwater has been exposed to in its travel path based on the sampled geochemical composition. Temperature estimates made from spring water sample compositions can then be used to provide an estimate of the maximum circulation depth reached in the subsurface, the hottest point. Geothermometers relate to specific mineral-solute reactions as the hot equilibrium temperature is ‘stored’ in the fluid and reflects the chemical signature of solute concentration.

Silica (SiO_2) solubility and cation exchange geothermometers (for example, Na/K, Na-K-Mg, Na-K-Ca and K/Mg) are some of the most widely used solute geothermometers applied to hydrothermal fluids (Wishart 2015). Geothermometer use was pioneered by Arnorsson (1975) and Reed and Spycher (1984). It was further developed and used, for example, by Powell and Cumming (2010) and Wishart (2015).

Geothermometers have been used in the deep spring UK context, for example by Andrews et al. (1982), Edmunds and Miles (1991), Edmunds et al. (2014) and Younger et al. (2015). However, many assumptions are involved with geothermometers being most reliable in high temperature geothermal systems. Edmunds et al. (2014) noted that, for the Bath spring system, only silica is likely to be applicable.

The lines of geochemical evidence in Box 4.1, combined with the geological and hydrogeological understanding of the time, enabled Andrews et al. (1982) to provide the conceptualisation of the provenance of the Bath Springs depicted in Figure 4.5 with reasonable quantification, albeit with some uncertainties that workers since have sought to address. The geochemical evidence appears consistent with and, indeed, reinforces the inference of hydraulic controls anticipated on the system. Provisional, Darcy’s Law estimates of flows over the approximately 15km Mendip–Bath travel distance gave travel times of 4,000 years. At Bath, thermal water under pressure was projected to rise relatively rapidly, via a southerly dipping east–west thrust fault in the vicinity, recharging a low storage Triassic sequence, probably by way of the Palaeozoic unconformity, with consequent discharge at the springs.

Although the techniques described in Box 4.1 are still not routine in many water resource assessments, they were available and used by Andrews et al. (1982) around 40 years ago to significant effect. The more recent work of Edmunds et al. (2014), continuing Edmunds’ work originally published in Andrews et al. (1982), reinforces much of the earlier findings while adding to them using more modern techniques. Quoting directly from Edmunds et al. (2014), their analysis of water, solutes, isotopes and dissolved gases undertaken in 2000 ‘provides the most comprehensive interpretation to date of the origins, age and circulation history of the Bath thermal springs’. The analysis consisted of:

> ‘Standard analytical methods were used, augmented by more specialised techniques where necessary: hydrochemistry by OES (optical emission spectrometry) and IC (ion chromatography), stable isotopes by IRMS (isotope ratio mass spectrometry), ^{14}C by AMS (accelerator mass spectrometry), noble gases by QMS (quadrupole mass spectrometry),

> ^{3}H/^{3}He by MS, and ^{37}Ar, ^{39}Ar and ^{85}Kr by decay counting. Analyses were carried out by laboratories at BGS Wallingford and Keyworth (chemistry, stable isotopes, reactive gases), ETH Zurich (noble gases), University of Bern (^{37}Ar, ^{39}Ar and ^{85}Kr), NERC Radiocarbon Laboratory (East Kilbride) and University of Arizona (^{14}C), and Spurenstofflabor, Wachenheim (CFCs).'

The statement 'augmented by more specialised techniques' is perhaps understated and should be recognised as significant as it drew on work by 7 laboratories of which 4 were outside the UK. Almost 20 years on, many of the techniques would today still be regarded as specialised, though now more readily available within the UK, albeit in research/university settings rather than commercial laboratories. The Bath study suggests that the forensic power of these geochemical techniques is likely to be vital to elucidation of provenance at deep spring sites elsewhere.

Some highlights of the modern provenance assessment tools used by Edmunds et al. (2014) and the key findings for the Bath system include the techniques summarised in Box 4.3. The studies of Andrews et al. (1982) and Edmunds et al. (2014) bracket the modern era of investigation, although are recognised to be a focused subset of the wider work on the Bath system. They nevertheless illustrate the nature of detailed geochemical-based forensic assessment that is possible and are appear to be consistent with, and reinforce, the geological and hydrogeological conceptualisation of the system.

Box 4.3: Modern groundwater provenance assessment tools (Edmunds et al. 2014)

^{39}Ar noble gas data conclusively demonstrated that the bulk of the thermal water has been in circulation within the Carboniferous Limestone for more than 1,000 years.

Other isotopic and noble gas measurements confirmed earlier findings and strongly suggested recharge within the Holocene period, that is, the last 12,000 years.

Dissolved ^{85}Kr and CFCs are extremely sensitive indicators of the presence of 'modern' (up to 60 year-old) waters and have helped to further constrain previous tritium indications that a small proportion of the thermal water originates as late stage leakage into the spring pipe passing through Mesozoic valley fill underlying Bath (the latter has become apparent since the work by Andrews et al. 1982). This accounts for small amounts of oxygen introduced into the system and consequent iron precipitation in the King's Spring. This cold water is modern and contributes <5% to the total discharge.

Developed use of silica geothermometry has helped to more confidently constrain the maximum temperatures reached of between 69°C and 99°C (probably nearer the lower figure), suggesting a most likely maximum circulation depth of 3km.

The rise of the water to the surface is sufficiently indirect that a temperature loss of >20°C is incurred.

The overwhelming evidence is that the water has evolved within the Carboniferous Limestone, but the chemistry alone fails to pinpoint the

geometry of the recharge area or circulation pathway, that is, other lines of evidence are required such as hydrogeological.
For a likely residence time of 1,000–12,000 years, volumetric calculations imply a large storage volume and circulation pathway (based on expected limestone porosities at depth); the important corollary arising is that much of the Bath–Bristol basin must be involved in the water storage. It is interesting to note that, although this value accords with the earlier estimates of Andrews et al. (1982), hydraulic considerations assuming low reservoir matrix porosity and fracture flow indicate residence times in the range 10–100 years could be feasible (Andrews 1991). The geochemical evidence, however, points to longer timescales.

4.4.3 Learning outcomes

The mapping of deep spring provenance is clearly a complex and demanding process. Recommendations arising from the literature relevant to the development of deep spring provenance mapping methodologies can be summarised as follows.

- Provenance mapping should adopt a ‘lines of evidence, approach, integrating geological, hydrogeological and geochemical evidence to a mutually consistent, but evolving, system conceptual model.
- The entire circulation from the recharge area, through the subsurface transmission pathway, to the depth and subsequent (rapid) rise to ground surface and spring discharge needs to be understood as a whole.
- Although the basic hydrogeological conceptualisation may sometimes be construed as simple if a single aquifer unit forms the main conduit of spring flow, the likely influence of neighbouring units should be recognised and quantified.
- The determination of spring provenance (origins, age and circulation history) should be informed by a geochemical forensic approach that includes high-end specialised techniques such as stable/reactive isotopes.
- It should be recognised that, while (hydro)geological data can be sparse at depth or remote from springs, they should be adequate to constrain recharge areas, pathways, ages, modern water source contributions and connectivity to depth.
- Spring protection should recognise:
  - recharge areas, perhaps remote
  - near spring discharge areas, vulnerable to local land use and shallow groundwater influence
  - deep pathway segments at risk from deep subsurface use

- The effort required to determine deep spring provenance is significant and demands advanced technical inputs. It is therefore recommended that efforts should be prioritised within a tiered approach. It is possible, however, that the cost of providing a sufficiently confident understanding of a deep spring provenance may be prohibitive for some proposed developments.

A methodology to map deep spring provenance, although implicit within the progressive assemblage of studies of the Bath Springs considered here, is not formally set out within the UK research or guidance literature per se.

4.5 Methodology for mapping deep spring provenance

4.5.1 Overview

The proposed methodology recommended for deep spring provenance mapping is set out in Figure 4.6. It is a tiered framework consisting of:

- **Tier 1** – Screening for deep spring occurrence
- **Tier 2** – Conceptualisation and mapping of deep spring provenance: the heart of the mapping methodology
- **Tier 3** – Implementation of deep spring protection measures: the practical outworking of the mapped provenance and implementation of deep spring protection measures

Tiers 1 and 2 are outlined below. Tier 3 is described briefly below and in more detail in Section 5, which focuses on protection.

When implemented, it is recommended that the tiered methodology should incorporate:

- decision points to permit prioritisation of effort such as:
  - the significance of the spring as a water supply or spa, or if it has hydroecological sensitivity, or significant flow rates
  - the proximity or possible vulnerability to deep oil/gas resource unit exploitation
  - the availability of supporting data and existing published/grey literature

an indication of the confidence in the deep spring provenance that has been estimated and identification of outstanding information necessary to reduce key uncertainties (which may potentially be taken forward for consideration by others, for example, within the establishment of environmental baseline conditions by a shale gas prospector).

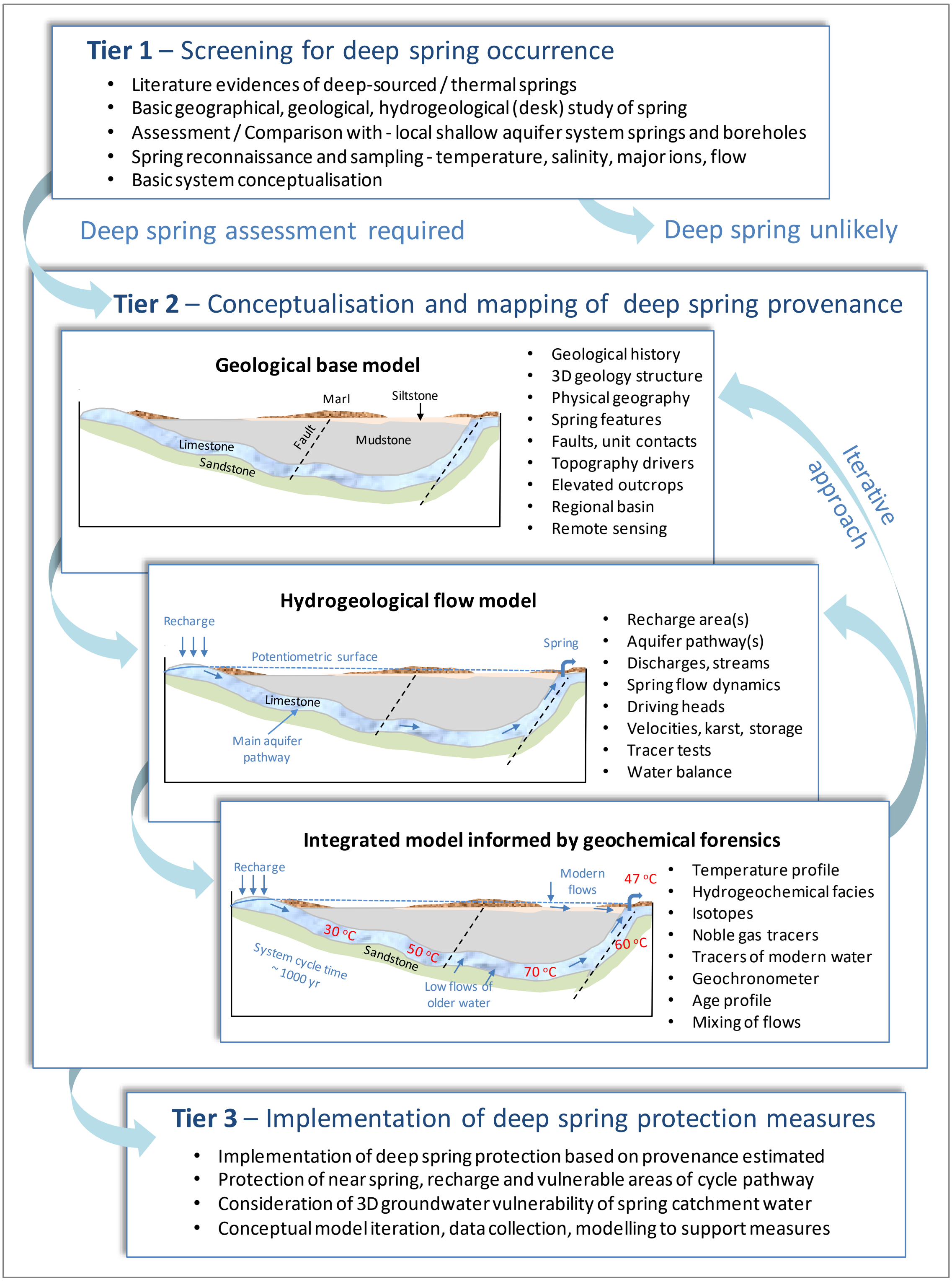


Figure 4.6 Proposed methodology for deep spring provenance mapping

Notes: Based around a typical Bath Springs conceptualisation sketch.

4.5.2 Tier 1: screening for deep spring occurrence

Tier 1 consists of a baseline, reasonably low cost, desk study and then reconnaissance visit sampling if the desk study provides robust support for the presence of a deep source spring. There should also be consultation with the

Environment Agency, the local Environmental Health Officer and the landowner about the spring's use as a licensed or private water supply.

The intent of Tier 1 is primarily to address whether other deep-sourced springs may exist in England in addition to the well-documented and known springs, and hence to evaluate the potential occurrence of 'unknown' or perhaps tentatively suspected deep springs. The latter may include, for instance, a spring known to be of higher salinity than is typically encountered in an area, which could be ascribed to it being a deep spring, among other possibilities such as a nearby pollution source. The intent is to provide a 'light touch' version of a more detailed Tier 2 assessment of deep spring provenance.

Tier 1 may include (Figure 4.6):

- literature evidence of deep-sourced/thermal springs
- a basic geographical, geological, hydrogeological (desk) study of the spring
- assessment/comparison with local shallow aquifer system springs and boreholes
- spring reconnaissance and sampling of temperature, salinity, major ions, flow
- basic system conceptualisation

Expanding on these Tier 1 aspects, an initial desk study is encouraged as this may identify literature (including archive data) on spring flows and spring water quality at the particular spring(s) in question and any surrounding springs. The desk study should include historical records or maps where perhaps former spring flows existed, but are now no longer apparent, and may add corroborative evidence.

Overall, significant data limitations are anticipated and judgements are likely to be made on the basis of sparse data availability. Nevertheless, topography, surface water occurrence, geological and, to varying extents, hydrogeological data are typically available. These data are often sufficient to build a basic system conceptualisation of the spring system, the aim being to align with the various spring conceptualisation types presented earlier.

Where the desk study offers some indication of a deep spring provenance, a site visit(s) is recommended and some reconnaissance sampling conducted to evaluate temperature, salinity, major ion composition and flows (for example, a predominant deep spring flow should not be markedly seasonal). The aim is for basic geochemical forensics to establish if these data endorse a deep spring's potential provenance.

The overall goal of Tier 1 is either to 'screen in' the site for a more detailed Tier 2 assessment, or to 'screen out' for no further study (Figure 4.6). Work at Tier 1 should provide the answers to the following questions.

- Can a recharge area can be envisaged with sufficient elevation (and hence head) to drive a deep spring system flow?

- Can the presence of the spring be reasonably accounted for by flows from a shallow aquifer flow regime, or does the structural geological data in particular add credence to the possibility of a deep spring system?

Exploring the potential for identification of unknown springs at a more regional, even national scale could entail the development of a methodology of mapping the spatial factors that contribute to deep source spring provenance on a national scale. This should take into account three-dimensional (3D) factors rather than simple two-dimensional (2D) mapping. It is envisaged, for instance, that use could be made of the BGS open data for the top of principal aquifers, intersected with topographic low points to identify candidate discharge points. The methodology could be verified by ensuring that it would identify many of the previously known springs. It would need to be established if such a spatial modelling approach, or similar, would be feasible given the complexity of England’s 3D geology (including superficial deposits cover) and the limitations of mapping.

The Tier 1 screening approach should hence aim to provide a foundational system conceptual model suitable for subsequent Tier 2 detailed assessment. It should be noted, however, that a fairly basic Tier 1 assessment may not be able to offer the detail of assessment (for example, geochemical forensics power) to fully resolve if there may be some spring components of flow from depth that are masked by the dilution of shallow system flows. Even more difficult to resolve would be deep contributions to shallow groundwater, but without spring discharge at ground surface. For example, thermal saline water may migrate up a fault-related pathway from depth and influence shallow system groundwater quality in any monitoring wells or boreholes present without manifestation at a spring. In the latter case, depth profile sampling of the groundwater (for example, via multilevel samplers) is likely to be required.

4.5.3 Tier 2: conceptualisation and mapping of deep spring provenance

Tier 2 represents the heart of the mapping methodology which aims to reliably establish spring provenance using a lines of evidence approach. An approach is proposed that builds and iterates a quantified, process-based conceptual model of the deep spring system. It consists of a geological base model that is developed to give a hydrogeological model, which in turn is developed to give an integrated conceptual model informed by geochemical forensics (Figure 4.6).

Tier 2 is designed to develop in detail the basic system conceptualisation of Tier 1. Effort and spend should be proportionate to the significance of the deep spring and its local context (for instance, the development of a shale gas resource nearby that may conceivably pose a risk to the spring and lend more significance to the assessment).

The Tier 2 assessment detail indicated below and in Figure 4.6 is not intended to be prescriptive, but rather a framework offering ideas for assessment. It may emerge during the course of a Tier 2 assessment and detailed lines of evidence that the spring is in fact not a deep spring. This may result in the assessment no longer being taken forward from that perspective (that is, the spring is screened out).

The components of Tier 2 are considered briefly below; the detail of some aspects is given above, notably in the Bath Springs case. As shown in Figure 4.6, development of the Tier 2 geological model should involve:

- geological history
- 3D geology structure
- physical geography
- spring features
- faulting and unit contacts
- topography drivers
- elevated outcrops
- regional basin structure
- remote sensing and/or geophysics

Exploring the detail of these aspects is beyond the scope of this report. However, it is emphasised that the geological model should not be seen to be static but as evolving in response to new datasets, emerging techniques (for example, geophysical) and the resolution of uncertainties. A well-researched geological model is prerequisite to effective hydrogeological conceptualisation of any subsurface system (Brassington and Younger 2010).

Approaches to the iterative development of hydrogeological conceptual models, recognising the need to consider alternative conceptual scenarios and uncertainties, were recently reviewed by Enemark et al. (2019). This review refers to a range of possible frameworks under which hydrogeological conceptual models may be developed, including those Brassington and Younger (2010) exemplified in the UK context.

Expanding on the Figure 4.6 bullet points, development of the Tier 2 hydrogeological flow model could involve:

- Recharge area(s) – including confirmation that potential recharge areas are at sufficient elevation and area to support spring flow rates.
- Aquifer pathway(s) – confirmation of the principal and possibly more minor aquifer pathways contributing to spring flows. The more minor flow contributions may be confirmed by geochemical forensics data.
- Discharges and streams – confirmation of discharge to springs and possibly baseflows to streams downstream arising from deep flows.
- Spring flow dynamics – monitoring and understanding of spring flow time-series data, recognising that if predominantly deep-sourced there may be little seasonal influence. Note that some shallower flow system seasonal contributions to a spring may mask the constancy expected and need resolution of both components.

- Driving heads – hydraulic head gradients between the recharge area and springs need to be sufficient to drive flows. This could necessitate the installation of monitoring (boreholes) in the recharge, pathway and discharge areas if existing monitoring is sparse at important sites.
- Velocities, karst and storage. Constraining groundwater system velocities can be surprisingly difficult, with significant variation possible in for instance the Carboniferous Limestones (accounting for all of the UK's main thermal springs), depending on whether flow at depth in particular is via high velocity in karst conditions (fissure and so on), or a much slower velocity (order(s) of magnitude lower) from porous matrix/minor fracture/fissures flow.
- Tracer tests. Related to the above velocity issues, tracer test injections have been widely used to confirm flow velocities in karst aquifer, particularly shallower (<400m depth) systems where travel times monitored are days or weeks to possibly months and even perhaps a year or so. In deeper systems, tracer tests would only offer value if timeframes were similar and to prove fast pathway connectivity or behaviour in shallow recharge area. They would not offer insight to decade/century/millennia deep spring cycle timescales where natural system environmental geochemical tracers need to be relied on.
- Water balance. The hydrogeological flow model (and any numerical flow model built) needs to have a reasonable water balance with flows at the spring and through sensible geological units.

Building a hydrogeological conceptual model of the deep subsurface is far from trivial. Hydrogeological data for even the relatively well-studied deep spring systems such as Bath and Buxton can still be sparse and expert interpretations of these systems vary despite the effort invested. Cognisance hence needs to be taken, and appraisal made of, the uncertainties in any hydrogeological conceptualisation offered (Enemark et al. 2019) and the associated risks in any decision-making arising from these uncertainties.

Recognising such uncertainties, determination of spring provenance (origins, age and circulation history) should be additionally informed by a geochemical forensic approach. The inclusion of more high-end specialised techniques potentially offers significant improvement in the prospects of resolving complexities of a deep spring system and increasing the weight of evidence to perhaps a particular hydrogeological conceptualisation.

Expanding on the Figure 4.6 bullet points, development of the Tier 2 final integrated conceptual model informed by geochemical forensics (see, for example, Box 4.1) could involve the following data or aspects:

- Temperature profile. Typically temperatures are measured in the spring itself (ideally long term) and perhaps fairly shallow boreholes around the discharge or recharge areas. However, the confirmation of depths in the pathway proposed is typically based on regional temperature gradients with depth and geochronometer estimates.

- Hydrogeochemical facies. Characteristic hydrogeochemical facies may be diagnostic of the geological units with which the groundwater has come into contact and provide evidence of major and minor pathways to a spring. Geochemical models may vitally underpin the understanding of processes controlling the facies (water types) present.
- Isotopes/noble gas tracers. A wide range of stable and decay isotopes (see text for examples), their ratios and noble gas tracers can be used to constrain ages, elucidate controlling processes and help to determine spring provenance from multiple sources.
- Tracers of modern water. A range of environmental tracers (see text for examples) may help to provide valuable evidence of recent recharge, either indicating rapid flows through the entire pathway or modern leakage into that pathway near the spring.

Geochronometer. Estimates based on cations or silica are used to help estimate the maximum temperatures reached in the spring system cycle and hence the maximum penetration depths in the flow path (see, for example, Box 4.3

The lines of geochemical evidence in Box 4.1, combined with the geological and hydrogeological understanding of the time, enabled Andrews et al. (1982) to provide the conceptualisation of the provenance of the Bath Springs depicted in Figure 4.5 with reasonable quantification, albeit with some uncertainties that workers since have sought to address. The geochemical evidence appears consistent with and, indeed, reinforces the inference of hydraulic controls anticipated on the system. Provisional, Darcy's Law estimates of flows over the approximately 15km Mendip–Bath travel distance gave travel times of 4,000 years. At Bath, thermal water under pressure was projected to rise relatively rapidly, via a southerly dipping east–west thrust fault in the vicinity, recharging a low storage Triassic sequence, probably by way of the Palaeozoic unconformity, with consequent discharge at the springs.

-).
  - Age profile. The combination of the various data streams above (for example, isotopes) and hydrogeological velocities allows the ages of groundwater at springs and at sampled points in the subsurface to be constrained.
  - Mixing of flows. The challenge of geochemical interpretation is often where groundwaters from various sources and pathways become mixed in the (spring) sample and the isolation of these various inputs. The whole range of tracers may be involved with the interpretation.

There should be iteration across the geological, hydrogeological and geochemical features of the model, with the overall goal being to produce a mutually consistent conceptualisation of the deep spring system provenance across these areas (Figure 4.6). As illustrated for the Bath spring system this can be challenging, but this is not unexpected given the flow and geochemical complexities inherent in deep, long pathway and timeframe spring system cycles.

4.5.4 Tier 3: implementation of spring protection measures

Tier 3 aims to apply the findings of a Tier 2 assessment and implement deep spring protection measures appropriate to the conceptualisation of the deep spring and its provenance estimated in Tier 2. as shown in Figure 4.6, specific aspects of a Tier 3 assessment involve:

- implementation of deep spring protection based on provenance estimated
- protection of near spring, recharge and vulnerable areas of cycle pathway
- consideration of 3D groundwater vulnerability of spring catchment water
- conceptual model iteration, data collection, modelling to support measures

Tier 3 may require further assessment of aspects of the Tier 2 output to underpin the spring protection measures that may be implemented via more formal, even statutory instruments. Establishing groundwater protection zones, for instance, is typically formal and requires targeted effort. Hence there could be further conceptual model iteration, targeted data collection and (numerical) modelling perhaps to underpin any specific protection measures implemented.

It is recommended that the Tier 3 assessment builds on the Tier 2 assessment of the deep spring's provenance and gives targeted consideration to the protection of the following 3 types of area around it:

- Recharge area(s) – perhaps outcrop areas quite remote from the spring
- Near spring discharge area – this is the most vulnerable to local land use and shallow groundwater influence
- Any deep pathway segments potentially at risk from deep subsurface use

The assessment should facilitate the development of groundwater protection zones, or other protection measures appropriate to these 3 areas. Section 5.3 explores the groundwater protection zones that could be established under Tier 3 activity.

5 Approaches to protection of deep springs

The provenance of a deep spring can be reasonably estimated via a Tier 2 assessment (Section 4.5.3). The primary aim of a Tier 3 assessment is therefore to use that information to help protect the deep spring resource. Within this context key questions to ask are:

- Is it appropriate to map 'source protection zones' for deep springs?
- And if so, how might a methodology be defined?

These questions are explored below. Section 5.1 examines the current context in England, while Section 5.2 makes a preliminary inspection of some European literature on deep spring protection approaches. Section 5.3 outlines a possible source protection zone based approach appropriate for deep springs.

5.1 Approaches to deep spring protection in England

Protection of important groundwater sources such as those used for public water supply, including springs, is achieved through Source Protection Zones (SPZs) in England. Three zones are defined (Environment Agency 2009):

- **SPZ1 Inner Protection Zone** is defined as the 50-day travel time from any point below the water table to the source, but of minimum radius of 50m.
- **SPZ2 Outer Protection Zone** is defined by a 400-day travel time.
- **SPZ3 Source Catchment Protection Zone** is defined as the area around a source within which all groundwater recharge is presumed to be discharged at the source. In confined aquifers, the SPZ3 source catchment may be displaced some distance from the source.

To protect the upwards of 70,000 small potable sources (including many springs, some of which could conceivably be deep springs) and recognising it is not practical or efficient to define zones via the modelling or manual methods typically used, a potable source is assumed to have a default minimum SPZ1 of 50m radius and default minimum SPZ2 of 250m radius (Environment Agency 2009).

Although there is scope within this and the approaches set out in Environment Agency (2009) to provide definition of SPZs for deep springs, a formal methodology for this specific application has not been considered nationally until now. Drawing on Environment Agency (2009), some points to consider when addressing this include the following.

- Deep springs may emerge from beneath confining layers, and as such, their source catchment (potential SPZ3) outcrop area may sometimes be some considerable distance (for example, several kilometres) remote from the spring.

- Deep springs are often associated with karst aquifers (for example, Carboniferous Limestone) with features that present some significant problems in defining SPZs that are adequately protective without being over-protective or covering very large areas of land.
- Most karst area SPZs are best delineated using field mapping (including groundwater tracer tests) and manual methods rather than analytical or numerical models that assume porous medium rather than fissure flow. Environment Agency (2009) therefore sets out a methodology for delineation of SPZs in karst.

The Bath Springs do not have a defined SPZ and water quality is not explicitly protected by any mechanism. Flow to the springs is protected by section 33 of the County of Avon Act 1982 and regulated by Bath and North East Somerset Council via the planning process (Bath and North East Somerset Council 2019). Concentric protection zones are defined around the springs and along the tentative trace of the key fault, within which consent from the Council is required for excavations of depths >5m in the central zone around the hot springs, 15m in a zone along the river valley, and 50m in the outer zone (roughly the boundary of the city plus an extension to Batheaston 4km away, where mine shaft construction in the 1800s caused a decrease in flow rate at the springs).

5.2 Approaches to deep spring protection in Europe

This section presents observations from a brief literature review of how other European countries delineate deep groundwater bodies for the Water Framework Directive, and particularly for spa waters.

The review of thermal water resources in carbonate rock aquifers by Goldscheider et al. (2010) discusses the detail of hot springs and baths associated with Europe’s largest thermal hot springs in the ‘Buda Karst’ in Hungary (Erőss et al. 2008), its second largest at the medicinal springs and baths of Stuttgart in Germany (Ufrecht 2006), and the Derbyshire springs as well as referring to other cases in these countries and France, Italy, Switzerland and Turkey. Figure 2 of Goldscheider et al. (2010) usefully conceptualises the importance of geochemical dissolution and mixing corrosion processes increasing the permeability of both epigenic (shallow) and hypogenic (deep) karst flow regimes. These processes allow high groundwater velocities within primarily gravity-driven flow systems from recharge to spring discharge due to topographic gradients in the detailed Hungarian and German cases to span tens of kilometres. The groundwater protection measures, if any, applied to these very remote recharge zones are not specifically detailed in the review.

Of general significance to groundwater protection, Goldscheider et al. (2010) concluded that deeply confined hypogenic karst flow systems causing deep regional groundwater circulation systems are probably much more widespread than previously suspected. The final points of their review, which align with the interests of this report, indicate that although deep spring/thermal confined aquifer systems may be considered well protected, ‘contamination of thermal and mineral water supplying spas does occur, although it is rarely reported’. The review refers to the case in Stuttgart studied by Goldscheider et al. (2003)

where a deep source spring of mineral water was found to contain trace chlorinated solvent contamination, likely a consequence of the solvent's dense non-aqueous phase liquid (DNAPL) properties allowing its influence to depth. Goldscheider et al. (2010) concluded that:

> 'A systematic assessment, evaluation and mapping of these [thermal water] resources, both at national scales and globally, would be an ambitious project but would provide a useful basis for the management of thermal water from deep carbonate-rock aquifers'.

Such mapping would be expected to precede definition of specific groundwater protection measures, which are thus inferred not to be that advanced for deep spring protection generally.

A leading edge research example is the work of Meerkhan et al. (2016), which focused on the protection of deep spring mineral waters at around 30°C by assessing groundwater vulnerability and mapping protection zones in the fractured granite of Caldas da Cavaca in central Portugal. The understanding of the hydrogeological system had previously been limited to samples from the spring and a few wells. The multi-technical approach included field investigation (including applied geomorphology, borehole drilling and geophysics) and laboratory techniques to gain insight into geology and hydrogeology. The aim was to apply the so-called DISCO index method, alongside other methods (for example, DRASTIC) within a multi-criteria intrinsic vulnerability assessment GIS framework. The DISCO method augmented the continuous vulnerability data from the vulnerability assessment framework by accommodating a highly fractured and heterogeneous media. This allowed the increased groundwater vulnerability (due particularly to the presence of lineaments) to be spatially mapped with high resolution over an area of <1km^2. This in turn allowed the 3 protection zones required under Portuguese law to be redrawn (Figure 5.1). In Portugal, polluting activities in the 'Intermediate' protection zone are less proscribed than for SPZ1 in England, but more than for SPZ2.

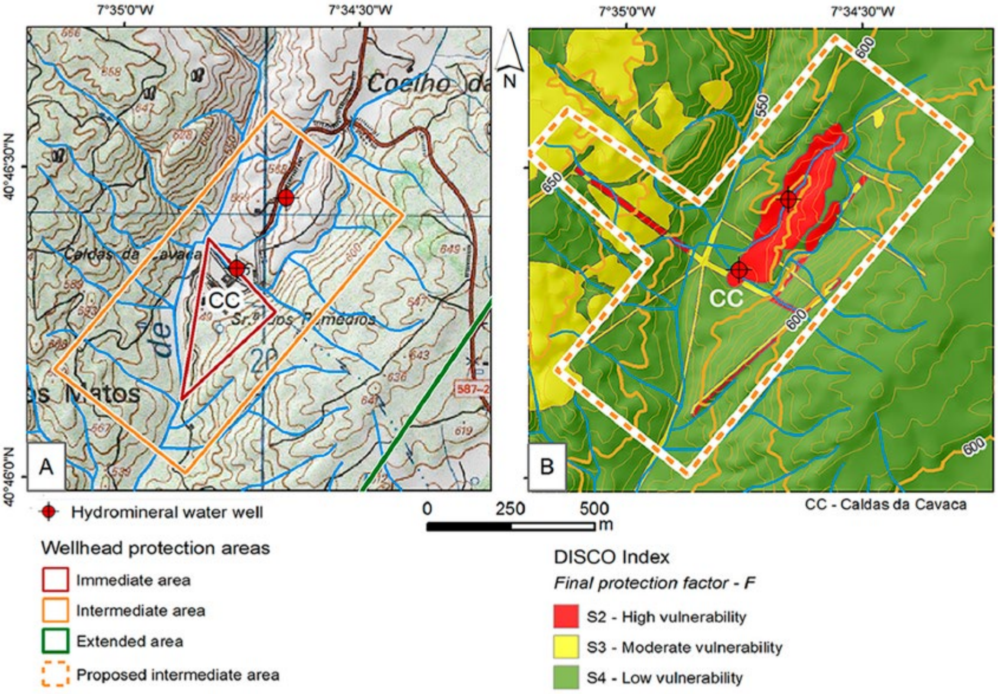


Figure 5.1 Wellhead protection areas (zones) for the Caldas da Cavaca hydromineral system in Portugal. (A) Wellhead protection areas defined in 1996. (B) Proposed intermediate wellhead protection area relative to contoured groundwater vulnerability

Notes: Used with permission from Meerkhan et al. (2016)
In (B), the Extended Protection Zone extends beyond the area shown.

Figure 5.1 contrasts the protection areas (zones) for a pair of deep source mineral wells (not springs) drawn in 1996 using simple criteria, and the new zones proposed using this advanced methodology and significantly improved knowledge of the hydrogeological system. The Intermediate Protection Zone (potentially contaminating activities forbidden or controlled) is proposed to be expanded to the north-east and to the north-west. This was to allow it to encompass all the high vulnerability zones (S2, coinciding with first-order lineaments) and the most important moderate vulnerability zones (S3 coinciding with second-order lineaments). The existing Extended Protection Zone largely retained its limits since it was judged large enough to include all the relevant deep-crustal geostructures and their related vulnerability zones. The proposed Immediate Protection Zone remained restricted to the vicinity of the wells. The case illustrates the refined protection zone definition possible, some of which was partly controlled by deep-crustal geostructures being largely resolved by an electrical resistivity tomography and electromagnetic method (especially electromagnetic conductivity) applied in the aquifer discharge zone.

5.3 Proposed approach to deep spring protection

'Source Protection Zones' have a specific definition in Environment Agency guidance and policy, and there are limitations on activities within SPZs that might not be justified in the context of the uncertainty over the catchments of deep springs. The term 'SPZ' is therefore not used here to describe protection zones for deep springs and the term 'Spring Protection Zone' (SprPZ) is used instead. In time, policy may come to decide that a SprPZ is to be used in the same way as a SPZ. However, the spatial delineation of SPZ3/SprPZ3, SPZ2/SprPZ2 and SPZ1/SprPZ1 could be seen as broadly analogous.

As identified under Tier 3 assessment (Section 4.5.4), it is proposed that groundwater protection measures and the potential use of groundwater protection zones should be considered for at least the following 3 types of area in a given deep spring scenario where its provenance has been determined with reasonable confidence.

- Recharge area(s) – perhaps outcrop areas quite remote from the spring (SprPZ3 consideration)
- Near spring discharge area vicinity that is most vulnerable to local land use and shallow groundwater influence (SprPZ1 or SprPZ2 consideration)
- Any deep pathway segments potentially at risk from deep subsurface use (a 'deep spring protection zone')

This is not to say SprPZs should necessarily be defined in every, indeed perhaps any, deep spring case. Working through this formal framework, however, would be deemed beneficial and allow consistency in approach for a decision to be made. Figure 5.2 provides a schematic illustration of the various SprPZs that could be considered in relation to deep spring protection that are discussed below.

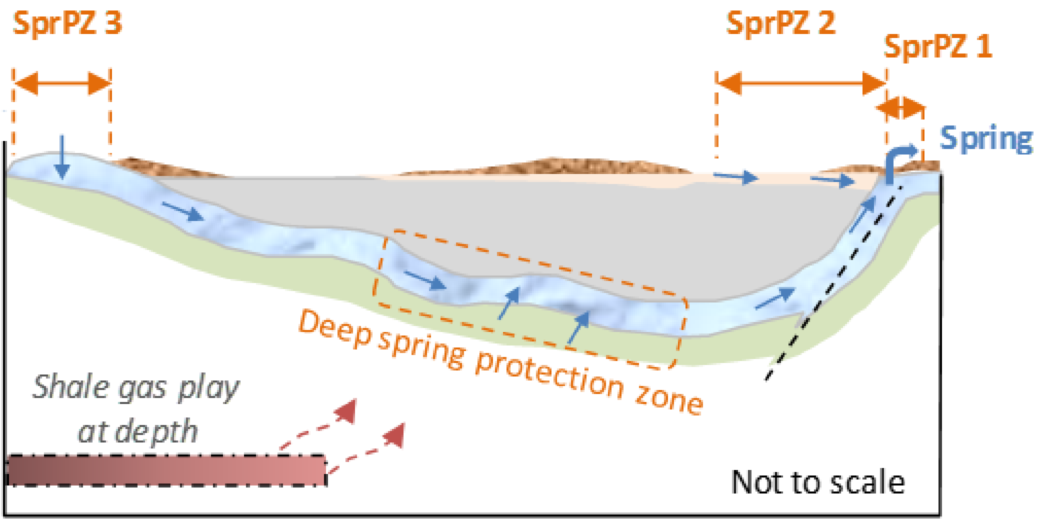


Figure 5.2 Schematic illustration of the potential application of SPZs to a deep spring and its subsurface pathway potentially vulnerable to a proposed shale gas play at significant depth

5.3.1 Recharge areas

The main recharge area to the identified outcrop of aquifer unit primarily presumed responsible for sustaining the bulk of deep system spring flows would comply with the SprPZ3 definition. The potential remoteness (many kilometres) from the spring site may, however, cause difficulties in establishing groundwater protection zones as they may be judged simply too remote to matter, particularly if the timeframes to migrate to the spring are judged at 100–1,000 years or more.

That said, it is not uncommon for a SPZ3 to be defined for confined aquifers in an area remote from the source, over the outcrop laterally beyond the confining layer. If velocities through the deep pathway are high, with hypogenic deep karst flow suspected, then the justification for the establishment of SprPZ3 becomes greater – especially where the spring has significant resource value (that is, it is a spa site, mineral/spring water of significant tourism or commercial value and of likely historical note). It is perhaps doubtful that modelling could further refine the SprPZ3 to a more localised portion of the identified outcrop. However, the varying groundwater vulnerability over the outcrop due to superficial deposits and depth to groundwater, as well as the proximity of portions of the outcrop to the spring, may nevertheless help to identify those parts of the outcrop of more significance.

5.3.2 Near spring (discharge) area

Establishment of the SprPZ1 minimum 50m zone would be assumed a given to afford very local protection of the emergent spring from depth.

There may be some grounds for the SprPZ2 definition to apply and for it to largely protect the shallow groundwater flow regime at important deep spring sites. The reasons for this are as follows.

- The pathway from depth may not be fully constrained and be locally uncertain within the typically complex (hydro)geological environment. These considerations dictate that a larger area should be protected rather than simply just where the spring is located, as there may be some lateral flow in the shallow systems prior to the spring discharge.

- The emergent deep groundwater pathway increasingly needs protection as it approaches ever closer to the ground surface and becomes more vulnerable.

- Some contaminants, notably DNAPLs, have the potential to have a significant impact deep within the subsurface and cause contamination of the near spring pathway at depth and around its ascent to the surface.

- Some deep springs have a proportion of their provenance relating to shallow aquifer flows and modern recharge. It would be important for this spring provenance to be identified (geochemical forensics) and these perhaps quite local areas of recharge to be protected. These areas could be close to the spring or somewhat further afield.

- Contamination sources affecting the near spring area might have limited opportunity for dilution should they be able to migrate to the spring.

There are therefore a range of reasons to establish SprPZ1 and SprPZ2 even though the bulk of spring flow may be anticipated to be from remote areas conveyed at depth. These zones could be established at a default radial or elliptical distance and/or predicted from local outcrops or simple modelling of shallow flows to allow more specific designation for important springs.

5.3.3 Deep pathway segments judged potentially at risk from deep subsurface use

There is some justification for the protection of deep pathway segments judged potentially at risk from deep subsurface use, and perhaps the potential modification of that subsurface activity (for example, not permitting it, modifying it, or moving it some further distance away). The deep pathway segment would perhaps constitute a ‘deep spring protection zone’. But although this would be synonymous with a ‘safeguard zone’ in the terminology offered alongside SPZ definitions (Environment Agency 2009), ‘safeguard zone’ has now taken on another meaning.

Although the overall spring cycle pathway length or timeframes may be large, those between the spring and deep activity that poses a hazard may be low; this recognises the potential final rapid groundwater ascent from depth to a spring. The 3DGWV assessment data (Loveless et al. 2018) may help to assess this interaction, but data are likely to be quite sparse. In addition, the onus will presumably be on the developer of the deep activity (for example, shale gas exploitation) to prove that it is unlikely to pose a risk to a protected deep spring pathway at depth that effectively offers a short circuit route to ground surface (as if it were an SprPZ2 or SprPZ3,but only between specified depth limits).

6 Conclusions, data gaps and recommendations

6.1 Conclusions

This report collates and expands on ideas associated with the exploitation of deep and/or brackish groundwater, and the risks associated with this, particularly with respect to deep springs. The ideas were prompted by a workshop and further discussion between the authors and the Environment Agency.

The exploitation of deep groundwater (that is, groundwater from deeper than 400m) may lead to impacts on near surface groundwater resources and groundwater quality. Abstraction of groundwater – from any depth – will lead to an eventual, though possibly very slight, reduction in water resource in the near surface fresh groundwater resource. However, temporary withdrawal of a finite volume of water from depth could lead to a small but persistent impact at the near surface. Subject to the usual hydroecological appraisals, this impact could be acceptable. Water quality above deep groundwater activities may be affected as water is removed from below shallow aquifers. Impacts may include:

- increased flushing of salinity from aquifers
- introduction of oxidising groundwater to previously anaerobic environments
- loss of deeper fresh groundwater as a resource that has not yet been affected by anthropogenic activities (that is, pollution)

Several national studies of water quality data have been reviewed to assess the frequency of occurrence of brackish groundwater in England. Of the groundwater quality data in the Environment Agency's WIMS database from 2017, 16.5% of sample locations yielded brackish groundwater (that is, TDS >600mg per litre). Most of the brackish groundwater sampled would be suitable for livestock watering and the irrigation of crops without treatment or blending. The report explores the constraints on reverse osmosis treatment to achieve potable water quality, but England's water distribution infrastructure is so well-connected that blending is likely to be the most suitable option for bringing concentrations to acceptable levels.

Generic hydrogeological settings of deep springs (that is, springs fed by groundwater from deeper than 400m) are considered, with particular reference to English deep springs and the Bath Springs with the aim of illustrating how best to assess their provenance. Two especially thorough studies (Andrews et al. (1982, Edmunds et al. 2014) offer a range of forensic geochemical techniques that might be employed in understanding deep spring provenance. These methods can tie in with the 3D geological mapping approach of the joint BGS/Environment Agency 3DGWV project (Loveless et al. 2018).

Provenance mapping is expected to be an important part of any risk assessment for activities within the 3D catchment of a deep spring. The report has reviewed the English approach to groundwater source protection in the light of deep spring protection and identified some European examples of protecting deep springs. These led to a recommendation for a tiered methodology of characterising and delineating deep spring protection zones. These methodology would be implemented if activities in deep groundwater could have an impact on deep springs.

6.2 Data gaps and recommendations

6.2.1 Quantifying the brackish groundwater resource

The Environment Agency is concerned that water demand from the country's rising population will shortly surpass capacity as climate change results in falling supply (Carrington 2019). The solutions proposed include:

- reducing water use and mains leakage
- building new reservoirs and desalination plants
- extending water transfers

However, if available in sufficient and sustainable amounts, deep and/or brackish groundwater could be used to compensate for increased demand for fresh water. The brackish resource is currently unquantified. It is therefore recommended that an in-depth study be undertaken to quantify the amount of available brackish water that is not already accounted for in existing catchment water balances.

The Environment Agency WIMS database has proved to be an excellent resource for this study and examination of the full database is recommended; many sample points have been dropped in the past few years and are not in the 2017 dataset used. As well as electrical conductivity (as a proxy for TDS), the dataset should be used for mapping water types (for example, halite-dominated water versus gypsum-dominated water) and saturation indices. Mapping phytotoxins such as boron and selenium would help to clarify whether brackish waters are truly suitable for irrigation.

Water quality data from pumped boreholes do not distinguish between whether an aquifer is full of well-mixed brackish groundwater, or whether the borehole abstracts fresh groundwater that is tainted by deeper saline water. The difference is key in establishing whether there is truly a resource of brackish groundwater. If an abstraction was to draw mostly fresh water with some saline water, the likelihood is that it would be:

- depleting the freshwater resource
- increasing the risk of movement of the saline water body, leading to the derogation of other, nearby fresh groundwater sources

The measurement of electrical conductivity with depth in monitored boreholes that produce brackish water should be carried out to provide an understanding of the vertical distribution of brackish water through aquifers.

Establishing the spatial and vertical distribution of brackish waters will allow the volumes of stored brackish groundwater to be assessed. The potential impact of the withdrawal of brackish groundwater on fresh water resources, on an aquifer-by-aquifer basis, needs to be understood before the brackish water is considered available in addition to currently quantified groundwater resources.

6.2.2 Deep spring protection

The definition of SprPZs and the constraints on development within them need to be explored. Development at the surface should not be constrained in a SprPZ in the same way as in a SPZ, as the evidence base for the pathway may not be robust. Furthermore, at points within a SprPZ, or a safeguard zone, the groundwater that feeds the spring may be several kilometres beneath ground surface. (An SprPZ needs to encompass the outcrop and the confined aquifer to ensure that deep activities that might have an impact on the spring are adequately regulated.)

While it is anticipated that the operator of a proposed deep groundwater scheme needs to do the bulk of the tiered risk assessment, there needs to be a method to flag up that an assessment needs to be done. Indicative SprPZs therefore need to be defined by the Environment Agency in advance and a methodology for defining these indicative SprPZs developed.

Although the majority of spring flows may originate from the deep system, protection of the near spring, shallow subsurface cannot be ignored and is recommended for discussion in the SprPZ definition. The reasons for this are:

- the potential vulnerability of deep system flows as they emerge near surface with perhaps some lateral near surface flows to the spring
- components of nearby recent recharge shallow system flows also contributing a proportion of the spring flow

For instance, confusion in the Bath spring system provenance partly relates to evidence of modern leakage into the spring flow system.

It is recommended that a more comprehensive literature review of European approaches to spring protection is undertaken. Recognising that carbonate aquifers constitute the most important thermal water resources outside of volcanic areas, the review should focus on countries where carbonate rock (for example, limestone) karst aquifer systems that typically support deep spring spa/mineral/thermal waters are more prevalent.

6.2.3 Other recommendations

Quantifying the scale of impact on near surface water resources of temporary deep abstraction would provide reassurance if such activities are proposed. This problem does not lend itself to analytical solutions, but modelling generic scenarios in a numerical model would give useful answers.

References

AER ENVIRONMENT GROUP, 2019. *Base of Groundwater Protection Query Tool* [online]. Available from: https://dds.aer.ca/BGP/UI/BGP-Main.aspx [accessed 20 May 2019].

ALBU, M., BANKS, D. AND NASH, H. (EDS.), 1997. *Mineral and Thermal Groundwater Resources.* London: Chapman and Hall.

ANDERSON, W., 1945. On the chloride waters of Great Britain. *Geological Magazine*, 82 (6), 267-274.

ANDREWS, J.N., 1991. Radioactivity and dissolved gases in the thermal waters of Bath. In *Hot Springs of Bath: Investigations of the Thermal Waters of the Avon Valley* (ed. G.A. Kellaway), pp. 157-170. Bath: Bath City Council.

ANDREWS, J.N., BURGESS, W.G., EDMUNDS, W.M., KAY, R.L.F. AND LEE, D.J., 1982. The thermal springs of Bath. *Nature*, 298, 339-343.

ARNORSSON, S., 1975. Application of the silica geothermometer in low temperature hydrothermal areas in Iceland. *American Journal of Science*, 275, 763-784.

AYERS, R.S. AND WESTCOT, D.W., 1996. *Water quality for agriculture.* FAO Irrigation and Drainage Paper 29 Rev. 1. Rome: Food and Agriculture Organization of the United Nations.

BANKS, D., 1997. The spas of England. In *Mineral and Thermal Groundwater Resources*. (ed. M. Albu, D. Banks and H. Nash), pp. 235-280. London: Chapman and Hall.

BANKS, D., YOUNGER, P.L. AND DUMPLETON, S., 1996. The historical use of mine-drainage and pyrite-oxidation waters in central and eastern England, United Kingdom. *Hydrogeology Journal*, 4 (4), 55-68.

BARKER, J.A., DOWNING, R.A., GRAY, D.A., FINDLAY, J., KELLAWAY, G.A., PARKER, R.H. AND ROLLIN, K.E., 2000. Hydrogeothermal studies in the United Kingdom. *Quarterly Journal of Engineering Geology and Hydrogeology*, 33, 41-58.

BATH, A., RICHARDS, H., METCALFE, R., MCCARTNEY, R., DEGNAN, P. AND LITTLEBOY, A., 2006. Geochemical indicators of deep groundwater movements at Sellafield, UK. *Journal of Geochemical Exploration*, 90 (1-2), 24-44.

BATH AND NORTH EAST SOMERSET COUNCIL, 2019. *County of Avon Act 1982 - section 33. Protection of the hot springs in Bath* [online]. Available from: https://www.bathnes.gov.uk/services/environment/bath-hot-springs/county-avon-act-1982-section-33 [Accessed 20 May 2019).

BGS, 2011. *Emerging contaminants in groundwater*. Science Briefing. Keyworth, Nottingham: British Geological Survey. Available from: https://www.bgs.ac.uk/downloads/start.cfm?id=2080 [Accessed 20 may 2019].

BOTTRELL, S., LOWE, D., GUNN, J., WORTHINGTON, S. AND BRASSINGTON, F.C., 2008. Discussion of ‘A proposed conceptual model for the genesis of the Derbyshire thermal springs' by F. C. Brassington. *Quarterly Journal of Engineering Geology and Hydrogeology*, 41, 119-120.

BRASSINGTON, F.C., 2007. A proposed conceptual model for the genesis of the Derbyshire thermal springs. *Quarterly Journal of Engineering Geology and Hydrogeology*, 40, 35-46.

BRASSINGTON, F.C. AND YOUNGER, P.L., 2010. A proposed framework for hydrogeological conceptual modelling. *Water and Environment Journal*, 24 (4), 261-273.

BURGESS, W.G, EDMUNDS, W.M., ANDREWS, J.N., KAY, R.L.F. AND LEE, D.J., 1980. *The hydrogeology and hydrochemistry of the thermal water in the Bath-Bristol Basin.* Report in the series 'Investigation of the Geothermal Potential of the UK'. London: Institute of Geological Sciences.

CARRINGTON, D., 2019. *England could run short of water within 25 years* [online], The Guardian, 18 March 2019. Available from: https://www.theguardian.com/environment/2019/mar/18/england-to-run-short-of-water-within-25-years-environment-agency [Accessed 20 May 2019].

COOPER, N., 2011. *Saline springs in Cumbria.* MSc thesis, University of Birmingham.

DOWNING, R.A., 1998. *Groundwater – our hidden asset*. Wallingford: UK Groundwater Forum.

DOWNING, R.A., EDMUNDS, W.M. AND GALE, I.N., 1987. Regional groundwater flow in sedimentary basins in the U.K. In *Fluid Flow in Sedimentary Basins and Aquifers* (ed. J.C. Goff and B.P.J. Williams), Geological Society Special Publications Volume 34 pp. 105-125. London: Geological Society.

DOWNING, R.A. AND GRAY, D.A., 1986. *Geothermal energy. The potential in the United Kingdom*. London: HMSO.

EDMUNDS, W.M., 1971. *Hydrogeochemistry of groundwaters in the Derbyshire Dome with special reference to trace constituents*. Report 71/7. London: Institute of Geological Sciences.

EDMUNDS, W.M., 2004. Bath thermal waters: 400 years in the history of geochemistry and hydrogeology. In *200 Years of British Hydrogeology* (ed. J.D. Mather), Geological Society Special Publications Volume 225, pp. 193-199. London: Geological Society.

EDMUNDS, W.M. AND MILES, D.L., 1991. The geochemistry of the Bath thermal waters. In *Hot Springs of Bath: Investigations of the Thermal Waters of the Avon Valley* (ed. G.A. Kellaway), pp. 143-156. Bath: Bath City Council.

EDMUNDS, W.M., TAYLOR, B.J. AND DOWNING, R.A., 1969. Mineral and thermal waters of the United Kingdom. In *Proceedings of Symposium 2 on Mineral and Thermal Waters of the World held during the 23rd International Geological Congress* (Prague, 1968), pp. 139-158.

EDMUNDS, W.M., DARLING, W.G., PURTSCHERT, R. AND ALVARADO, J.A.C., 2014. Noble gas, CFC and other geochemical evidence for the age and origin of the Bath thermal waters, UK. *Applied Geochemistry*, 40, 155-163.

ENEMARK, T., PEETERS, L.J.M., MALLANTS, D. AND BATELAAN, O., 2019. Hydrogeological conceptual model building and testing: a review. *Journal of Hydrology*, 569, 310-329.

ENVIRONMENT AGENCY, 2009. *Groundwater Source Protection Zones – review of methods*. Integrated catchment science programme. Science Report SC070004/SR1. Bristol: Environment Agency.

ERŐSS, A., MÁDL-SZŐNYI, J. AND CSOMA, A., 2008. Characteristics of discharge at Rose and Gellért Hills, Budapest, Hungary. *Central European Geology*, 51 (3), 267-281.

GALLOIS, R.W., 2006. The geology of the hot springs at Bath Spa, Somerset. *Geoscience in south-west England*, 11, 168-173.

GALLOIS, R.W., 2007. The formation of the hot springs at Bath Spa, UK. *Geological Magazine*, 144 (4), 741-747.

GLANVILL, J., 1669. Observations concerning the Bath-Springs, communicated by Mr. Joseph Glanvill, in a letter to the publisher dated June 16. 1669, at the Bath. *Philosophical Transactions*, 4 (49), 977-982.

GOLDSCHEIDER, N., HÖTZL, H., KÄSS, W. AND UFRECHT, W., 2003. Combined tracer tests in the karst aquifer of the artesian mineral springs of Stuttgart, Germany. *Environmental Geology*, 43 (8), 922-929.

GOLDSCHEIDER, N., MÁDL-SZŐNYI, J., ERŐSS, A. AND SCHILL, E., 2010. Review: thermal water resources in carbonate rock aquifers. *Hydrogeology Journal*, 18 (6), 1303-1318.

GOVERNMENT OF WESTERN AUSTRALIA, 2019. *Water quality for livestock* [online]. South Perth, Western Australia: Agriculture and Food Division, Department of Primary Industries and Regional Development. Available from: https://www.agric.wa.gov.au/livestock-biosecurity/water-quality-livestock [Accessed 20 May 2019].

GUNN, J., BOTTRELL, S.H., LOWE, D.J. AND WORTHINGTON, S.R.H., 2006. Deep groundwater flow and geochemical processes in limestone aquifers: evidence from thermal waters in Derbyshire, England, UK. *Hydrogeology Journal*, 14 (6), 868-881.

JACKSON, C.R., MACKAY, J.D. AND BLOOMFIELD, J.P., 2013. *Changes in groundwater levels, temperature and quality in the UK over the 20th century: an assessment of evidence of impacts from climate change.* A climate change report card for water – Working Technical Paper 4. Living with Environmental Change. Available from: http://nora.nerc.ac.uk/id/eprint/503271/ [Accessed 20 May 2019].

KELLAWAY, G.A., 1991a. The work of William Smith at Bath (1799–1813). In *Hot Springs of Bath: Investigations of the Thermal Waters of the Avon Valley* (ed. G.A. Kellaway), pp. 25-54. Bath: Bath City Council.

KELLAWAY, G.A., 1991b. Investigation of the Bath hot springs (1977–1987). In *Hot Springs of Bath: Investigations of the Thermal Waters of the Avon Valley* (ed. G.A. Kellaway), pp. 97-126. Bath: Bath City Council.

KELLAWAY, G.A., 1994. Environmental factors and the development of Bath Spa, England. *Environmental Geology*, 24 (2), 99-111.

KELLAWAY, G.A. AND WELCH, F.B.A., 1948. *British Regional Geology: Bristol and Gloucester District,* 2nd edition. London: HMSO.

LEMAY, T.G., 2009. *Description of the process for defining the base of groundwater protection*. ERCB/AGS Open File Report 2009-04. Edmonton, Alberta: Energy Resource Conservation Board, Alberta Geological Survey.

LOVELESS, S., LEWIS, M.A., BLOOMFIELD, J.P., TERRINGTON, R., STUART, M.E. AND WARD, R.S. 2018. *3D groundwater vulnerability*. Joint study by the British Geological Survey and the Environment Agency. BGS Internal Report OR/18/12. Keyworth, Nottingham: British Geological Survey.

MCCANN, C., MANN, A.C., MCCANN, D.M. AND KELLAWAY, G.A., 2002. Geophysical investigations of the thermal springs of Bath, England. In *Sustainable Groundwater Development* (ed. K.M. Hiscock, M.O. Rivett and R.M. Davison), Geological Society Special Publications Volume 193, pp. 41-52. London: Geological Society.

MCCANN, C., MANN, A.C., MCCANN, D.C. AND KELLAWAY, G.A., 2013. Insights into the origin of the thermal springs of Bath and Bristol, England, from geophysical data. *Quarterly Journal of Engineering Geology and Hydrogeology*, 46 (3), 267-279.

MEERKHAN, H., TEIXEIRA, J., MARQUES, J.E., AFONSO, M.J. AND CHAMINÉ, H.I., 2016. Delineating groundwater vulnerability and protection zone mapping in fractured rock masses: focus on the DISCO Index. Water, 8, 462, doi:10.3390/w8100462.

MEPS INTERNATIONAL, 2019. *Steel price forecasts to 2023* [online]. Sheffield: MEPS International Ltd. Available from: http://www.meps.co.uk/index.htm [Accessed 18 March 2019].

PEARCE, G.K., 2008, UF/MF pre-treatment to RO in seawater and wastewater reuse applications – a comparison of energy costs. *Desalination*, 222 (1-3), 66-73.

POWELL, T. AND CUMMING, W., 2010. Spreadsheets for geothermal water and gas geochemistry. In Proceedings of 35th Workshop on Geothermal Reservoir Engineering (Stanford, CA, 2010). Paper SGP-TR-188. Available from: https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2010/powell.pdf [Accessed 20 May 2019].

QTAISHAT, T., SEDER, N., AL-KARABLIEH, E., SALMAN, A., TABIEH, M. AND AL-QUDAH, H.F., 2017. Economic analysis of brackish-water desalination used for irrigation in the Jordan Valley. *Desalination and Water Treatment*, 72, 13-21.

REED, M.H. AND SPYCHER, N., 1984. Calculation of pH and mineral equilibria in hydrothermal waters with application to geothermometry and studies of boiling and dilution. *Geochimica et Cosmochimica Acta*, 48 (7), 1479-1492.

ROBINS, N.S. AND SMEDLEY, P.L., 2013. Groundwater: medicine by the glassful? In *A History of Geology and Medicine* (ed. C.J. Duffin, R.T.J. Moody and C. Gardner-Thorpe), Geological Society Special Publications 375, pp. 261-267. London: Geological Society.

RWM, 2019. *National Geological Screening for a GDF. Central England – Subregion 1, version 1.0*. Harwell, Didcot: Radioactive Waste Management. Available from: https://www.gov.uk/guidance/central-england-subregion-1 [Accessed 20 May 2019].

SOUTHERN WATER, 2014. *Trade effluent charges, 2014/2015. A guidance leaflet for customers*. Worthing: Southern Water. Available from: https://www.southernwater.co.uk/Media/Default/PDFs/TradeEffChgs.pdf [Accessed 120 May 2019].

SMEDLEY, P.L., 2010. A survey of the inorganic chemistry of bottled mineral waters from the British Isles. *Applied Geochemistry*, 25 (12), 1872-1888.

SMITH, A.J., KHOW, J., LODGE, B AND BAVISTER, G., 2001. Desalination of poor quality brackish groundwater for non-potable use. *Desalination*, 139 (1-3), 207-215.

STANTON, J.S., ANNING, D.W., BROWN, C.J., MOORE, R.B., MCGUIRE, V.L., QI, S.L., HARRIS, A.C., DENNEHY, K.F., MCMAHON, P.B., DEGNAN, J.R. AND BÖHLKE, J.K., 2017. *Brackish groundwater in the United States.* Professional Paper 1833. Reston, VA: US Geological Survey.

STEPHENS, J.V., 1929. *The Wells and Springs of Derbyshire*. Memoir of the Geological Survey of Great Britain. London: Ordnance Geological Survey.

STUYFZAND, P.J. AND RAAT, K.J., 2010. Benefits and hurdles of using brackish groundwater as a drinking water source in the Netherlands. *Hydrogeology Journal*, 18 (1), 117-130.

THAMES WATER, no date. *Thames Gateway Water Treatment Works: how the treatment works operates* [online]. Available from: https://www.thameswater.co.uk/help-and-advice/water-quality/where-our-water-comes-from/thames-gateway-water-treatment-works/how-the-treatment-works-operates [Accessed 21 May 2019].

TURNBULL, R., 2010. *Selection of steel casing and well screen for brackish ground water production boreholes*. Roscoe Moss Company Technical Information Sheet 008-3. Available from: https://roscoemoss.com/wp-content/uploads/techmemos/TechMemo008-3SteelSelectionforBrackishWaterConditionsattheMmamabulaProject.pdf [Accessed 20 May 2019].

UFRECHT, W. (ED.), 2006. *Hydrogeologie des Stuttgarter Mineralwassersystems* [Hydrogeology of the Stuttgart Mineral Water System]. Schriftenriche des Amters für Umweltschutz Issue 3/2006. Stuttgart: City of Stuttgart, Department of Environmental Protection.

UKTAG, 2012. *Defining and reporting on groundwater bodies.* Edinburgh: UK Technical Advisory Group on the Water Framework Directive.

USGS, no date. *How is brackish groundwater being used?* [online]. Reston, VA: US Geological Society. Available from: https://water.usgs.gov/ogw/gwrp/brackishgw/use.html [Accessed 20 May 2019].

WATEREUSE ASSOCIATION, 2012. *Seawater desalination costs*. White Paper (September 2011, revised January 2012). Alexandria, VA: WateReuse Association.

WATER TECHNOLOGY NET, no date. *Thames Water desalination plant, London* [online]. Available from: https://www.water-technology.net/projects/water-desalination/ [Accessed 21 May 2019].

WHITE, D.E., 1957. Thermal waters of volcanic origin. *Bulletin of the Geological Society of America*, 68 (12), 1659-1682.

WHO, 2011. Acceptability aspects: taste, odour and appearance. In *Guidelines for Drinking-water Quality*, 4th edition, Chapter 10. Geneva: World Health Organization.

WISHART, D.N., 2015. *Comparison of silica and cation geothermometers of Bath Hot Springs, Jamaica WI.* Presented at the World Geothermal Congress 2015 (Melbourne, Australia, 2015). Available from: https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/14130.pdf [Accessed 20 May 2019].

YOUNGER, P.L., BOYCE, A.J. AND WARING, A.J., 2015. Chloride waters of Great Britain revisited: from subsea formation waters to onshore geothermal fluids. *Proceedings of the Geologists' Association*, 126 (4-5), 453-465.

List of abbreviations

3D	three-dimensional
3DGWV	3D groundwater vulnerability
BGS	British Geological Survey
BGWP	Base of Groundwater Protection
CFC	chlorofluorocarbon
DNAPL	dense non-aqueous phase liquid
GDF	geological disposal facility
Ml	million litres
NWEBS	National Water Environment Benefit Survey [Environment Agency]
ppm	parts per million
SEC	specific electrical conductivity
SprPZ	Spring Protection Zone
SPZ	Source Protection Zone
TDS	total dissolved solids
WIMS	Water Management Information System [Environment Agency]
UKTAG	UK Technical Working Group on the Water Framework Directive

Would you like to find out more about us or your environment?

Then call us on

03708 506 506 (Monday to Friday, 8am to 6pm)

Email: enquiries@environment-agency.gov.uk

Or visit our website

www.gov.uk/environment-agency

incident hotline

0800 807060 **(24 hours)**

floodline

0345 988 1188 **(24 hours)**

Find out about call charges (https://www.gov.uk/call-charges)

Environment first

Are you viewing this onscreen? Please consider the environment and only print if absolutely necessary. If you are reading a paper copy, please don’t forget to reuse and recycle.