A pilot groundwater temperature network for England

Environmental Change, Adaptation & Resilience Programme

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James Sorensen and Peter Williams (BGS) measuring a groundwater temperature profile at the Lower Chance Farm OBH, Blewbury, Oxfordshire, 14 Jan 2022.

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BGS Foreword

The project described in this report was commissioned by the Environment Agency and conducted by the British Geological Survey between November 2021 and March 2022. The project consisted of obtaining groundwater temperature profiles for selected OBHs and the design and implementation of a pilot groundwater temperature monitoring network within four pilot catchments in England. The purpose was to obtain information that can be used by the EA to inform the development of a future national groundwater temperature monitoring network for England.

This report details the selection of the pilot catchments, describes the groundwater temperature profiles obtained and design and implementation of the pilot network, and identifies lessons learnt relevant to the development of a future national groundwater temperature network.

The project forms part of the UK's wider Natural Capital and Ecosystem Assessment (NCEA) programme.

EA Foreword

Natural Capital & Ecosystem Assessment

UK Government has set world-leading ambition on protecting our natural assets, internationally through the Convention of Biodiversity and domestically via the ground-breaking 25 Year Environment Plan. Intrinsically linked to the successful delivery of Net Zero, protecting our environmental services has never been more vital.

Achieving these goals is underpinned by the provision of systematic and robust evidence. For the first-time, Defra are developing a programme to deliver up-to-date, UK-wide environmental data to allow for agile policy making grounded in the best available evidence – to truly understand where we are and where we need to get to.

The NCEA Programme

Currently in a pilot phase, NCEA is a transformative programme to understand the extent, condition and change over time of environmental assets across England's land and water environments, supporting the government's ambition to improve the environment within a generation.

Built on data amassed from across England's natural environment; NCEA aims to deliver a robust framework of statistics that facilitate **landscape-level intelligence**. It would manage and maintain vital, accurate, high quality and up to date information from source to delivery as part of a multi-year, multi-million-pound technology programme to enable macro and micro views of our environment. A separate but linked programme of Marine work is also currently being scoped to assess the extent of work needed to form the basis of a complementary programme.

Using satellite earth observation, professional surveyors, citizen scientists, membership organisations and legacy data, NCEA **will build a highly detailed bank of assessments and integrated datasets** covering ecological domains, spatial scales and locations. **Expert analytics and insight** will complement raw data, using a range of parameters including type, coverage, density, and change over time in flexible reporting units for users from national and local government to national parks and authorities to utility providers, private sector companies and individuals.

A pioneering partnership between Defra, Natural England, Environment Agency, Forest Research and the Joint Nature Conservation Committee, NCEA blends capability, expertise and experience to build **a richer, more comprehensive picture of** our natural environment, monitoring quality and quantity, assessing the impact of or need for interventions and helping to manage and protect our natural capital.

Acknowledgements

Thanks are due to the Environment Agency project managers, Mario Manganaro and Laura Ward for their support and enthusiasm for the work, as well as to the EA Project Steering Group for their advice. We would particularly like to thank EA colleagues and Hydrometry & Telemetry staff in the Derwent, Thames and central London catchments who provided valuable insights, data and generously contributed their time to enable and support field work. We are particularly grateful to the following for their time and support for the project: Alex Chambers, Nigel Hoad, Pawel Kania, Michael Kehinde, Andrew Pearson, Steph Rose, Rob Wilson, and Richard Woodbridge.

Contents

FIGURES

TABLES

Summary

This report describes a project commissioned by the Environment Agency (EA) in November 2021 to design and deploy a pilot groundwater temperature monitoring network (GTMN) for England (EA project reference: GA/21F/079, British Geological Survey (BGS) project reference: NEE7790). The aim of the project was to deploy a pilot GTMN within selected catchments in England to enable the EA to obtain information to inform the development of a future national GTMN for England. The project is part of Defra's four-year Natural Capital Ecosystem Assessment (NCEA) programme - a comprehensive, long-term programme to transform landscape decision-making in England by providing a rich picture of the state of terrestrial and water environment and how they are changing. In total 12 new groundwater temperature (GWT) sensors were deployed as the pilot network at 11 sites (at 10 observation boreholes (OBHs) and at one stilling well at the site of a mine discharge to surface water).

The project consisted of four tasks:

- identification of pilot catchments;
- selection of sites for instrumentation in the pilot catchments (including, a light-touch assessment of existing infrastructure in the pilot catchments, profiling of GWT at selected OBHs), and subsequent design of the pilot GTMN network;
- purchase and deployment of the monitoring equipment to the pilot sites; and
- documentation of lessons learnt for implementation of a future national GTMN.

Six catchments were considered for inclusion in the pilot GTMN, five previously identified by Ward et al (2021) in a pre-cursor study (Berkshire Downs Chalk Groundwater Body (GWB), Derwent GWB, River Itchen Chalk GWB, Thames Gravels GWB, and West Midlands surface water catchment) plus an additional GWB, the confined Chalk of central London. Following a semi-quantitative analysis of the pros and cons of each catchment against selection criteria including the degree and nature of potential sensitivity of groundwater systems in connection with surface waters; consideration of the opportunities and practicalities of deployment of groundwater temperature sensors; and, the extent of previous relevant research in the catchment, four of the six catchments were selected at a workshop on the 2nd December 2021 with the EA Project Managers and Steering Group. The four pilot catchments were: Berkshire Downs Chalk GWB, confined Chalk of central London, Derwent GWB, and Thames Gravels GWB

Since the EA do not currently hold systematic information on *in-situ* GWTs, with the vast majority of GWT data is derived from measurements of GWTs at headworks (Ascott and McKenzie, 2022), it was essential to acquire new GWT profiles for sites in advance of decisions on the design of the pilot GTMN. A long list of candidate sites was identified through an iterative process of discussion with EA project Steering Group and members of Hydrometry & Telemetry (H&T) staff in the respective EA Areas. Given the limited resources available to the project, it was estimated that new instrumentation may be able to be deployed for the pilot network at between eight to 12 sites in total or at about two to three sites per catchment. So, a target long-list of between two to three times as many candidate sites was set and a final long-list of 32 candidate sites across the four catchments was identified including 16 sites in the Berkshire Downs Chalk GWB, nine sites in the Derwent GWB, six sites in the Thames Gravels, and one site in the confined Chalk of central London. Following visits to the 32 sites across the four pilot catchments and groundwater temperature profiles were obtained for 25 OBHs, including from 16 OBHs in the Berkshire Downs, two in the Derwent, 6 in the Thames Gravels, and 1 in the confined Chalk of central London. In total, almost 1km of GWT profiles was recorded. In addition, other sites were also visited in the Derwent catchment including a number of soughs (mine outflows).

GWTs obtained from the temperature profiling range from about 8.5°C in the Derwent up to about 14°C in the confined Chalk of central London. In any given catchment there is an absolute

range in GWTs of between 1°C to 2°C with the largest absolute range in the Thames Gravels and the smallest range in the Derwent catchment. Generally, though not always, GWT was observed to gradually increase with depth below the groundwater table at unconfined sites. There is a consistent difference in absolute GWTs between the pilot catchments, with groundwater in the Derwent being systematically cooler than in the Berkshire Downs, which is in turn slightly cooler than groundwater in the Thames Gravels, which in turn is slightly cooler than the confined Chalk of central London. Comparison with air temperatures for unconfined sites shows that air temperature is the first order control on unconfined GWTs in the pilot catchments and that variation in groundwater temperatures between catchments, controlled by the national gradients in mean air temperature, is significantly greater than variation in GWTs with a given catchment.

The 16 GWT profiles obtained from the Berkshire Downs Chalk GWB enable some exploration of evidence for systematic changes in GWT within a catchment. The temperature profiles that were obtained for the Berkshire Downs catchment typically varied by about 1°C between about 9.75°C and 10.75°C and usually increased slightly with depth below the groundwater table. Overall there is a strong coherence in GWT profiles across the catchment, however, there is some evidence that GWT profiles for individual sites are influenced by the location of the OBH in the catchment (catchment setting), by borehole construction, and by lithostratigraphic controls. Relatively cool GWTs are typically present below recharge areas across interfluve areas of the catchment, e.g. between Lambourn and Pang at Oak Ash OBH, and relatively warm GWTs are associated with the lower catchment, e.g. at Marlstone Farm OBH. Intermediate GWTs are present in the mid-catchment, for example in the vicinity of the River Lambourn at the Great Shefford OBH. However, the absolute differences in GWTs between these different catchment settings are small, typically <1°C. At some sites, small changes in the GWT depth profiles may correlate with changes in Chalk stratigraphy (inferred to be associated with stratigraphic controls on local or catchment-wide groundwater flow), and borehole construction (particularly casing depth). For example, relatively cool groundwater is present within the cased-off interval at the top of the Great Shefford OBH with transitions to progressively warmer GWT at depth associated with the Upper to Middle and Middle to Lower Chalk stratigraphic transitions.

In the Derwent catchment historic measurements of water temperature from soughs (outflows of mine drainage to the surface water in the catchment) are systematically warmer, by between 1°C and 5°C, than the groundwater at Ryder House.

GWTs at the six sites in the Thames Gravels range between 10°C and 12.5°C. GWTs in the Thames Gravels OBHs are warmer than those in the OBHs from the Berkshire Downs and Derwent catchments consistent with the warmer air temperatures over the Thames Gravels. Mean GWTs at the sites are a function of the total depth (TD) of the OBHs with mean GWT increasing with OBH TD. It has been inferred that this reflects the relative cooling of static groundwater in the shallower OBHs associated with cool winter air temperatures across the catchment.

The GWT in the confined Chalk is consistently warmer than that of sites in the shallow unconfined Thames Gravels with temperatures typically in the range 13°C to 14°C. A depth profile of GWT at Ashley Gardens shows a slight cooling in groundwater temperatures in the first 20 m below the water table from about 13.7 °C down to about 13°C and then relatively constant temperatures down to a depth of about 75 m below the water table.

Based on the findings of the GWT profiling work, 11 sites (10 OBHs and one stilling well in the Derwent) were identified for inclusion in the pilot GTMN as follows: eight sites in Berkshire Downs Chalk GWB, one site in the confined Chalk of Central London, one site in the Derwent GWB, one site in the Thames Gravels. The sites were discussed and agreed with the EA Project Managers and Steering Group at a meeting on the 4th February 2022 and the infrastructure deployed throughout March 2022.

At each of the sites one or more GWT sensor was deployed in the OBH or stilling well and an addition air temperature sensor deployed in the headworks. Given that GWT measurements from a future national GTMN need to be capable of characterising the effects of climate change on GWTs over decadal time scales and that Ascott and McKenzie (2022) have already reported representative recent rates of change in shallow unconfined GWTs in the range 0.27 to 0.87°C /decade, GWT sensors and sensors in the headworks should have an accuracy of a similar order of magnitude, i.e. of +/-0.3°C or better. Consequently, for the purposes of the pilot GTMN sensors have been specified with an accuracy of +/-0.3°C or better (currently some EA GWT sensors typically have an accuracy of only +/- 0.5°C). It is recommended that GWT data is collected from these sensors at 1/hr for consistency with commonly reported air temperature data. This would reflect the potential response times of the fastest responding groundwater systems (e.g. shallow unconfined Thames Gravels) to rapid recharge events such as the passage of frontal rainfall systems or summer convective storm events.

Lessons learnt from the deployment of the pilot GTMN have been compiled and include:

- observations related to the aims and requirements of a future GTMN;
- ‘ownership’ and management of a GTMN within the EA;
- the effectiveness of the catchment and site selection processes to identify representative catchments and sites for the pilot study;
- the use of existing sites and GWT monitoring infrastructure; OBH metadata and conditions;
- equipment and telemetry considerations; observations related to the installation of the pilot sensors; and,
- and considerations of the management and maintenance, data storage, QA and analysis associated with the pilot network.

1 Introduction

In 2021 the Environment Agency (EA) commissioned the British Geological Survey (BGS) to develop recommendations for enhancements to existing groundwater monitoring networks and for setting up new groundwater monitoring networks (Ward et al., 2021) that included:

- enhanced, systematic monitoring of groundwater-quality,
- monitoring of groundwater-dependent terrestrial ecosystems,
- monitoring groundwater temperature, and
- monitoring of groundwater ecology

As part of that study, a series of recommendations were made related to the establishment of pilot catchments for groundwater temperature (GWT) monitoring, prior to the development, at some future date, of a national groundwater temperature monitoring network (GTMN).

This report describes a project ('the project') subsequently commissioned by the EA in November 2021 to design and deploy a pilot groundwater temperature surveillance network for England (EA project reference: GA/21F/079, BGS project reference: NEE7790). The project is part of Defra's four-year Natural Capital Ecosystem Assessment (NCEA) programme - a comprehensive, long-term programme to transform landscape decision-making in England by providing a rich picture of the state of terrestrial and water environment and how they are changing (see EA Forward above for details of the NCEA).

The aim of the project was to deploy a pilot GWT monitoring network within selected catchments in England to enable the EA to obtain information to inform the development of a future national GTMN for England. As described in the Project Specification, a future GTMN will need to establish a representative, robust baseline for GWT and be capable of monitoring long term change in GWTs, for example from climate change. The data collected by a future national GTMN should meet the requirements of the NCEA, i.e. it should enable long term monitoring capable of observing trends and understanding the implications of government policies. In addition, the EA require that a future GTMN should also be capable of providing information on GWT issues where the EA has regulatory interests and responsibilities. For example, these include changes in GWT from ground source heating and cooling (GSHC) schemes, the monitoring and management of legacy historic anthropogenic activities, such as mine drainage where GWT may impact the environment, and potential changes in GWT and how they may affect temperature-sensitive groundwater-dependent terrestrial ecosystems (GDTEs) and surface waters, such as cold-water refuges for salmon and trout, or impact ecosystems such as those of Chalk streams.

The project consisted of the following tasks:

- Task 1 – identification of pilot catchments based on a light-touch review of existing data for catchments previously identified by Ward et al. (2021).
- Task 2 – following a light-touch review of existing infrastructure in the pilot catchments and profiling of GWTs at selected OBHs, design the pilot GWT surveillance network to include recommended instrumentation, monitoring locations, depth of GWT observations, and monitoring frequencies.
- Task 3a & 3b – a. purchase and deploy instrumentation in the pilot network and provide appropriate training materials for EA field staff, and b. assess lessons learnt for implementation of a future national GWTMN.

The structure of this report reflects the project activities. Section 2 of this report documents the process and decisions that led to the identification of the pilot catchment that were signed-off by the EA Project Managers and Steering Group at a meeting on the 2nd December 2021. Section 3 of this report details the work of Task 2 and presents the justification for and description of the design of the pilot GWT network including choices of instrumentation in each of the pilot catchments. The pilot network design was signed-off by the EA Project Managers and Steering Group at a meeting on the 4th February 2022.

Section 4 summarises the lessons learnt from the establishment of the pilot GWT network and includes notes on information and evidence gaps and proposals for a series of prioritised options for future actions. These lessons learnt were presented to the EA Project Managers and Steering Group at an end of project meeting in the 31st March 2022. Throughout sections 2 and 3 of the report there are breakout boxes noting specific lessons learnt and these are collated, and in some cases expanded on, in section 4.

2 Selection of pilot catchments

Based on an analysis of EA-owned boreholes in the National Groundwater Level Archive (NGLA) network and considering the EA's existing surface water temperature monitoring network, Ward et al. (2021) recommended the selection of two pilot catchments at the groundwater body (GWB) scale. It was proposed that one should be one of two Chalk-dominated groundwater bodies and that the second catchment should be one from three other proposed catchments. The five catchments proposed by Ward et al (2021) for consideration were:

- The Berkshire Downs Chalk GWB (Chalk)
- the River Itchen (Chalk)
- Derwent GWBs (Carboniferous Limestone and Millstone Grit)
- Thames Gravel GWB (Sand and Gravel)
- West Midlands Surface Water Catchment (multiple GWBs)

with the justification for these catchments given in Table A1 in the Appendix. Ward et al (2021) noted that the criteria for selecting the second, non-Chalk, pilot catchment were "potentially vast" and that "further discussion is needed to select and refine the proposed pilot catchments".

Note that in contrast to the recommendations of Ward et al (2021), the Project Specification for the current project required three catchments to be identified from the list of five candidates provided by Ward et al. (2021). The following section describes the approach adopted for the selection of the pilot catchments.

2.1 ASSESSMENT CRITERIA FOR CATCHMENT SELECTION

Working with the EA project manager (PM) and Steering Group (SG) via the weekly project management meetings and via e-mail correspondence, the BGS team developed a set of criteria to inform the pilot catchment selection process. These criteria drew on the EAs current aims for the wider national GTMN, as articulated in the Project Specification and concepts related to selection criteria in Ward et al. (2021).

The current EA aims for a GTMN can be summarised as follows:

- provide baseline data from which to measure changes in GWTs from seasons to decades (25+ years)
- provide information to enable the development of strategies to manage future impacts of climate change, and in particular climate warming on groundwater systems
- to provide evidence to support EA decisions to grant licences and permits and undertake other regulatory functions for a range of activities, including for example:

    - ground source heating/cooling schemes (GSHC),
    - groundwater abstractions, and
    - any other activities where changes in GWT could have an impact of the receiving environment and particularly groundwater dependent terrestrial ecosystems (GWDTEs).
- The network should be a national-scale network to establish a representative, robust baseline for GWT observation and should be capable of monitoring long term change.
- The network should be capable of providing observations related to local issues such as changes in GWT on GSHC schemes.
- The network should enable an assessment of GT changes on cold-water refuges for salmon and trout, the impact on ecology, in groundwater fed wetlands and surface waters, such as Chalk streams.
- The network should be unbiased and statistically representative.

Lessons learnt 1.1 & 1.2: The aims or requirements for a monitoring network are very high-level and may benefit from refinement prior to the commissioning of a new national GTMN. The requirement for a long-term national GWT change monitoring network is potentially quite different from a GWT monitoring network to support regulatory activities or for monitoring sites to address particular data requirements, such as improved understanding of groundwater temperature in the vicinity of groundwater-supported river reaches associated with salmonid spawning.

There may be multiple users of GWT monitoring data within the EA each with different requirements from such data.

Based on the above considerations, the following selection criteria were used for the assessment of the five potential pilot catchments:

Potential for temperature sensitive groundwater systems in connection with surface waters

1. Are there temperature-sensitive groundwater bodies and hydraulically connected GWDTEs and surface waters in the catchment?
2. Is there unconfined Chalk in the catchment?
3. Is there a high baseflow river in the catchment?
4. Are there operational GSHC schemes within the catchment?

Opportunities for instrumentation

5. Are there multiple opportunities for instrumentation of EA boreholes?
6. Are there opportunities for instrumentation of streams near to EA boreholes within the catchment?
7. Are automated data loggers capable of temperature monitoring already deployed in EA boreholes within the catchment?
8. Are telemetered groundwater levels already being obtained from EA boreholes within the catchment?
9. Are there EA staff available to facilitate access to EA infrastructure in a timely manner during the design and the implementation phases of the pilots?
10. Sustainability and practicality of access during the Pilot phase?

Extent of previous relevant research in the catchment

11. Has there been previous research undertaken on GWT in the catchment?
12. Has there been previous work undertaken to model the impact of climate change on groundwater in the catchment?
13. Has there been previous work on the temperature sensitivity of GWDTEs or groundwater-related surface water ecosystems?
14. Is there a 3D geological model and groundwater model of the catchment?

2.2 ANALYSIS OF SUITABILITY OF IN-SCOPE CATCHMENTS

Each of the five catchments suggested by Ward et al (2021) as potential pilot catchments (Table A1.) are schematically illustrated Figures 1 to 5 with high-level graphical summaries of key characteristics.

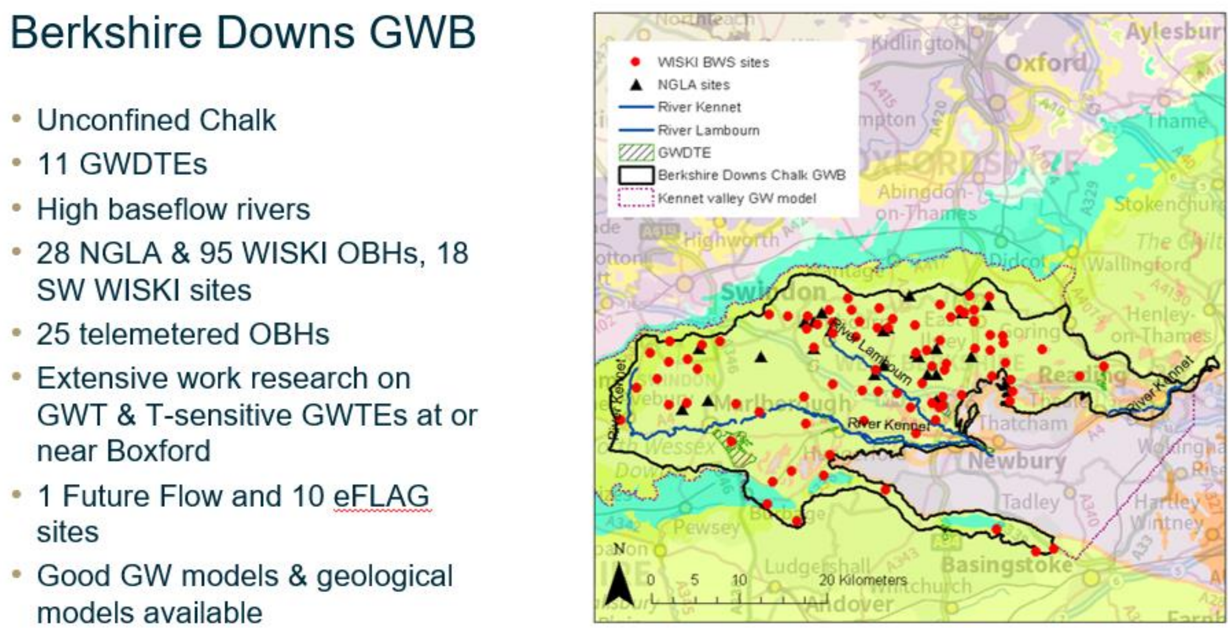

Figure 1 Graphical summary of Berkshire Downs GWB. Contains BGS data © UKRI 2022. Contains Environment Agency data © 2022 Copyright and database rights. Contains Ordnance Survey data © Crown Copyright and database right 2022. Ordnance Survey Licence No. 100021290 EUL.

River Itchen

- Unconfined Chalk
- 66 GWDTE's in Test & Itchen
- 5 NGLA & 279 WISKI OBHs & 27 SW WISKI sites
- 34 OBHs telemetered
- 1 Future Flows site & 2 eFLAG sites
- No peer-reviewed work on T-sensitive GWDTEs
- Good GW & geological models

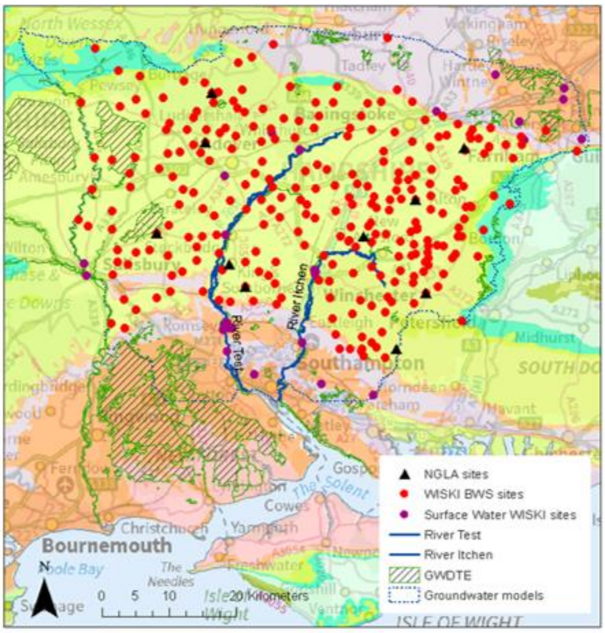

Figure 2 Graphical summary of River Itchen. Contains BGS data © UKRI 2022. Contains Environment Agency data © 2022 Copyright and database rights. Contains Ordnance Survey data © Crown Copyright and database right 2022. Ordnance Survey Licence No. 100021290 EUL.

West Midlands SWBs

- Large area with 278 GWDTEs
- 83 NGLA & 663 WISKI sites
- 42 sites within the West Midlands are on GWDTEs
- 83 sites telemetered with high density near Shropshire Groundwater Scheme
- Extensive work research on GWT & T-sensitive GWTEs in Tern catchment
- 1 site included in Future Flows and eFLAG
- Numerous GW models and geological models available

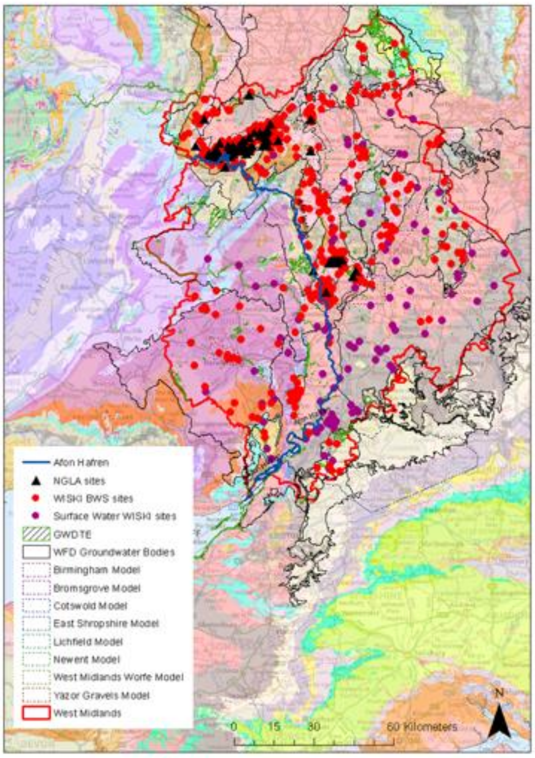

Figure 3 Graphical summary of West Midlands SW catchment. Contains BGS data © UKRI 2022. Contains Environment Agency data © 2022 Copyright and database rights. Contains Ordnance Survey data © Crown Copyright and database right 2022. Ordnance Survey Licence No. 100021290 EUL.

Thames Gravels GWB

- 7 GWDTEs
- Moderate baseflow
- 1 NGLA & 4 WISKI OBHs
- 1 telemetered OBH
- No systematic research into GWT or effects of CC on GW resources
- No peer-reviewed work on T-sensitive GWDTEs
- Three GW models & geological models available

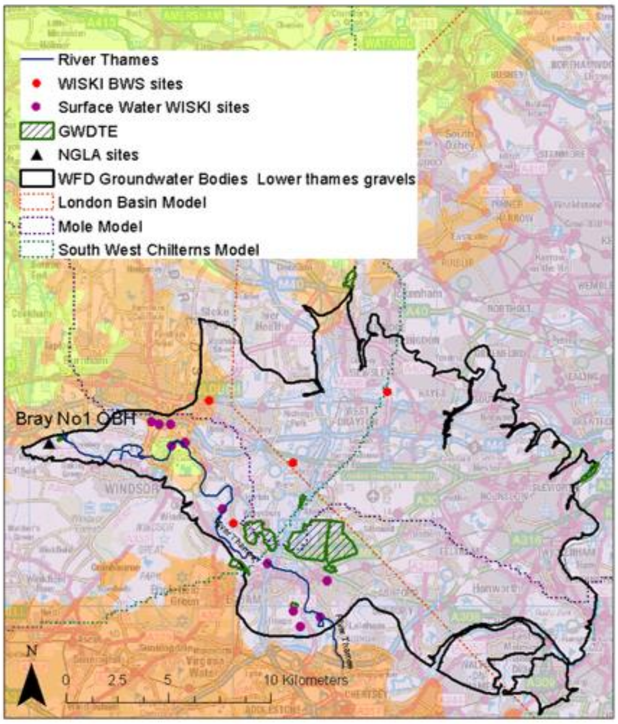

Figure 4 Graphical summary of Thames Gravels GWB. Contains BGS data © UKRI 2022. Contains Environment Agency data © 2022 Copyright and database rights. Contains Ordnance Survey data © Crown Copyright and database right 2022. Ordnance Survey Licence No. 100021290 EUL.

Derwent GWB

- Carb. Lstn. GWB high vulnerability, Millstone Grit GWB medium vulnerability & 30 SSSI in catchment
- Moderate baseflow
- 2 NGLA & 12 WISKI OBHs & 6 SW WISKI sites
- No OBH telemetry in GWBs
- No systematic research into GWT
- One Future Flows but no eFLAG site
- No peer-reviewed work on T-sensitive GWDTEs
- Derwent GW model & geological models available

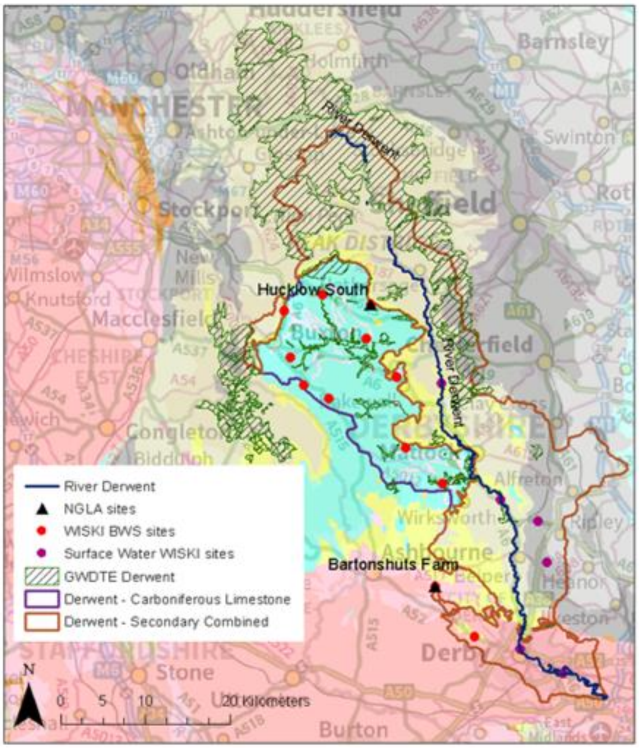

Figure 5 Graphical summary of Derwent GWBs. Contains BGS data © UKRI 2022. Contains Environment Agency data © 2022 Copyright and database rights. Contains Ordnance Survey data © Crown Copyright and database right 2022. Ordnance Survey Licence No. 100021290 EUL.

Each of the five catchments were assessed against the catchment selection criteria (section 2.1) with the assessments detailed in the Appendix in Table A2. In Table A2, for each catchment, notes on data or evidence available is listed against each assessment criterion, followed by a list of pros and cons and finally a semi-quantitative high (3), medium (2) or low (1) scoring.

Table 1 is a summary of the scores from these assessments for each catchment and Table 2 is a qualitative assessment of the pros and cons of each catchment for inclusion in the pilot study. These materials were prepared for and discussed at a meeting of the project Steering Group on the 2nd Dec 2021.

Table 1 Summary of assessment criteria scores (note W Midlands scored relatively highly due to the relatively large area compared with the other GWBs)

Criterion	**Berks Downs**	**R. Itchen**	**W Midlands SWBs**	**Thames Gravel GWB**	**Derwent GWBs**
	Chalk catchments	Chalk catchments			
Temperature sensitive groundwater systems					
1	3	3	3	3	3
2	3	3	1	1	1
3	3	3	2	2	2
	9	*9*	*6*	*6*	*6*
Opportunities for instrumentation					
4	3	2	3	3	3
5	3	2	3	2	1
6	3	2	3	1	2
7	3	3	3	2	1
8	3	3	1	3	3
9	3	3	1	3	1
	18	*15*	*14*	*14*	*11*
Previous research context					
10	3	1	3	1	3
11	3	2	2	1	2
12	3	1	1	1	1
13	3	2	2	2	2
	12	*6*	*8*	*5*	*8*
Total	**39**	**30**	**28**	**25**	**25**

Table 2 Summary of high-level pros and cons for each catchment.

GWB / Catchment	**Pros**	**Cons**
Berkshire Downs Chalk GWB (Chalk)	A Chalk GWB with multiple NGLA & WISKI boreholes, multiple automated data loggers and telemetered sites, & extensive previous research in to GT in the Pang-Lambourn	Limited telemetry in headwaters & none directly associated with GWDTEs.
River Itchen (Chalk)	A Chalk GWB with numerous GDTEs & multiple NGLA & WISKI boreholes, multiple automated data loggers & telemetered sites.	Limited headwater telemetry is available. Limited previous work on GW & CC & GWDTEs
Derwent GWBs (Carboniferous Limestone and Millstone Grit)	Two NGLA & 12 WISKI sites with 12 automated loggers listed in BWS. 6 surface water sites. One NGLA site in Future Flows study. Extensive previous research on deep geothermal waters in Derbyshire Dome.	No SW sites within 10 kms of NGLA sites & no telemetry in GWB. No previous research on shallow GT & interaction with GWDTEs or SWs

GWB / Catchment	Pros	Cons
Thames Gravel GWB (Sand and Gravel)	One NGLA & 4 WISKI sites with SW sampling sites within ~5km of NGLA OBH. Four active automated loggers (BWS) & one telemetered site. GTs may be influenced by urban heat island effect.	Although there are number of studies of groundwater heating/cooling in the gravels there is no previous research on shallow GT & interaction with GWDTEs or SWs.
West Midlands Surface Water Catchment (multiple GWBs)	Multiple NGLA & WISKI sites. Multiple GWDTEs. Multiple loggers & telemetered OBHs. Extensive research on GT in the R. Tern sub-catchment. One NGLA site in Future Flows & eFLAG studies	Very large area with multiple GWBs. Vast majority of sites have no data on installed equipment recorded. Monitored sites near abstractions, e.g. Shropshire groundwater scheme.

It was evident that all five catchments were potentially suitable for use in the GWT pilot study (Tables 1 and 2). The Berkshire Downs catchment was the highest scoring catchment as well as being a Chalk catchment and was hence selected as the preferred Chalk pilot catchment (although it was noted that it does not contain any salmonid streams). Following discussion with the EA Project Managers and the Steering Group at the workshop on the 2nd December 2021, based on a balance between the opportunities offered by each of the remaining catchments to contribute to the pilot network and the potential of different combinations of catchments to provide insights and lessons learnt for a future GWTN, it was agreed that the following three catchments were to be used in the pilot study:

- Berkshire Downs GWB (Chalk)
- Thames Gravels GWB
- Derwent GWB

During the site selection phase of the project (Section 3) it became apparent that the Thames Gravels, although potentially providing GWT data from a catchment that was subject to multiple urban impacts including urban heat island effects, sites were unlikely to be suitable for the monitoring the effects of GSHC schemes. Consequently, the confined Chalk of central London was added to the pilot monitoring network. Table 3 is a high-level mapping of which catchments were potentially capable of providing GWT information relevant to requirements of the pilot network.

Table 3 Ability of potential pilot catchments to address requirements of the GWT pilot network.

Pilot catchment to provide information on	**Berkshire Downs**	**Derwent**	**Thames Valley**	**Confined Chalk London**
National temperature gradient /	Y	Y	Y	Y
Climate Change	Y	Y	Y	Y
GWT/SWT linkages	Y	Y	Y	
GWT & GWDTEs	Y	Y		
Chalk systems	Y			
Ground heating / cooling				Y
Urban heat island			Y	Y
Instrumentation deployment	Y	Y	Y	Y
Telemetry	Y	Y	Y	Y

Lessons learnt 2.1: Criteria for selecting the pilot catchments were semi-quantitative, pragmatic, and largely focussed on practical aspects. They benefitted significantly from the detailed catchment-specific knowledge and experience of the EA PMs and members of the Steering Group. However, the pilot catchments do not include a Permo-Triassic Sandstone or other sandstone-dominated catchment in England and do not include aquifers in the any of the four areas in the 'North' region of the EA. To complement the current pilot study, and prior to the commissioning of a national GTMN, obtaining GWT profiles for OBHs from a Permo-Triassic Sandstone catchment and /or from OBHs in representative aquifers from at least one catchment in the four 'North' regions of the EA may provide useful information to inform the design of a national GTMN.

3 Design proposal of temperature pilot network

The following section describes the site and instrumentation selection and design of the pilot network. Central to this activity was the acquisition of new GWT profiles for a number of candidate sites in each of the pilot catchments to inform the design of the pilot network - this was essential since the EA do not currently hold systematic information on *in-situ* GWTs as the vast majority of their GWT data is derived from measurements of GWTs at headworks (Ascott and McKenzie, 2022).

The following section of the report includes a description of how a long list of candidate sites in each of the pilot catchment was identified in discussion with EA project Steering Group members and how GWT profiles and associated metadata was acquired for those sites (section 3.1). Section 3.2 describes and discusses the resulting GWT profiles, and section 3.3 details of the recommendations for the instrumentation of the pilot network that were discussed and agreed at the meeting of the EA Project Managers and Steering Group on 4th February 2022.

3.1 SELECTION OF CANDIDATE SITES

The long-list of candidate sites in each of the four pilot catchments was established through an iterative process of discussions with hydrogeologists and H&T staff in the respective EA Areas. The BGS project team collated available information related to site access, construction and completion, and existing instrumentation for sites within each pilot catchment provided by the EA Project Managers. They then met with the EA Steering Group member that was the technical lead for each of the pilot catchments to agree a long-list of potential or candidate sites for instrumentation. Meetings were held with Nigel Hoad (Thames Gravels and Berkshire Downs Chalk) on 14th Dec 2021 with Andrew Pearson and colleagues (Derwent) on 16th Dec 2021, and additional information on the confined Chalk of Central London was provided by Michael Kehinde by email correspondence throughout January 2022.

Given the resources available to the project, it was estimated that new instrumentation may be able to be deployed for the pilot network at between 8 to 12 sites (or at about 2 to 3 sites per catchment). So, a target long-list of between two to three times as many candidate sites was set. Based on the considerations above and the available infrastructure within each catchment a long-list of 28 candidate sites across the four catchments was identified as follows:

- sixteen in the Berkshire Downs;
- five in the Derwent;

- six in the Thames Gravels and
- one in the confined Chalk of Central London.

The locations of these long-listed sites for instrumentation are illustrated in Figures 6 to 8 and details of their construction, completion and current instrumentation are given in Appendix Tables A3a to A3e.

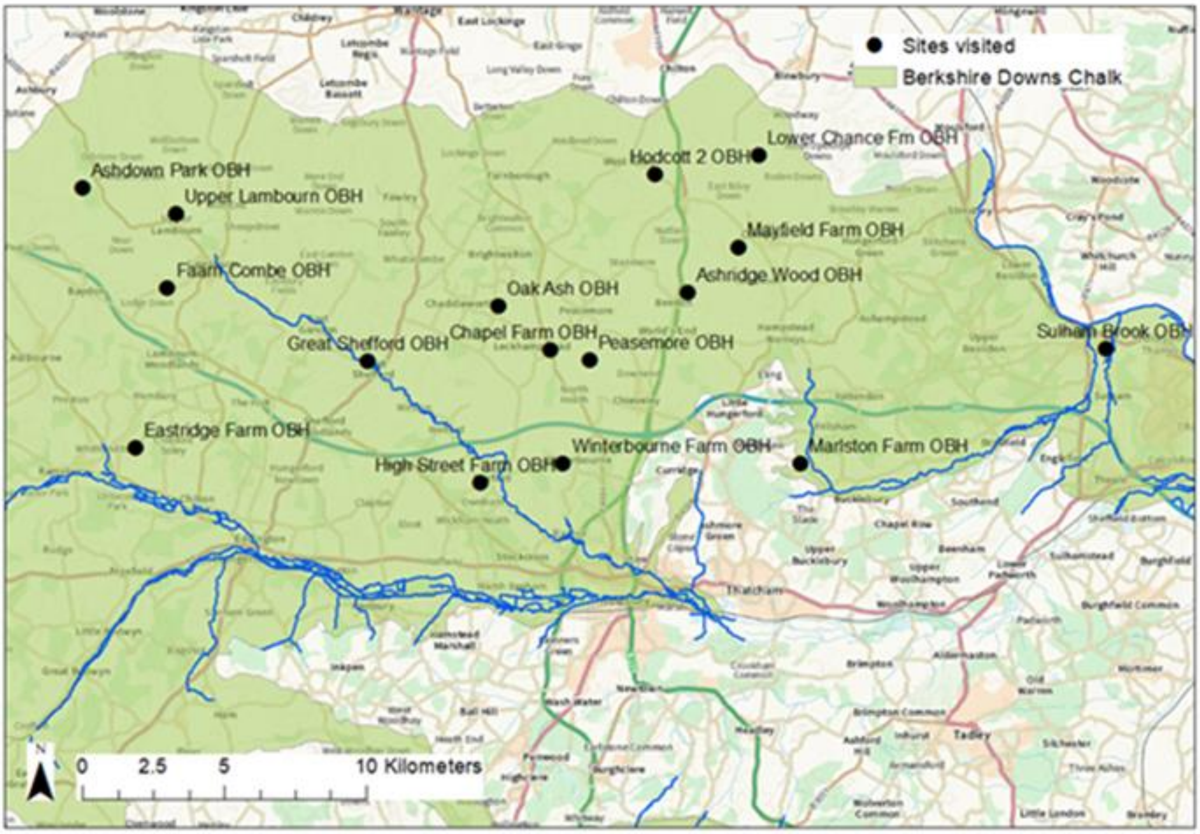

Figure 6 Location of Berkshire Downs candidate sites. Contains BGS data © UKRI 2022. Contains Environment Agency data © 2022 Copyright and database rights. Contains Ordnance Survey data © Crown Copyright and database right 2022. Ordnance Survey Licence No. 100021290 EUL.

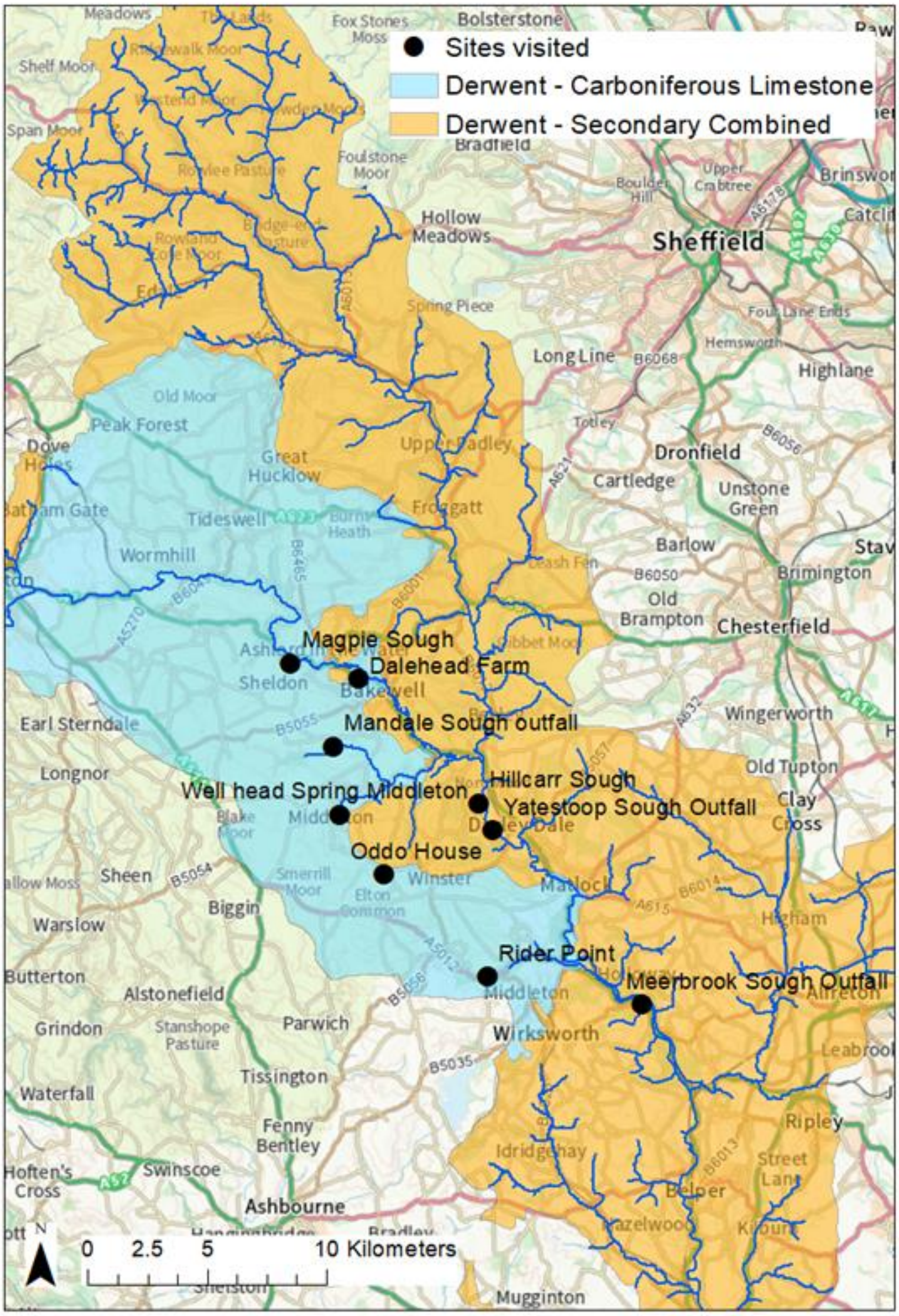

Figure 7 Location of Derwent candidate sites. Contains BGS data © UKRI 2022. Contains Environment Agency data © 2022 Copyright and database rights. Contains Ordnance Survey data © Crown Copyright and database right 2022. Ordnance Survey Licence No. 100021290 EUL.

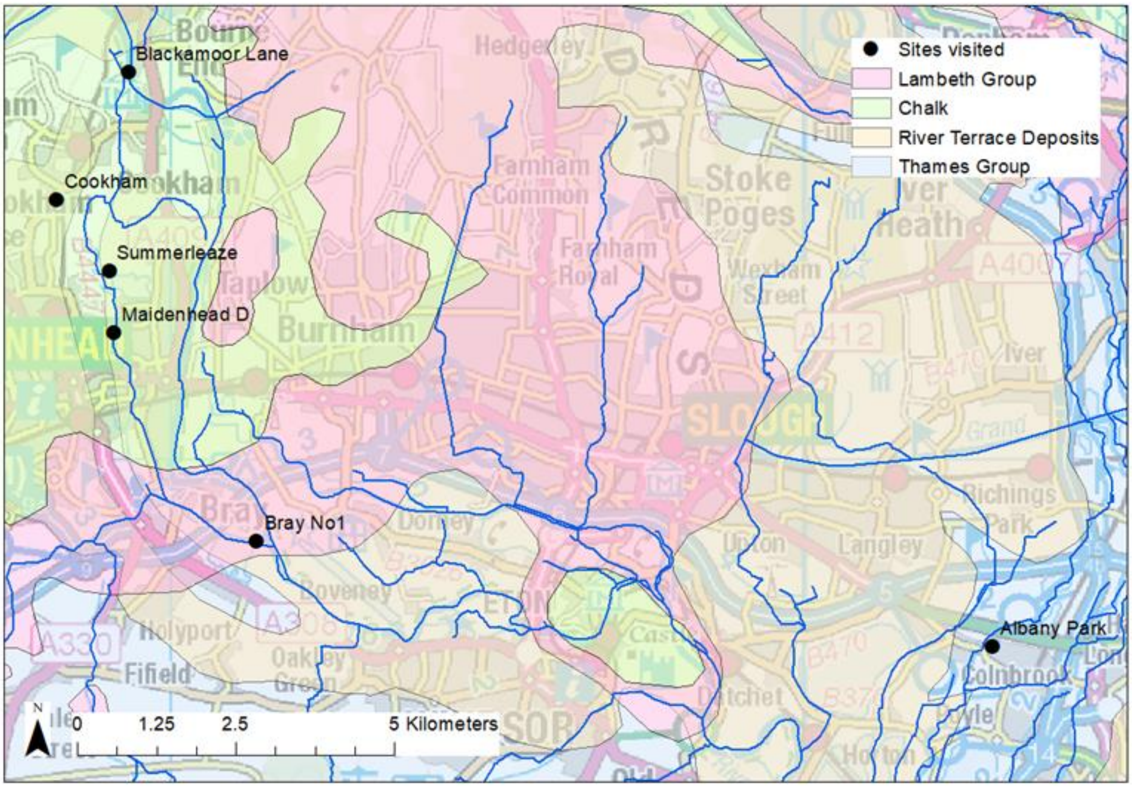

Figure 8 Location of Thames Gravels candidate sites. Contains BGS data © UKRI 2022. Contains Environment Agency data © 2022 Copyright and database rights. Contains Ordnance Survey data © Crown Copyright and database right 2022. Ordnance Survey Licence No. 100021290 EUL.

Lessons learnt 3.1 to 3.3: Although it was simple to identify a range of sites representative of contrasting hydrogeological and climate settings, it was more challenging to identify suitable sites that may reflect site specific influences on GWTS. For example, it was difficult obtaining information regarding active GSHC schemes and data on the location of temperature-sensitive GDTEs. The design of a national GTMN may benefit from additional work being undertaken to: understand spatial variation in the potential sensitivity of GWT to climate change; develop a better understanding of temperature-sensitivity of specific GDTEs in context of regulatory requirements; and, to investigating evidence for GWT change related to GSHC schemes as a function of their location, type, and operation.

The pilot network was by necessity restricted to existing monitoring sites. If this is also to be the case for a national GTMN, then such a network must be representative of the diversity of hydrogeological settings and so will not be “unbiased and statistically representative”.

There may be sites on the EAs list of OBHs for decommissioning that may be appropriate for inclusion in a future national GTMN. Consequently, to provide the opportunity for optimum GTMN design, an additional criterion in the EAs OBH decommissioning assessment should be the potential for inclusion of an OBH in a future GTMN.

There would be benefit in compiling an accurate, up-to-date inventory of all EA and third-party instrumentation currently deployed that is capable of providing a telemetered feed of GWT to WISKI.

3.1.1 Acquisition of GWT profiles for the candidate sites

Each of the candidate sites were visited to obtain new GWT profiles and confirm borehole construction and existing instrumentation at the sites. Prior to these visits, the EA Project Management Team provided information on construction and instrumentation for the candidate sites as well as other relevant contextual information such as groundwater level and temperature time series. Note that BGS characterisation of the candidate sites showed that some of the EA information regarding construction and installed instrumentation was not always accurate. Candidate sites were also checked for their status with respect to the EA's current site decommissioning review.

Fieldwork in all three pilot catchments was undertaken by a team of BGS staff between 7th and 21st Jan 2022. All visits were pre-arranged with local EA staff, and permissions obtained from land-owners where required. Once on site, a set field protocol ensured the same data was taken at all sites, and recorded systematically on field sheets.

Upon entry to the site, staff assessed any potential hazards in and around site including traffic and environmental factors. Each borehole was uncovered and the current EA equipment was inspected; the sensor model, range, and logger details, were recorded wherever possible. If available, a review of completion details was undertaken and recorded at this time, including the depth to any existing sensors and spare cabling. A photograph was taken of the site and mobile phone signal check before starting to dip the groundwater level. If necessary, any EA instrumentation was removed from the borehole at this time by the EA staff member present on site. Once a groundwater dip was recorded, a plumb line was used to assess the total depth. In the case of any shallow obstructions (<30m datum), a small camera could be employed to assess.

Finally, a temperature profile was taken from each site. The temperature probe was set up with a field laptop to be able to visualise the profile in real time. The probe was set to fast linear in setup and the logging frequency set to maximum (1-2 seconds) for depth and temperature. The probe was lowered carefully down and into water to avoid hydrostatic shock, and held under 0.3m of water for 5 minutes to allow the probe temperature to equilibrate in water. Once equilibrated, the probe was brought back to water surface and then profiling downwards could commence. Live readings were used to ensure that data are being collected at least at 0.25 m resolution. At a number of sites repeat depth profiles were obtained. There was some evidence in the results from repeat profiling of disturbance to the water column at some sites. Once recorded, logging was stopped and downloaded to the field laptop. Further assessment of these profiles was completed back in the office. Table A3 lists the metadata collected at each of the candidate sites, including: borehole name , eastings and northings, notes on any access issues, OBH construction, TD, and current instrumentation. Data from the depth profiles have been compiled into a spreadsheet ("Compiled T profiles.xls") that was provided to the EA at the end of the project.

3.2 SUMMARY OF DATA AND FIELD SURVEYS

Twenty-eight sites were visited across the four pilot catchments and groundwater temperature profiles were obtained for the 25 OBHs (the other three sights were soughs in the Derwent catchment), including from 16 OBHs in the Berkshire Downs, 2 in the Derwent, 6 in the Thames Gravels, and one in the confined Chalk of central London (Tables A3a to A3d). In total, almost 1km of groundwater temperature profiles were recorded across the 25 OBHs.

Figure 9 shows the GWT data the 25 depth (below groundwater level) profiles plotted on a consistent temperature / depth scale across the three pilot catchments. In addition, it includes four historic GWT depth profiles from 4 confined sites in the Chalk of the Central London from 30/01/2020.

Figure 9 shows that measured GWTs range from about 8.5°C in the Derwent up to about 14°C in the confined Chalk of central London, and that in any given catchment there is an absolute range in GWTs of between 1 to 2°C with the largest absolute range in the Thames Gravels and the smallest range in the Derwent catchment. Generally, though not always, GWT was observed to gradually increase with depth below the groundwater table.

There is a consistent difference in absolute GWTs between the pilot catchments with groundwater in the Derwent being systematically cooler than in the Berkshire Downs, which is in turn slightly cooler than groundwater in the Thames Gravels, and which in turn is slightly cooler than the confined Chalk of central London. Figure 10 illustrates this difference in mean GWTs between the catchments and shows that the first order control in the unconfined GWTs in all three pilot catchments is air temperature. Figure 10 shows that mean GWT in the pilot catchments is an approximately linear function of both mean maximum and minimum December air temperature (where air temperatures are taken from Met Office stations in or near each of the pilot catchments).

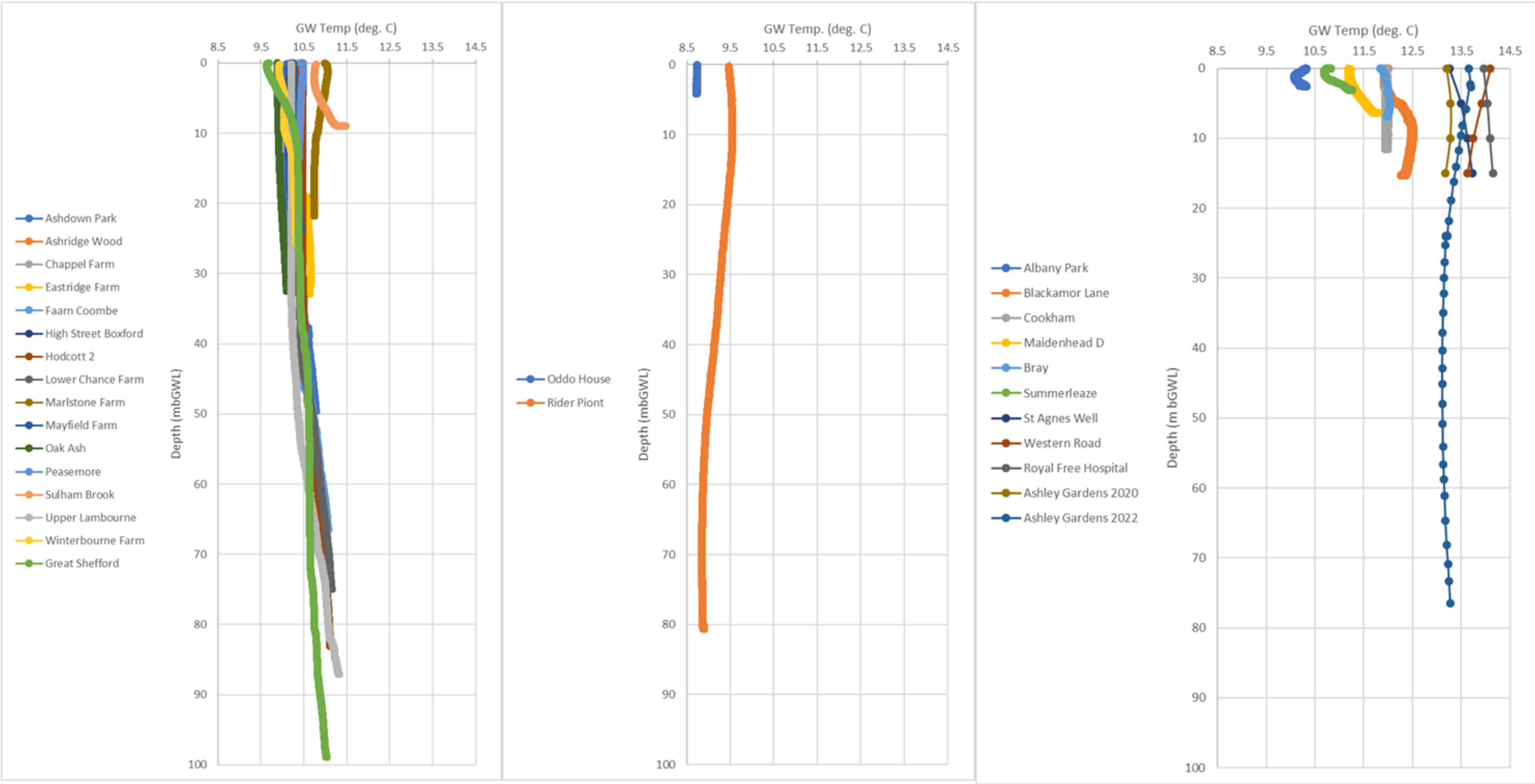

Figure 9 Groundwater temperature profiles for 28 sites across the four pilot catchments.

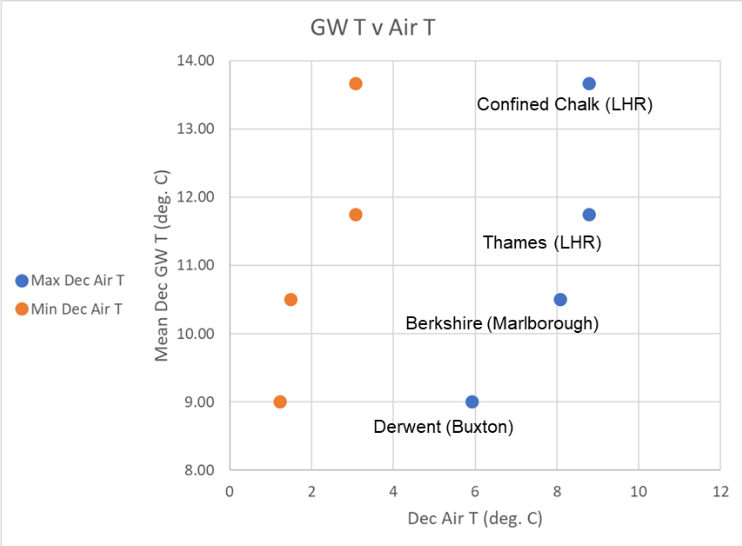

Figure 10 Illustration of relationship between mean GWT and minimum and maximum December air temperature for each of the three pilot catchments.

3.2.1 Berkshire Downs

16 sites were visited in the Berkshire Downs between 05/01/22 and 07/01/22 to obtain GWT depth profiles. Sites on the unconfined Chalk were selected, following discussion with Nigel Hoad, EA, to be representative of three broad hydrogeological settings, as follows: recharge / interfluve areas (e.g. Ashdown Park, Lower Chance Farm and Oak Ash); adjacent to Chalk streams (e.g. Upper Lambourn and Great Shefford); and, lower catchment settings (e.g. Marlstone Farm and Sulham Brook).

The temperature profiles that were obtained typically varied between about 9.75°C and 10.75°C and typically increased slightly with depth below the groundwater table. Based on Figure 11, it is clear that across the catchment there is a strong coherence in GWT. At individual sites the GWT profiles are influenced by the location of the OBH in the catchment. At some sites, minor changes in the GWT depth profiles correlate with changes in Chalk stratigraphy (inferred to be associated with stratigraphic controls on local or catchment-wide groundwater flow), and borehole construction (particularly casing depth) also influences some of the GW T depth profiles. For example, Figure 12 is an illustration of how GWT at the Great Shefford OBH appears to be influenced by both borehole construction (cased interval) and how changes in GWT with depth corresponded with depth intervals where there are changes in Chalk stratigraphy. Relatively cool groundwater is within the cased-off interval down to 12.5 mbGL. There is then a transition to progressively warmer waters below the Upper-Middle Chalk transition at 24.38 and 35.05 mbGL and the Middle-Lower Chalk transition between 76.81 to 82.91 mbGL.

Figure 13 illustrates how the location of boreholes within the catchment influences GWT. Relatively cool GWTs are typically present below recharge sites in the interfluve area between Lambourn and Pang at Oak Ash OBH and relatively warm GWTs are associated with the lower catchment at Marlstone Farm OBH. With intermediate GWTs present in the mid-catchment in the vicinity of the R. Lambourn at Great Shefford. However, the absolute differences in GWTs between these different catchment settings are small, typically <1°C, compared with differences in GWTs between the Berkshire Downs and other pilot catchments (Figure 9).

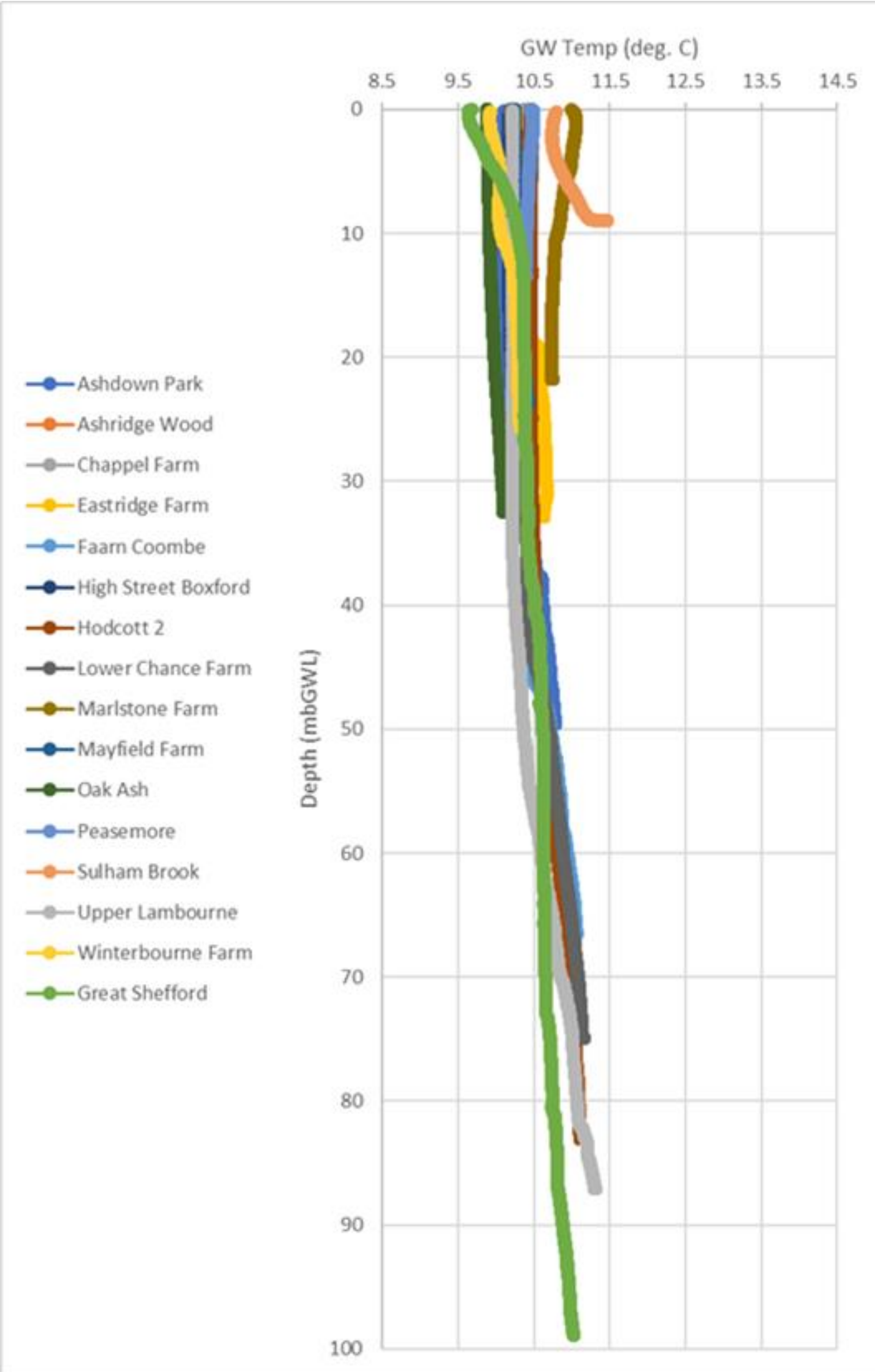

Figure 11 Berkshire Downs GW T depth profiles as a function of depth below groundwater level.

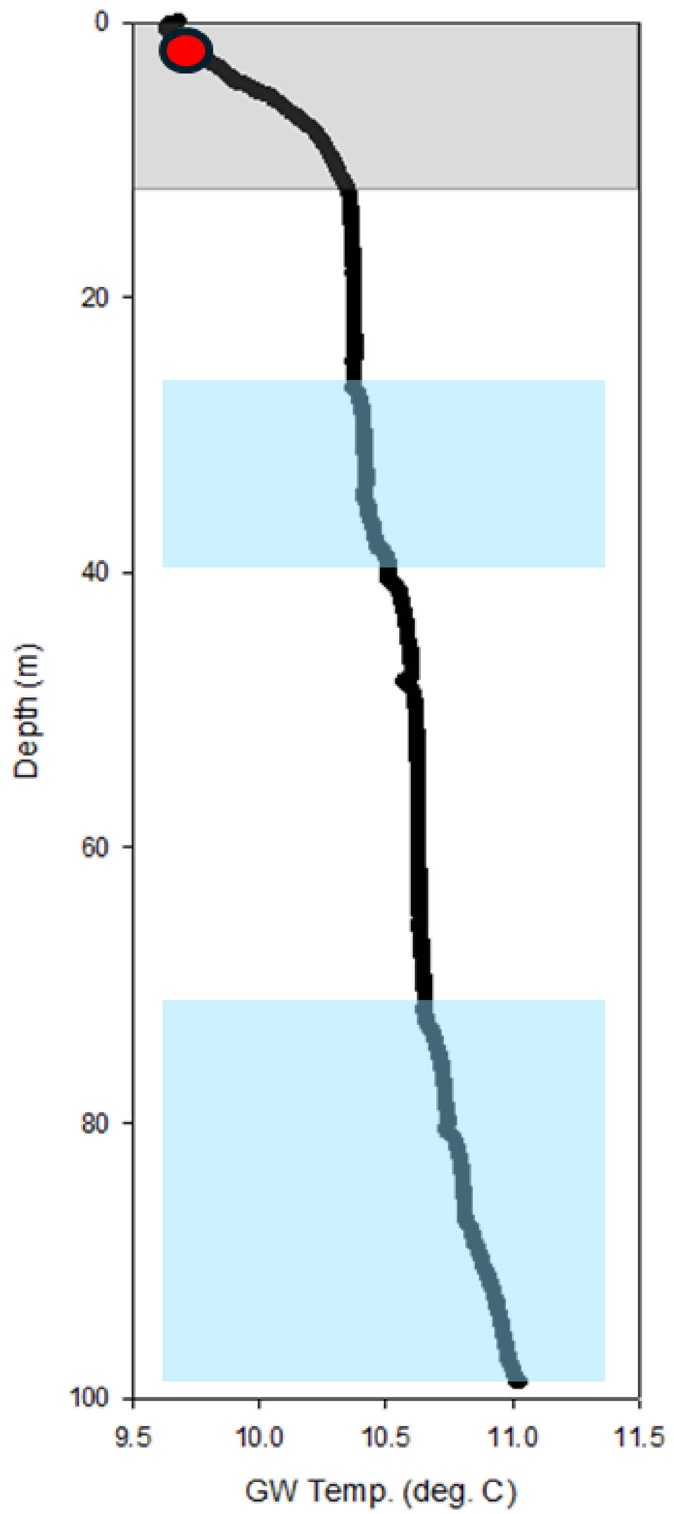

Figure 12 Illustration of change in GWT with depth at Great Shefford. The current EA GW level transducer (red dot) is in the cased interval (grey) at 1.9 mbGL. The OBH is cased down to 12.5 mBGL. There are transitions is Chalk stratigraphy from Upper to Middle Chalk between 24.38 and 35.05 mbGL and from Middle to Lower Chalk between 76.81 to 82.91 mbGL (pale blue).

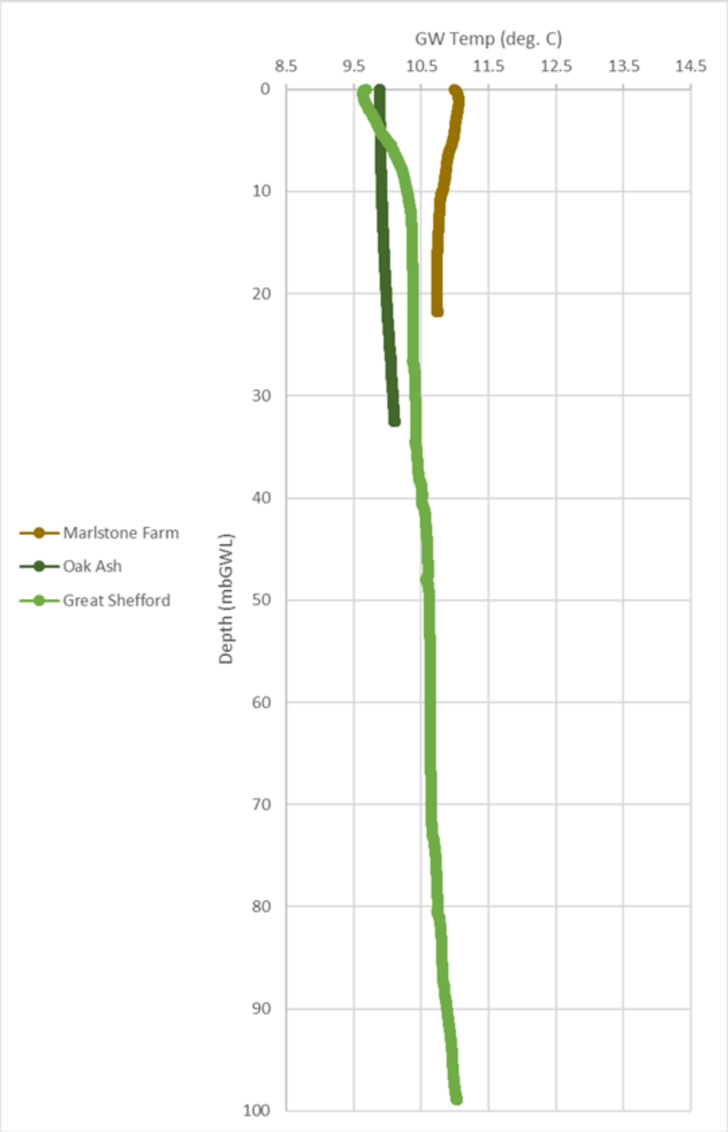

Figure 13 GWT depth profiles as a function of depth below groundwater level for three representative sites in the Lambourn catchment.

3.2.2 Derwent

Two observation boreholes, Ryder Point and Oddo House, were visited, however, a new GWT profile was only obtained from Ryder Point OBH as the collapse of the Oddo House borehole prevented a GWT profile of significant depth being obtained. Figure 12 shows the GWT profile obtained for Ryder House OBH and summarises some historic groundwater level and GWT time series data for this site. Figure 14 summarises historic water temperature data for six soughs (mine outflows) in the Derwent catchment.

GW temperature at Ryder House is relatively cool compared with GWTs obtained from OBHs in other pilot catchments. It shows limited variation with depth although it decreases slightly with depth from about 9.5°C at the water table to about 8.75°C at about 80 mbGWL. Details of the completion are uncertain. It is cased with 47 mm dia. tubing down to 100.16 mbGL, but it is uncertain over what interval it is slotted (if at all). Consequently, it is unclear to what extent the GWT depth profile represents the GWT of groundwater in the aquifer over a given depth interval. Groundwater levels fluctuate by about 25 m at the OBH.

There is no systematic relationship between GW level and GWT data obtained from the EA sensor at 41.89 mbGL in the Ryder Point OBH.

Figure 15 shows that the water temperatures from the soughs typically (with the exception of Well Head and Mandale) exhibit a greater range than GWTs at Ryder House OBH and that outflows from the soughs are also typically about 1°C (or 5°C in the case of Meerbrook) warmer than the groundwater at Ryder House.

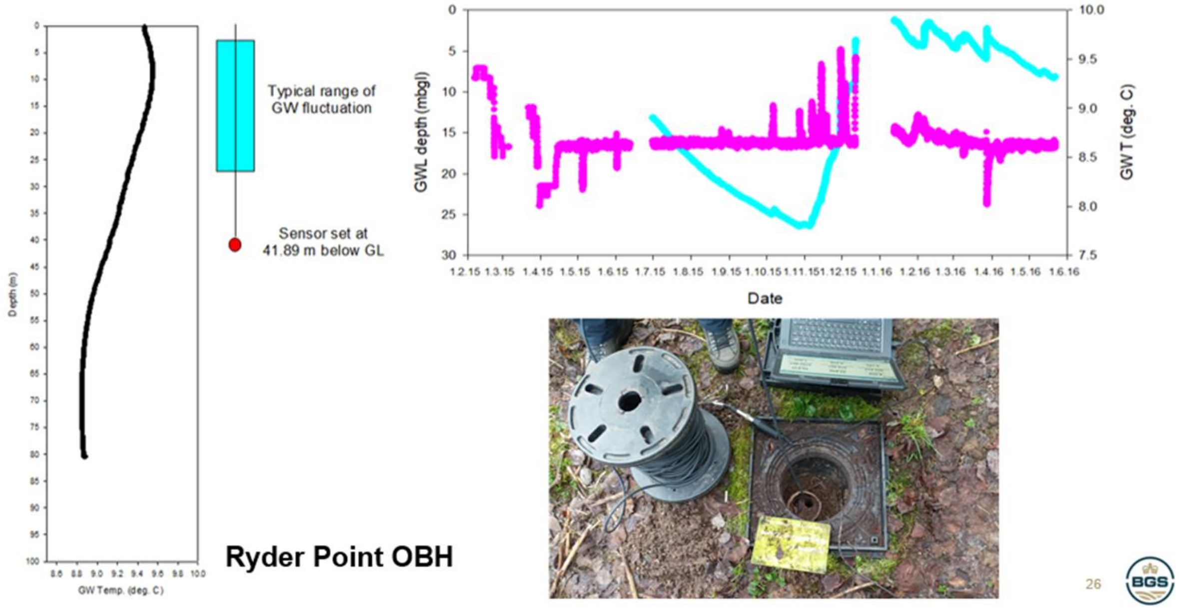

Figure 14 a. Depth profile of GW T at Ryder point obtained by BGS in Jan 2022. b. time series plots of GW level (blue) and GW T (pink) for Ryder Point for a period between February 2015 and June 2016 (data provided by EA). c. photograph of surface completion of Ryder Point OBH. Contains Environment Agency data © 2022 Copyright and database rights.

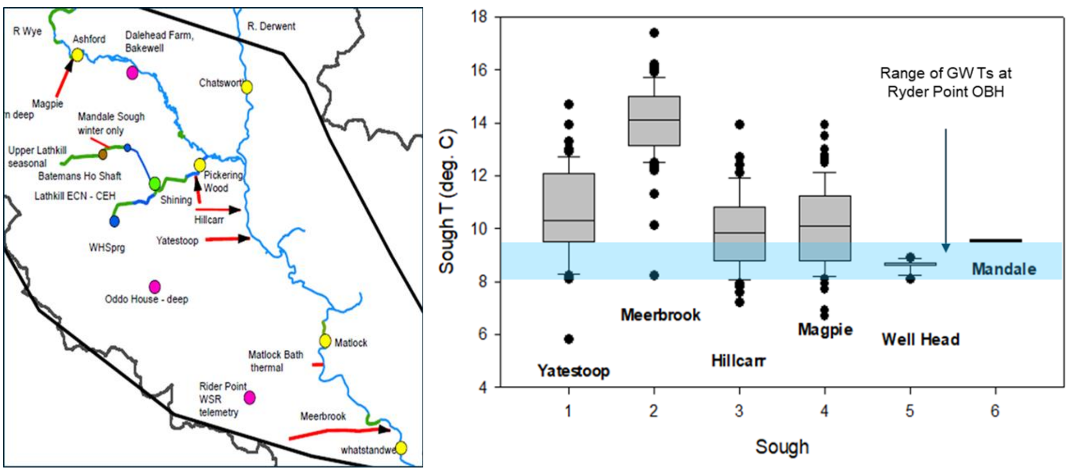

Figure 15 Location of the soughs in the Derwent catchment (left panel) and box plots of historic water temperature data for the soughs compared with range of GW Ts from Ryder Point (blue shading) (right panel). Contains Environment Agency data © 2022 Copyright and database rights.

3.2.3 Thames Gravels

Four sites were visited on 07/01/22 and two sites visited on 20/01/22 and GWT depth profiles were obtained, Figure 16. All six OBHs are shallow with a maximum TD at Cookham OBH of 23m and the shallowest being Albany Park with a TD of 2.8 m. Mean GWT at the sites is a function of the TD of the OBHs with mean GW T increasing with OBH TD (Figure 16b). It is inferred that this reflects the preferential cooling of groundwater in the shallower OBHs associated with cooling winter air temperatures in the catchment. Overall, the GWTs in the Thames Gravels OBHs are warmer than those in the OBHs from the Berkshire Downs and Derwent catchments. This is consistent with the warmer air temperatures over the Thames Gravels (Figure 10).

It is clear from reviewing the data from the Thames Gravels that although the data is intrinsically interesting, reflecting the London urban heat island effect and the potential sensitivity to changes in air temperature, none of the sites provide unambiguous evidence that they sample a groundwater system where GWTs may be influenced by GSHC. Discussion with the EA Project Managers and other colleagues in the EA led to an additional site in the confined Chalk of central London being identified for temperature profiling and instrumentation.

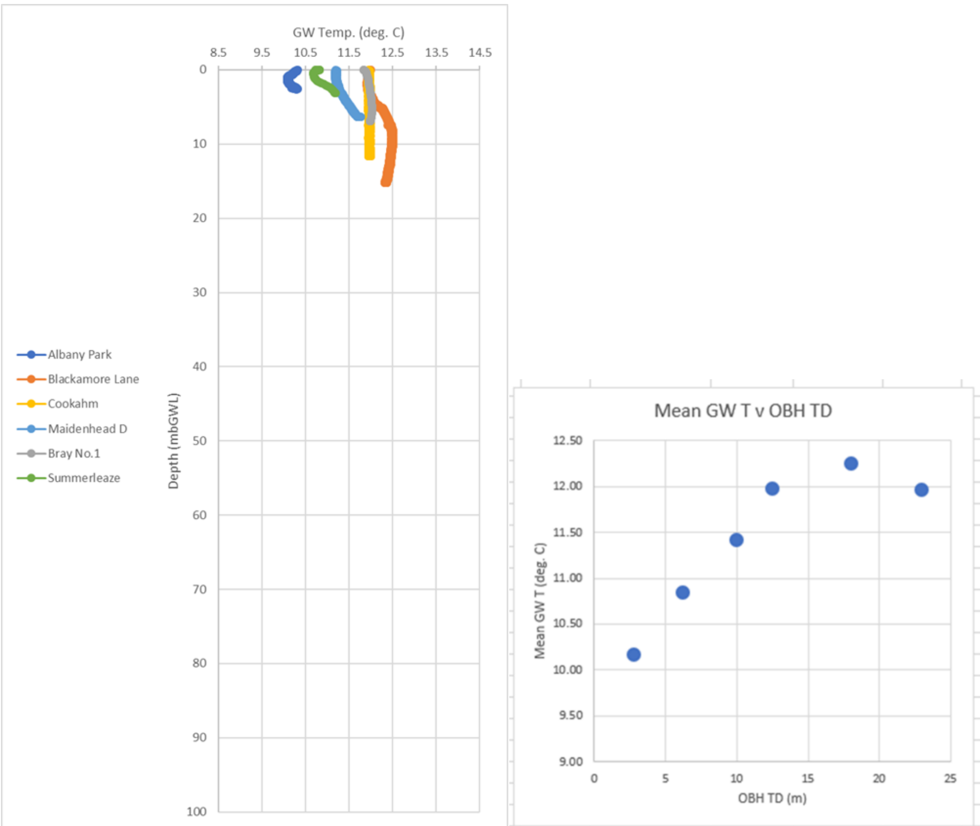

Figure 16 a. Temperature profiles in the Thames Gravels and b. mean GWT at each OBH as a function of TD.

3.2.4 Central London Confined Chalk

Figure 17 shows GWT historic depth profiles for four sites in the confined Chalk of Central London (data from January 2020) compared with the depth profiles for the Thames Gravels from January 2022. The GWT in the confined Chalk is consistently warmer than that of sites in the shallow unconfined Thames Gravels (both winter temperatures) with temperatures typically in the range 13°C to 14°C. At Ashley Gardens there is a slight cooling in groundwater temperatures in the first 20 m below the water table from about 13.7 °C down to about 13°C and then relatively constant down to a depth of about 75 m below the water table.

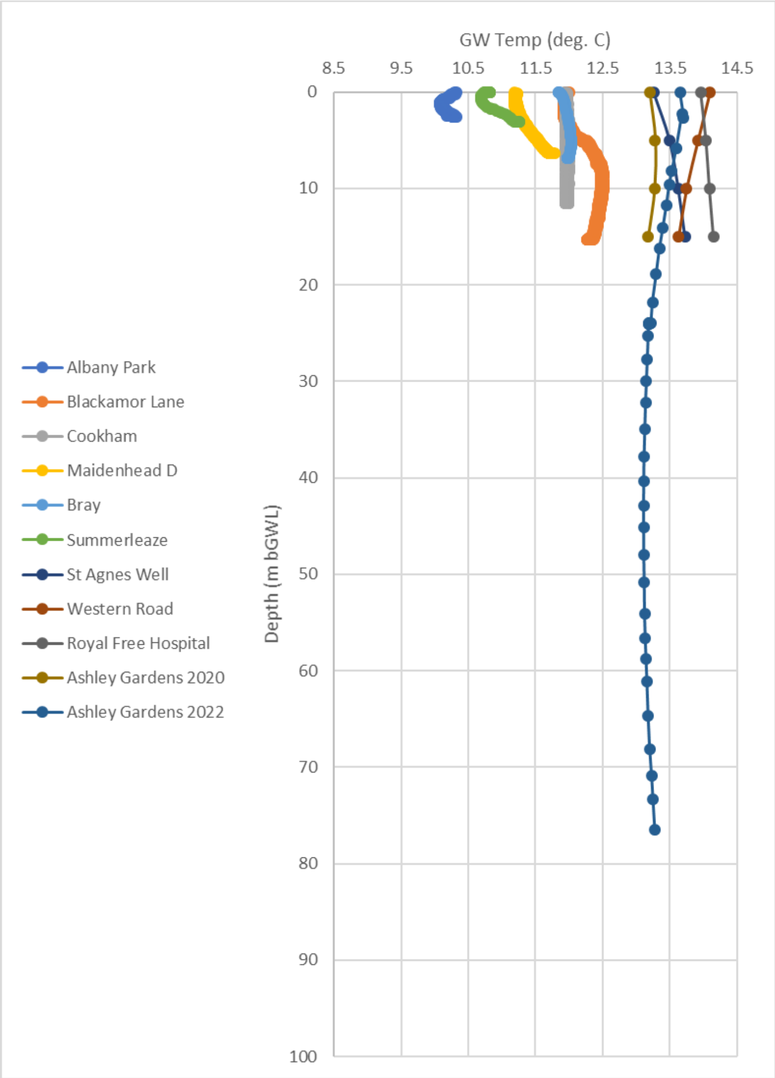

Figure 17 Temperature profiles at four sites in the confined Chalk of Central London compared with six sites in the Thames Gravels.

Lessons learnt 3.4 to 3.6: It was not possible to undertake repeat GWT depth profiles over different seasons during this pilot project. It would be instructive to make repeat profiles when air temperatures are significantly warmer in late summer.

The local EA H&T teams provided metadata covering most aspects, with the exception of construction/completion details which were sourced from BGS records. These records, usually based on drilling records, did not usually include information related to borehole completions or subsequent changes in completion, such as the installation of narrow diameter dip tubes. Local EA H&T representatives responsible for individual sites were well-informed though and are a key source of on-the-ground information and site-specific knowledge. Their involvement will be critical for the efficient deployment of a national GTMN.

There were some challenges accessing some sites due to third party ownership, where site visits were infrequent. A water hygiene card was required for one site on a water company site, which also required the sanitisation of all equipment inserted in the borehole. For the development of a long-term GTMN, the instrumentation of only EA owned sites with associated reliable access may be preferable.

3.3 RECOMMENDATIONS FOR PILOT INSTRUMENTATION

3.3.1 GWT sensor locations

Table A3 summarises the temperature profile data for each of the 25 sites and assesses the potential of all sites for inclusion in the pilot GTMN. Based on the assessments in Table A3, the following proposals regarding the location of temperature sensors were discussed and agreed with the EA Project Managers and Steering Group at a meeting on the 4th February 2022.

3.3.1.1 Berkshire Downs

- OBHs representative of upgradient interfluve, Chalk stream, and lower catchment settings should be selected for instrumentation to enable the range of GWTs in the unconfined Chalk of the catchment to be monitored. The following three sites are proposed:
  - a recharge site - Oak Ash OBH (1 sensor)
  - a Chalk stream site - Great Shefford OBH (2 sensors)
  - a lower catchment site - Marlston Farm OBH (1 sensor)
- One sensor should be deployed at Oak Ask and Marlston Farm and two at Great Shefford at depths as indicated in Table A3.
- At each of the three sites, additional temperature sensors should be deployed in the headworks of the OBHs 3.3.2 below).
- In addition, five further sites have been identified where GWT sensors and temperature sensors in headworks could be deployed if additional resources are available. These sites would enable insights into the spatio-temporal variability of GWTs across the catchment. They are as follows:
  - Ashdown Park;
  - Faarn Combe;
  - Hodcott 2;
  - Mayfield Farm; and
  - Upper Lambourn Farm

- Data from groundwater sensors for other long-listed sites within the catchment where the EA has telemetered, GWT-capable sensors should be made available in Wiski.
- Surface water temperature data from the R. Lambourn in the vicinity of Great Shefford should be made available in Wiski for analysis with the pilot GW T data.

3.3.1.2 Derwent

- The stilling well at Magpie sough should be instrumented with a GWT transducer and a sensor to measure air temperature at the site.
- Data from the groundwater sensor at the Rider House OBH should be enabled and made available in Wiski.
- Ensure surface water T data from the R. Wye in the vicinity of Magpie sough is deposited in Wiski for analysis with the pilot GWT data.

3.3.1.3 Thames Gravels

- The Maidenhead Ditch OBH should be instrumented with a new GWT sensor at the depth indicated in Table A3, and an associated temperature sensor deployed in the headworks of the OBH.
- Data from other GWT capable sensors in the catchment should be enabled and made available in Wiski.

3.3.1.4 Central London confined Chalk

- The Ashley Gardens OBH should be instrumented with a new GWT sensor at the depth indicated in Table A3 and an associated temperature sensor deployed in the headworks of the OBH.

3.3.2 Sensor specifications

There is currently no preferred GWT sensor in use by the EA agency and there was no requirement as part of the project to deploy sensors from a specific manufacturer.

An extract from the EA MARS database showed at least 21 different temperature capable sensors from at least five manufacturers are currently deployed by the EA (Table 4) although many of the sensors are to the similar S12S standard.

Table 4 Temperature-capable sensors currently deployed by the EA

Manufacturer	Sensor	No. deployed
InSitu	9500	1
InSitu	9600	64
GEMS	DCL 9500/9600	10
GEMS	GEMS 9500	46
GEMS	GEMS 9500 - SDI-12	3
GEMS	GEMS 9500Z	6
GEMS	GEMS 9600	42
GEMS	GEMS 9600 - SDI-12	12
GEMS	GEMS SDi - 12	3
Hobo	HOBO MX2001	10
Impress	Impress S12S (SDI12)	1
Impress	SDI-12L	9
Ott	Orpheus Mini	157
Ott	Ott PLS	31
Ott	PLS	2
Ott	PLS SDI-12	19
?	Ptx S12S (silcone Stainless)	16
?	S12C	7
?	S12S	109
?	S12S G0400	1
?	S12S G3000	1
	Grand Total	**2706**

The primary constraints on sensor choice for the pilot study were that:

- sensors were to be acquired at short notice, i.e. were available direct from suppliers stock, due to the short turn-around time between design of the network (early February 2022 and completion of deployment by end March 2022),
- that sensors were to be stand-alone and self-contained:
    - that they would not require an external power supply, and that they would not be telemetered,
- that their installation would have minimal impact on any existing instrumentation at the selected sites,
- that GWT data could be easily downloaded
    - EA staff should need minimal training and no additional support to acquire the data from the sensors in the field,
- that sensors would be capable of being deployed at a range of groundwater heads, and
- that there was a limited budget for equipment on the pilot study.

In addition to having no preferred sensor for measuring GWT, the EA currently have no guidance on the accuracy or frequency required of GWT measurements. In their review of EA GWT data, Ascott and McKenzie (2022) have reported representative rates of change in shallow unconfined GWTs in the range 0.27°C to 0.87 C/decade. Given that GWT measurements from a future national GTMN need to be capable of characterising the effects of climate change on GWTs over decadal time scales then sensors should ideally have an accuracy of a similar order of magnitude, i.e. of +/-0.3°C or better. Consequently, for the purposes of the pilot GTN sensors have been specified with an accuracy of +/-0.3°C or better (note that currently, EA sensors typically have an accuracy of +/- 0.5°C).

The EA has a large set of measurements of groundwater temperature recorded in borehole headworks. In an early analysis of that data, Stuart et al (2010) concluded that groundwater temperatures recorded in headworks may be a poor estimate of in-situ groundwater temperatures. More recent work by Ascott and McKenzie (2022) support this observation. It is therefore important to understand the relationship between headworks and in-situ temperatures. Consequently, to enable comparisons between headworks and in-situ GWT measurements any new observations of GWT in headworks should also be at an accuracy of +/-0.3°C or better.

To constrain the sampling frequency it is reasonable to consider the most rapidly-responding groundwater systems that may be sampled as part of the pilot GTMN. Habib et al (2017) noted responses in groundwater levels in the Thames Gravels, Oxfordshire, to frontal rainfall and summer advective storms at the sub-hourly time scale. The study also collected high-frequency (1/min) measurements of GWT but these were not reported in Habib et al (2017). Ascott and McKenzie (2022) have subsequently analysed this GWT data set for long-term changes in GWT (seasonal to decadal time scales) but did not investigate high-frequency changes in GWT at the site in Oxfordshire. GWT data from the pilot study will need to be analysed in the context of high-frequency driving climate data. Although karst systems were not targeted for monitoring during this pilot study they may be one of the hydrogeological settings that will require monitoring in a national network. Maurice et al 2022 reported velocities in the Chalk karst of the UK with mean velocities of 4600 m/d. Air temperatures are typically measured at 1/min or 1/15 min and are commonly reported at 1/hr. Given that there is no significant overhead in collecting high frequency data from the GWT sensors, and in the context of the notes above, for the purposes of the pilot study GWT data will be collected at 1/hr.

Based on these constraints, the following instrument specifications were recommended to and accepted by the EA Project Management and Steering Group at the meeting in the 4th February 2022.

- All GW transducers to be InSitu Rugged TROLL 100 data loggers with a 0.01°C resolution and +/-0.3°C accuracy with a head range suitable for their depth of deployment
- All air T transducers in headworks to be InSitu Baro Trolls with a 0.01°C resolution and +/-0.1°C accuracy
- All transducers are to record GW T and headworks T at a frequency of once every hour

Lessons learnt 4.1 to 4.3: The selection of equipment for the pilot network was driven by a requirement for simple, rapid, deployment of relatively high-resolution sensor to maximise data acquisition during the pilot. To gauge the effects of surface temperature on observations InSitu Baro Trolls were installed in the headworks – balancing the cost of these against the simplicity of a single environment for field data download and processing. For the pilot most sites have been instrumented to record headworks temperature. This may turn out to be redundant if there is access to in-catchment meteorological records.

The equipment used for the pilot GTMN has been deployed elsewhere on EA projects and there were no issues regarding procurement. However, it may be timely for the EA to review the capability of current providers to supply suitable GWT sensors as there may be alternative suppliers that might provide procurement savings for the EA when developing the national GTMN.

Although outside the scope of the current project, there would be benefit in analysing existing EA logger/telemetry capability and any planned changes to EA telemetry systems (e.g. 4G upgrades) to inform a future-proofed design for GWT telemetry as part of the development of a national GTMN.

4 Deployment of the pilot network & lessons learnt

The pilot network instrumentation was deployed throughout March 2022. Details of the deployed instrumentation are given in Table 5. Photographs of the deployed infrastructure / sites are also available in Figure A1 in the Appendix.

Table 5 Details of GWT sensors deployed to the pilot network.

Site	Date installed	Time installed	Dip (m bd)	Submerged sensor	Depth (m bd)	Air sensor	Notes
Berkshire Downs							
Ashdown	01/03/2022	11:30	24.44	SN 864012	75	SN 883267	
Upper Lambourn	01/03/2022	13:30	9.39	SN 864602	80	SN 875954	
Faarn Combe	01/03/2022	14:15	16.62	SN 863743	75	SN 881758	
Great Shefford	01/03/2022	15:55	0.86	SN 863756	20	SN 880808	
Great Shefford	02/03/2022	16:55	1.86	SN 864583	60	SN 880808	
Oak Ash	01/03/2022	16:25	60.45	SN 864647	80	SN 883284	
Hodcott 2	29/03/2022	10:50	17.55	SN 845492	90	SN 879651	
Mayfield Farm	29/03/2022	11:35	35.66	SN 864628	55	SN 883282	
Marlstone Farm	29/03/2022	12:00	6.59	SN 864600	20	SN 875939	
Derwent							
Magpie Sough	31/03/2022	12:00	0.2	SN 894387	NA	SN 875948	Dip to stage board
Thames Gravels							
Maidenhead D	08/04/2022	10:15	2.28	SN 864597	7.2	SN 880430	
Central London confined Chalk							
Ashley Gardens	29/03/2022	17:00	44.92	SN 864010	70	SN 881798	

4.1 LESSONS LEARNT

One of the purposes of establishing a pilot GWT monitoring network was to identify lessons learnt for the design, deployment and management of a future national GTMN. Table 5 collects together and expands on the lessons learnt noted in sections 2 and 3 above. It highlights information and / or knowledge gaps identified during the pilot study, and gives details of recommend actions for work prior to the commissioning of a future national GTMN. Relative priorities of the recommended actions have also been indicated (as high, medium and low).

Note that although operation of the pilot network was outside the scope of the project some, additional observations and suggested actions related to the management and running of the network and of analysis of the data obtained from the network are included under item 5 in the list of Lessons learnt.

The lessons learnt and associated recommended actions were reviewed by the EA Project Managers and the project Steering Group and discussed at the end of project meeting on 31st March 2022.

Table 6 Lessons learnt and suggested actions

Item	Lessons learnt	Information and/or knowledge gap	Actions & priority (H - orange, M – yellow, or L - green)
1. AIMS OF GWT MONITORING			
1.1 Aims and requirements of a future GTMN	The NCEA requirements for a national GTMN would benefit from being more clearly enumerated, in particular specific aims for each of the different drivers, e.g. for monitoring GWT under climate change; for monitoring the effects of GWT on GDTEs; for support of regulation associated with GSHC systems and urban settings; and for the regulation and management of legacy GWT effects, for example from mine drainage. The NCEA requirements for a future GTMN would also benefit from clarification in the context of wider NCEA requirements for: • monitoring of temperature across a variety of catchment settings (for example surface water temperature), and • related to temperature-sensitive environmental parameters (such as water quality and ecological / habitat status) There may be benefit in the co-ordination of planning multiple temperature-related NCEA monitoring networks to ensure efficiencies in deployment and operation.	Understanding if and how a developing programme of NCEA monitoring networks is being / will be co-ordinated within the EA and with other regulatory bodies, such as Natural England. Relationship of future NCEA monitoring networks with other national monitoring infrastructure initiatives such as those co-ordinated through the UKEOF https://www.ukeof.org.uk/about/management-group currently chaired by the EA.	A1.1 Document specific requirements of a GTMN in context of the wider NCEA.
1.2 'Ownership' and management within the EA of a GTMN with multiple aims.	There is no one person with responsibility to oversee the management and planning of GWT monitoring in the EA. There will potentially be multiple requirements of a future GTMN (see 1.1 above). Consequently, there are potentially multiple 'owners' of the management of and outputs from a future GTMN within the EA.	Understanding who currently collects and uses GWT data in the EA and why, and who would need to use data from a future GTMN and why.	A1.2 Review who currently collects and uses GWT data in the EA and why, and canvas future data requirements.
2. CATCHMENT SELECTION			
2.1 Effectiveness of the catchment selection process to identify representative catchments for the pilot study	Criteria for selecting the pilot catchments were semi-quantitative, largely focussed on pragmatic and practical aspects, and benefitted significantly from the detailed regional and catchment-specific knowledge and experience of the EA PMs and members of the Steering Group. This process was very effective but to be rolled-out at a national scale would require co-ordination of input from a wide range of EA staff. Work to investigate statistical approaches to pilot network design, and that may be relevant to the design of a national network, was not relevant for the current study. Three EA Areas were represented in the pilot study catchments (two in the 'South East' and one in 'West	No catchments were monitored in any of the four areas in the 'North' region of the EA. Statistical approaches to pilot network design were not considered.	A2.1a Undertake a review of statistical techniques relevant to the design of a nation GWT monitoring network. A2.1b To complement the current pilot study,

Item	Lessons learnt	Information and/or knowledge gap	Actions & priority (H - orange, M – yellow, or L - green)
	and Central'), however, due to limited time and resources the range of hydrogeological and GW-SW settings was limited and a sandstone-dominated catchment was an omission from the pilot study. Flexible iteration between catchment and site selection decisions during the project was important to enable an additional catchment (Central London confined Chalk) to be identified where GSHCs operate and to be included in the study. Such flexibility is likely to be important during the design phase of a national network.		and prior to the commissioning of a national GTMN, undertake T profiling and instrument: • a Permo-Triassic Sandstone catchment, such as the Tern, Shropshire, where there have been previous studies of GWTs a catchment in at least one of the four areas in the 'North' region of the EA representative of aquifer systems in that region.
3. Site selection			
3.1 Effectiveness of the site selection process to identify representative catchments for the pilot study	The requirements of a GTMN with regard to observational accuracy, frequency, and density of GWT measurements have been specified (see 3 and 4 below). However, the design of a future national GTMN may benefit from additional work being undertaken: to understand spatial variation in potential sensitivity of GWT to climate change; developing a better understanding of temperature-sensitivity of specific GDTEs in context of regulatory requirements; and, investigating evidence for GWT change related to GSHC schemes as a function of their location, type, and operation.	Prediction of changes in GWT due to climate warming over next 25+ years as a function of hydrogeological setting.	A3.1a Commission analytical models of changes in GWT using UKCP18 scenarios and a range of representative hydrogeological settings in England to support design of national GTMN.
		Detailed understanding of temperature sensitivity of specific GDTEs in context of regulatory requirements.	A3.1b Commission study to review evidence for and quantify temperature sensitivity of GDTEs in England.
		Understanding of GWT response to GSHC schemes in context of regulatory requirements.	A3.1c Commission study to review evidence for GWT change (absolute and rate of change) related to GSHC schemes as a function of their location, type, and operation, and consider implications for regulation and licensing.
3.2 Use of existing sites (OBHs, springs, stilling wells)	The pilot network was restricted to the instrumentation of existing monitoring sites. Assuming that there are no resources to locate new OBHs as part of a national GTMN, the selection of monitoring sites will be similarly restricted. As a consequence, it will not be possible to achieve an "unbiased and statistically representative" GTMN as is the stated aim of the NCEA programme. Rather, a national GTMN that is representative of the diversity of hydrogeological settings should be the aspiration. One site in the pilot study (Great Shefford) from the Berkshire Downs was on the EAs list of sites for decommissioning. Consequently, it was removed from that list to provide more options for GWT monitoring in the Berkshire Downs. Potential GWT monitoring sites should be available for inclusion in a future GTMN to provide the opportunity for optimum network design.	Absence of reliable, systematic national GWT data (Ascott and McKenzie, 2022) to facilitate the design of a representative national GTMN. It is unclear what assessment criteria are currently used by the EA to prioritise OBHs for decommissioning.	A3.2 Add suitability of sites for use in the long-term monitoring of GWT as an additional criterion in the EAs OBH decommissioning assessment.

Item	Lessons learnt	Information and/or knowledge gap	Actions & priority (H - orange, M – yellow, or L - green)
3.3 Existing EA and third party GWT monitoring infrastructure	There are a number of sites within the pilot catchments where existing instrumentation is capable of monitoring GWT and in some instances of providing a telemetered data feed into EA's WISKI database. Different sources of EA information provided different details concerning site instrumentation or lack of it at many sites. In addition, a number of third parties, primarily water companies, also monitor GWT at abstraction and OBHs.	There is no national overview of the extent of EA and third-party instrumentation already deployed that is capable of i.) monitoring GWT, and ii.) providing a telemetered feed of GWT to WISKI. Note that the EA are in conversation with the Coal Authority regarding use of their data and similarly have been in touch with some water companies	A3.3 Compile an up-to-date list of all EA and third-party instrumentation currently deployed that is capable of i.) monitoring GWT, and ii.) providing a telemetered feed of GWT to WISKI, and assess resources required to ensure that GWT data from those instruments can be captured in WISKI.
3.4 Variability of GWT within a catchment and with depth and implications for site selection	GWT profiles were obtained for 16 sites across the Berkshire Downs to enable the investigation of the variability of GWT within a catchment. It indicated variability in GWT as a function of: • OBH location in the catchments (GWT tended to be slightly cooler in recharge areas and slightly warmer in the lower catchment) • stratigraphic control of flow into boreholes; borehole construction (with casing effecting GWT profiles); • a general tendency for increasing T with depth; but that • <u>within catchment variability in GWT was significantly less than between catchment variability in GWT</u> As part of the implementation of a national GTMN, GWT profiling of multiple sites to establish within-catchment variability of GWTs will be important. Such profiles take 0.25-1.5 hours depending the depth of the water column and sensors need to have an exterior temperature sensor to enable sufficient response time for profiling. EA equipment may need to be removed before profiling in narrow (<50 mm) diameter holes, which may perturb the profile. 30mm diameter piezometers are the minimum accessible size for the InSitu Rugger Troll 100 given it's 26.2 mm diameter. Profiles during different times of the year are likely to produce different results in holes with a dynamic hydrological regime within the borehole. Furthermore, profiles obtained when there are large contrasts between air and GWTs would be preferable. In the pilot, on several days, air temperature was similar to GWT and any stagnant water in the casing would not be easily interpreted.	No repeat GWT profiles available to reflect seasonal influences on GWT.	A3.4b Undertake repeat GWT profiling at sites in the Berkshire Downs in late summer to constrain seasonal influences on the within-catchment variation in GWT. This will require suitable equipment and direct read cables.
3.5 Obtaining up-to-date OBH metadata and conditions	H&T teams provided metadata covering most aspects, with the usual exception of construction/completion details which were sourced from BGS records. These records were often drilling records and often they did not include information related to dual completions or subsequent changes in completion, such as the installation of narrow diameter dip tubes. Local H&T representatives responsible for individual sites were well-informed though and are a key source of on-the-ground information and site-specific knowledge. On one occasion, it was clear that an OBH had collapsed at a defined depth and previous EA recorded minimum water levels may have been the depth of the collapse.	Lack of up-to-date completion information and site conditions.	A3.5 Ensure completion information and information on site conditions is kept up to date on EA databases (see also A3.3).

Item	Lessons learnt	Information and/or knowledge gap	Actions & priority (H - orange, M – yellow, or L - green)
3.6 Site access	Challenges accessing some sites due to third party ownership, where site visits were infrequent. A water hygiene card was required for one site on a water company site, which also required the sanitisation of all equipment inserted in the borehole. For the development of a long-term GTMN, the use of EA owned sites with reliable access would be preferable. If third party sites are used in a network it may be necessary to use a separate set of equipment, such as a temperature dipper for validating subsurface measurements that conforms to the site owners access conditions.		
4. EQUIPMENT SELECTION			
4.1 Selection of equipment for the pilot GTMN	The selection of equipment for the pilot network was driven by a requirement for simple, rapid, deployment of a high-resolution sensor to maximise data acquisition during the pilot. The InSitu level Rugged Troll 100s deployed have 0.01°C resolution and +/- 0.3°Caccuracy, but require removal from the borehole and manual downloading. To gauge the effects of surface temperature on observations InSitu Baro Trolls were installed in the headworks – balancing the cost of these against the simplicity of a single environment for field data download and processing. For the Pilot most sites have been instrumented to record headworks temperature. This may turn out to be redundant if there is access to in-catchment meteorological records. OTT sensors on the existing EA framework agreements can be calibrated for temperature at an additional cost to provide GWT measurements with +/- 0.1°C accuracy. Current EA digital sensors are accurate to +/- 0.5°C, if enabled. EA analogue sensors may not output GWT. Consider deploying sensors with greater temperature accuracy when replacing/upgrading current equipment.	No work was done to assess effectiveness of telemetry (see 4.3 below).	A4.1 Assess whether the measurement of headwork temperature adds value during/following the GTMN Pilot. Note: the equipment purchased for the GWT Pilot can be readily redeployed to other groundwater projects in the future as needed.
4.2 EA framework provider considerations	The InSitu equipment used for the pilot GTMN has been deployed elsewhere on EA projects. This simplified procurement and avoided questions over supplier participation in EA framework agreements. With a focus just on temperature measurement, there may be alternative suppliers of sensors that might provide procurement savings for the EA when developing the national GTMN.	Details of equipment suppliers in the EA framework agreements, and which suppliers are used by individual H&T teams was unclear.	A4.2 Consider reviewing tendering requirements for GWT monitoring; request specifications for temperature monitoring and pressure/temperature monitoring sensors from existing framework suppliers; and, explicitly include temperature sensors in future framework tendering exercises.
4.3 GTMN and telemetry considerations	Given the scope and resources available to the project and to avoid additional requirements of H&T staff, the pilot GTMN sensors were not connected to existing EA telemetry or data loggers, although this may be a requirement of a national GTMN. Analysis will be needed of existing logger/telemetry capability (i.e. spare channel, power supplies and ambient temperature sensors) (see Action 3.3 above) and any planed changes to EA telemetry systems (e.g. 4G upgrades) to future-proof any GWT telemetry as part of the development of a national GTMN (see Action 4.3a).		A4.3a Following A1.2, EA lead managing the implementation of a national GTMN should liaise with EA telemetry lead to ensure GWT equipment is compatible with and future-proofed with respect to EA telemetry systems. A4.3b EA should consider pros and cons of a standardised

Item	Lessons learnt	Information and/or knowledge gap	Actions & priority (H - orange, M – yellow, or L - green)
	Depending on the site, and on the target for monitoring, either T/P sensors or just T sensors can be deployed. Above ground telemetry units or data loggers frequently log ambient temperature and additional T sensors in headworks may be redundant. Where P sensors are integrated with loggers, temperature recording is normally an option. A resolution of +/- 0.1°C should be the minimum resolution of telemetered GWT sensors (see A4.1 above). Future temperature-focussed installations should use EA framework sensors wired directly into telemetry-enabled loggers,		installation protocols at sites where temperature data are required, and avoid procurement or installation of sensors with less than 0.1°C resolution.
5. INSTALLATION			
5.1 Observations from pilot GTMN installation	Sensors were installed on kevlar cord to depths up to 80 m. These cords are liable to tangle during repeated lifting to the surface, as noted during install. Sensors become caught on two occasions between dip tubes and the annulus in dual completion holes in Berkshire during installation, where the annulus was representative of the Chalk. This was difficult to identify given the limited weight and lack of direct read cables. Training support and use of experienced field staff in deployment of a future national network will be important.		
6. NETWORK OPERATION			
6.1 Network management and maintenance	Although outside the scope of the current project, the pilot network will require management and maintenance. Even where sensors are telemetered and equipment functioning can largely be checked remotely and automatically, a minimum annual physical and independent measurement / validation to check for instrument drift may be considered best practice. Given the need to manually download data from the pilot network (see 6.2 below) maintenance activities can be combined with data download. Network maintenance and management of a future national GTMN may entail significant resourcing and efficiencies should be sought with the management of existing and other NCEA monitoring networks.	A requirement to manage and oversee the maintenance of the pilot network was not detailed in the Project Specification. Unclear who will download these loggers and where the data will be stored	A6.1 Identify resources for the management and maintenance of the pilot network and to consider resources that may be required to manage and maintain a future national GTMN.
6.2 Downloading data from the Pilot network	Non-telemetered equipment has been deployed by the pilot network on the basis of cost, to enable the activity to be completed within the short time-frame. Consequently, site visits and downloads of the data from the deployed instrumentation will be needed. It is recommended that data is downloaded ideally quarterly to facilitate QA/QC. A future national GTMN should be fully telemetered (see A4 above).	It is not clear who in the EA will be responsible for the downloading of data from the pilot network.	A6.2 EA to download data from the pilot study quarterly.
6.3 Data storage	The data from the pilot, and any national GTMN, should be stored centrally in a consistent and accessible format. One option will be to store the data in the existing Hydrometric WISKI database, which should be the easiest option for sites with EA operated Pressure/Temperature sensors. A limitation of WISKI is that it may not be suitable for storing data from nonstandard sensors (including the Rugged Troll sensors used in the pilot study), sensors operated by third parties and vertical temperature profiles. It stores limited site-specific metadata, which is important for effective interpretation of data results. Setting up a stand-alone database specifically for temperature, with data aggregated from all sources, with procedures for import of WISKI data, may be valuable.	Are there any licencing/capacity limitations on using WISKI? Do existing EA databases have the capacity to record required metadata Will data in WISKI be readily accessible for analysis?	A6.3a EA to request H&T teams to archive any downloaded temperature data, in WISKI if appropriate. A6.3b EA to consult data specialists and draw up a data management strategy for temperature data in EA.

Item	Lessons learnt	Information and/or knowledge gap	Actions & priority (H - orange, M – yellow, or L - green)
6.4 Data QA/QC, analysis and reporting	Time series plots of GWT from each of the deployed sensors as well as cross plots between GW, headworks and Met. Office published air temperature should be produced quarterly. These should be checked for QA/QC purposes with any outliers or unexpected steps or trends in GWT data identified and flagged. Quarterly reports of QA/QC and data analysis could be prepared summarising the pilot GWT data. In a wider GTMN with permanently installed sensors calibration should be carried out on installation and periodically to check sensor drift. This is probably easiest if a lab calibrated sensor is taken into the field to cross check sensors after installation. Achieving accuracy better than +/- 0.1°C would almost certainly be prohibitive in terms of capital and operational cost, but simple calibration protocols will improve confidence in interpretation of trends and spatial variability. Air temperature in the headworks may not to reflect wider air temperatures. Sensors targeted specific features of the GWT profile, often in addition to GWT features where current EA digital temperature capable sensors were vertically located.	It is not clear who in the EA will be responsible for the data QA/QC from the pilot network.	A6.4a Establish a calibration protocol, and consider procurement of the equipment required to calibrate sensors (if not currently available equipment/capability in EA laboratories).
		It is not clear who in the EA will be responsible for the reporting and analysis of GWT data from the pilot network.	A6.4b Establish a quarterly data reporting and analysis protocol. A6.4c To support analysis of the GWT data, obtain • daily Met Office air temperature for each of the pilot catchments, and • surface water temperature for the R Wye (Derwent) and the R Lambourn (near Great Shefford)

In summary, the following are the recommended actions following the lessons learnt review.

<u>High priority actions</u>

- A1.1 Document specific requirements of a GTMN in context of the wider NCEA.
- A1.2 Review who currently collects and uses GWT data in the EA and why, and canvas future data requirements.
- A2.1a Undertake a review of statistical techniques relevant to the design of a nation GWT monitoring network.
- A3.2 Add suitability of sites for use in the long-term monitoring of GWT as an additional criterion in the EAs OBH decommissioning assessment.
- A3.3 Compile an up-to-date list of all EA and third-party instrumentation currently deployed that is capable of i.) monitoring GWT, and ii.) providing a telemetered feed of GWT to WISKI, and assess resources required to ensure that GWT data from those instruments can be captured in WISKI.
- A3.5 Ensure completion information and information on site conditions is kept up to date on EA databases (see also A3.3).
- A6.1 Identify resources for the management and maintenance of the pilot network and to consider resources that may be required to manage and maintain a future national GTMN.
- A6.2 EA to download data from the pilot study quarterly.
- A6.3a EA to request H&T teams to archive any downloaded temperature data, in WISKI if appropriate.
- A6.3b EA to consult data specialists and draw up a data management strategy for temperature data.

Medium priority actions

- A3.1a Commission analytical models of changes in GWT using UKCP18 scenarios and a range of representative hydrogeological settings in England to support design of national GTMN.
- A3.1b Commission study to review evidence for and quantify temperature sensitivity of GDTEs in England.
- A3.1c Commission study to review evidence for GWT change (absolute and rate of change) related to GSHC schemes as a function of their location, type, and operation, and consider implications for regulation and licensing.
- A3.4b Undertake repeat GWT profiling at sites in the Berkshire Downs in late summer to constrain seasonal influences on the within-catchment variation in GWT. This will require suitable equipment and direct read cables.
- A4.2 Consider reviewing tendering requirements for GWT monitoring; request specifications for temperature monitoring and pressure/temperature monitoring sensors from existing framework suppliers; and, explicitly include temperature sensors in future framework tendering exercises.
- A4.3a Following A1.2, EA lead managing the implementation of a national GTMN should liaise with EA telemetry lead to ensure GWT equipment is compatible with and future-proofed with respect to EA telemetry systems.
- A4.3b EA should consider pros and cons of a standardised installation protocols at sites where temperature data are required, and avoid procurement or installation of sensors with less than 0.1°C resolution.

Low priority actions

- A2.2 To complement the current pilot study, and prior to the commissioning of a national GTMN, undertake T profiling and instrument:
    - a Permo-Triassic Sandstone catchment, such as the Tern, Shropshire, where there have been previous studies of GWTs
    - a catchment in at least one of the four areas in the ‘North’ region of the EA representative of aquifer systems in that region.
- A4.1 Assess whether the measurement of headwork temperature adds value during/following the GTMN Pilot.
- A6.4a Establish a calibration protocol, and consider procurement of the equipment required to calibrate sensors (if not currently available equipment/capability in EA laboratories).
- A6.4b Establish a quarterly data reporting and analysis protocol.
- A6.4c To support analysis of the GWT data, obtain
    - daily Met Office air temperature for each of the pilot catchments, and
    - surface water temperature for the R Wye (Derwent) and the R Lambourn (near Great Shefford).

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6 Appendix

Table A1 Summary of the hydrogeological context of the five potential pilot catchments from Ward et al (2021)

Catchment / GWB	Notes from Ward et al (2021)
Berkshire Downs Chalk GWB (Chalk)	The Berkshire Downs Chalk GWB contains three main chalk streams; the Kennet and its primary tributary the Lambourn, and the Pang, plus a number of tributaries. The Kennet, Lambourn and Pang all have surface water gauging stations, whilst there are a number of NGLA boreholes and groundwater WISKI data points within the groundwater body. The groundwater body is supported by both EA (Kennet) and BGS (MabSWeC; Jackson et al, 2011) groundwater models. Groundwater bodies are potentially large areas for a pilot catchment, and thus the Kennet, which is the largest river and has the most surface water gauging stations and NGLA monitoring boreholes could be an attractive option for a pilot scheme. Significant investigation of the Pang and Lambourn has also been undertaken, including the LOCAR project and this could also provide useful catchment and conceptual understanding to underpin a pilot catchment. Various papers and reporting have been published on the Pang and Lambourn including a special issue of the Journal of Hydrology dedicated to the LOCAR program (Wheater et al 2006). Papers in this special issue cover multiple topics including: hydrological infrastructure (Adams et al 2003) and water quality (Neal et al 2004). The hydrogeology is complicated with the groundwater catchment areas of the Pang and Lambourn varying seasonally and are also quite different to the surface water ones. The area contributing to the Blue Pool via karst networks is not fully defined, but at times of low flow contributes more than half the flow to the Pang. The Kennet and Lambourn floodplain include several wetlands that are Special Areas of Conservation (SAC) and the whole length of the Lambourn is a Site of Special Scientific Interest (SSSI). There is a groundwater augmentation of surface water scheme in this area (IGS and TWA, 1978). The West Berkshire groundwater scheme comprises 27 boreholes in the unconfined Chalk aquifer of the Pang and Lambourn catchments, plus a further 6 in the confined aquifer east of Newbury (of which four lie within the Kennet catchment). These boreholes abstract groundwater from the Chalk at times of drought and low flows that is piped to the perennial river network, which is utilised to transport the water downstream to meet demands for surface water abstractions. The effects of pumping from the scheme is monitored by 67 purpose drilled observation boreholes as well as 83 private wells and boreholes, providing a dense network of observation points distributed throughout the catchment, that could be utilised for temperature monitoring.

Catchment / GWB	**Notes from Ward et al (2021)**
River Itchen (Chalk)	The headwaters of the River Itchen (proposed by Dr Mark Whiteman) are formed by the River Alre, Cheriton Stream and Candover Stream. There is a groundwater augmentation of surface water scheme in this area (IGS and SWA, 1979). The Itchen groundwater scheme comprises six boreholes in the unconfined Chalk aquifer in the Candover catchment. These boreholes abstract groundwater from the Chalk at times of drought and low flows that is piped to the perennial section of the Candover Stream, which is utilised to transport the water downstream to meet demands for surface water abstractions near the tidal limit of the Itchen. The effects of pumping from the scheme is monitored by 15 purpose drilled observation boreholes as well as 70 private wells and boreholes, providing a dense network of observation points distributed throughout the catchment, that could also be utilised for temperature monitoring.
Derwent GWBs (Carboniferous Limestone and Millstone Grit)	The Derwent Carboniferous and Millstone Grit groundwater bodies and the River Derwent were proposed as they have multiple inputs, from thermal groundwater and mine waters which could be useful temperature tracers, coupled with a local interest of the impact of in stream ecology including fish spawning grounds (pers. comm. Andrew Pearson). However, the combined size of these groundwater bodies is large, and further work to decide on a smaller part of the catchment – potentially focused around areas of in stream temperature sensitive habitats, will be required. The main groundwater component enters the river system in the Middle Derwent (which has 4 surface water gauges), including 'thermal' waters via mine water sough discharges which will provide a higher temperature contrast than many other rivers. There has been some interest in the past from fisheries colleagues in this river with respect to climate change implications for fish (areas of tree shade/ refuge in very hot weather).
Thames Gravel GWB (Sand and Gravel)	The Middle Thames Gravels between Windsor and Richmond, west of London (underlying bedrock predominantly low permeability London Clay Formation), contribute a significant volume of groundwater for public supply. The sands and gravels consist of three different terraces (Boyn Hill, Taplow and Kempton Park), vary in thickness from 1 to 13 m (Naylor, 1974), but saturated thickness varies from less than 2 m to more than 6 m (Naylor, 1974). They are generally unconfined, but locally confined by low permeability alluvium or brickearth. They have been commercially excavated by several companies, some of these have been restored for agriculture, or used for landfills, but many have been left as open water sites. They would offer a complementary study to that of the Chalk, due to the differences in flow mechanism and effective porosity. They are also close to London, and could exhibit effects of its urban heat island. However, like the Chalk they are in hydraulic continuity with associated surface water (the River Thames) and due to their maximum thickness, all sites could show seasonal variations in temperature.

Catchment / GWB	Notes from Ward et al (2021)
West Midlands Surface Water Catchment (multiple GWBs)	Large surface water catchment included (as recommended by Drew Constable) as a recent review of 41 in-situ temperature sensors at surface water gauging stations has been undertaken (EA, 2020). The in-situ temperature sensors were all matched to known fish and macroinvertebrate sites monitored by the Environment Agency. The catchment would need to be reduced significantly, as it contains multiple groundwater bodies, however it offers the potential to supplement surface water temperature, fish and macroinvertebrate sites with nearby groundwater monitoring locations.

Table A2 Assessments of the five potential pilot catchments

Table A2a Berkshire Downs GWB

Berkshire Downs Chalk GWB (Chalk)						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Are there i) temperature-sensitive groundwater bodies and ii) hydraulically connected GWDTEs and iii) surface waters in the catchment?	GIS: Rivers, Bedrock vulnerability maps, GWDTEs, Bedrock geology	i) Berkshire Downs GWB ii) 11 GWDTEs iii) Lambourne, Pang		3		
Is there unconfined Chalk in the catchment?	GIS: Bedrock/superficial geology	Yes		3		
Is there a high baseflow river in the catchment?	GIS: Rivers, CAMELS GB	CAMELS-GB areas: 39019; BFI - 0.88, CEH BFI – 0.97		3		
Are there multiple opportunities for instrumentation of EA boreholes?	GIS: WISKI monitoring boreholes, NGLA	28 NGLA boreholes, 94 WISKI boreholes		3		
Are there opportunities for instrumentation of streams near to EA boreholes within the catchment?	GIS: WISKI surface water sites, watercourse	18 surface water WISKI sites, multiple within 5km of NGLA boreholes		3		
Are automated data loggers capable of temperature monitoring already deployed in EA boreholes within the catchment?	GIS: WISKI monitoring boreholes, NGLA boreholes	94 active sites on BWS. Snelsmore common (SSSI), Sulham & Tidmarsh Woods & Meadows (SSSI) GWDTEs have associated BWS sites.	No data on equipment installed.	3		
Are telemetered groundwater levels already being obtained from EA boreholes within the catchment?	GIS: NGLA boreholes, list from EA	106 boreholes in catchment are telemetered. 4 of the telemetered sites are incorporated in the NGLA archive. Telemetry within catchment focused on flooding issues, most sites are close to rivers. Majority of telemetered sites are temperature capable	Limited headwater telemetry available. Two sites directly associated with GWDTEs	3		

Berkshire Downs Chalk GWB (Chalk)						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Are there EA staff available to facilitate access to EA infrastructure in a timely manner during the design and the implementation phases of the pilots?	Nigel Hoad			3		
Sustainability and practicality of access during the Pilot phase	GIS	Within a day's drive of BGS office using an electric vehicle		3		
Has there been previous research undertaken on groundwater temperature in the catchment?	Ward et al (2021) and light touch summary of peer-reviewed lit.	• Mackey & Berrie (1991); Musgrave & Binley (2011); House et al (2015); Uhlemann et al (2016) – Boxford, R. Lambourn studies	• The Boxford site has been the focus for extensive groundwater temperature research. Although findings from the studies may be representative of shallow groundwater systems on the Chalk in good hydraulic connection with SW the findings may not be more widely applicable throughout the catchment or outside the Chalk.	3		
Has there been previous work undertaken to model the impact of climate change on groundwater in the catchment?	Future Flows and eFLAG. Ward et al (2021) and light touch summary of peer-reviewed lit.	• The Berkshire Downs and sites within it have been the focus of research into the effects of CC on Groundwater. For example: Jackson et al., (2011); Prudhomme et al (1 future flows site (Rockley SU17/57 at [416500 171700]) and 10 eFlag sites 2013); Ascott et al. (2019)		3		
Has there been previous work on the temperature sensitivity of GWDTEs or groundwater-related surface water ecosystems.	Ward et al (2021) and light touch summary of peer-reviewed lit.	• Lapworth et al (2009); Allen et al (2010); House et al (2016) – Boxford, R. Lambourn studies	• The Boxford site has been the focus for some research on the sensitivity of GWDTEs. Although findings from the studies may be representative of shallow groundwater systems on the Chalk in good hydraulic connection with SW the findings may not be more widely applicable throughout the catchment or outside the Chalk.	3		

Berkshire Downs Chalk GWB (Chalk)						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Is there a 3D geological model and groundwater model of the catchment?	GIS: GW models	• The RBD sits within the BGS' London and Thames Valley 3D Regional Geological Model. In addition, there is extensive and detailed understanding of the geology of the catchment, particularly of the Chalk. • The EA have a hydrogeological model of the RBD (Whiteman et al., 2012), namely: Kennet Valley groundwater model. • A number of groundwater models have been developed by the BGS for the Berkshire Downs, including: Jackson et al. (2011) – climate change assessment; Upton & Jackson (2011) and Collins et al. (2020) – groundwater flooding	• Currently there are no groundwater models calibrated to model groundwater temperature in the catchment (although this is thought to be the case for all catchments being considered)	3		

Table A2b River Itchen

River Itchen (Chalk)						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Are there i) temperature-sensitive groundwater bodies and ii) hydraulically connected GWDTEs and iii) surface waters in the catchment?	GIS: Rivers, Bedrock vulnerability maps, GWDTEs, Bedrock geology	i)Test and Itchen GW body ii) 66 GWDTE's overlapping Test and Itchen GW model iii) Yes, Test, Itchen		3		
Is there unconfined Chalk in the catchment?	GIS: Bedrock/superficial geology	Yes		3		
Is there a high baseflow river in the catchment?	GIS: Rivers, CAMELS GB	30 gauges in CAMELS-GB database. For example, CAMELS-GB areas: 42016 (Itchen at Easton) BFI - 0.92, CEH BFI – 0.97		3		
Are there multiple opportunities for instrumentation of EA boreholes?	GIS: WISKI monitoring boreholes, NGLA	5 NGLA sites, 279 WISKI boreholes			2	

River Itchen (Chalk)						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Are there opportunities for instrumentation of streams near to EA boreholes within the catchment?	GIS: WISKI surface water sites, watercourse	27 surface water WISKI sites			2	
Are automated data loggers capable of temperature monitoring already deployed in EA boreholes within the catchment?	GIS: WISKI monitoring boreholes, NGLA boreholes	42 sites. Majority of sites with instrumentation are P/T capable	P only sites in west part of catchment.		2	
Are telemetered groundwater levels already being obtained from EA boreholes within the catchment?	GIS: NGLA boreholes, list from EA	42 boreholes in catchment are telemetered. 4 of the telemetered sites are incorporated in the NGLA archive. Telemetry within catchment focused on flooding issues, most sites are close to rivers. Sites close to or in Bourley & Long Valley (SSSI) and Porton Down (SSSI).	Limited headwater telemetry available.	3		
Are there EA staff available to facilitate access to EA infrastructure in a timely manner during the design and the implementation phases of the pilots?	Sarah Richie			3		
Sustainability and practicality of access during the Pilot phase	GIS	Within a day's drive of BGS office using an electric vehicle		3		
Has there been previous research undertaken on groundwater temperature in the catchment?	Ward et al (2021) and light touch summary of peer-reviewed lit.		• No specific previous studies. • Some representative groundwater temperature data (fluid temperature logs & average temperatures for selected sites) is available for the Wessex Basin (Allen & Crane, 2011) but no data specific to the R Itchen. Stuart et al (2009) report limited, representative data for the Hampshire Basin.			1

River Itchen (Chalk)						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Has there been previous work undertaken to model the impact of climate change on groundwater in the catchment?	Future Flows and eFLAG. Ward et al (2021) and light touch summary of peer-reviewed lit.	• Future flows – Clanville Gate Lodge • eFlag sites – Kings Somborne, Tile Barn Farm, Clanville Lodge • Fung et al (2013) undertook an analysis of “Large Climate Ensembles to Plan for the Hydrological Impact of Climate Change in the Freshwater Environment” but only used SW models	• Sites in the River Itchen have not been subjects of the Future Flows and eFLAG analyses of CC impacts on groundwater.		2	
Has there been previous work on the temperature sensitivity of GWDTEs or groundwater-related surface water ecosystems.	Ward et al (2021) and light touch summary of peer-reviewed lit.		• Fung et al (2013) did not look at the effects of temperature on GWDTEs in the catchment. There are no other specific studies relating groundwater temperature and GWDTEs in this catchment.			1
Is there a 3D geological model and groundwater model of the catchment?	GIS: GW models	• The catchment lies within the BGS' Hampshire Basin 3D Regional Geological Model. In addition, there is good understanding of the geology of the catchment, particularly of the Chalk. • The EA have a hydrogeological model of the R Itchen (Whiteman et al., 2012).	• Currently there are no groundwater models calibrated to model groundwater temperature in the catchment (although this is thought to be the case for all catchments being considered)		2	

Table A2c Derwent RBD

Derwent						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Are there i) temperature-sensitive groundwater bodies and ii) hydraulically connected GWDTEs and iii) surface waters in the catchment?	GIS: Rivers, Bedrock vulnerability maps, GWDTEs, Bedrock geology	i) Carboniferous limestone GWB high vulnerability, Milstone Grit GWB medium vulnerability ii) 30 SSSI in or intersecting catchment iii) Yes		3		

Derwent						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Is there unconfined Chalk in the catchment?	GIS: Bedrock/superficial geology		No			1
Is there a high baseflow river in the catchment?	GIS: Rivers, CAMELS GB	CAMELS-GB areas: 28009; BFI - 0.67, CEH BFI – 0.63			2	
Are there multiple opportunities for instrumentation of EA boreholes?	GIS: WISKI monitoring boreholes, NGLA	2 NGLA sites (Hucklow South SK17/13 and Burtonshuts Farm SK24/22). 12 WISKI sites		3		
Are there opportunities for instrumentation of streams near to EA boreholes within the catchment?	GIS: WISKI surface water sites, watercourse	6 surface water sites	0 surface water sites within 10 km of NGLA site.			1
Are automated data loggers capable of temperature monitoring already deployed in EA boreholes within the catchment?	GIS: WISKI monitoring boreholes, NGLA boreholes	12 active sites on BWS. Hurdlow Meadows (SSSI)GWDTE has an associated monitoring site, as has the headwater of Monks Dale (SSI)	No data on equipment installed.		2	
Are telemetered groundwater levels already being obtained from EA boreholes within the catchment?	GIS: NGLA boreholes, list from EA	No boreholes in catchment	No existing telemetry.			1
Are there EA staff available to facilitate access to EA infrastructure in a timely manner during the design and the implementation phases of the pilots?	Alex Chambers			3		
Sustainability and practicality of access during the Pilot phase?	GIS		The sites would not be within a day’s drive using an electric vehicle and would require overnight stays within the study area.			1

Derwent						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Has there been previous research undertaken on groundwater temperature in the catchment?	Ward et al (2021) and light touch summary of peer-reviewed lit.	• Extensive work has been undertaken on the temperature of deep groundwater at the thermal springs of the Derbyshire Dome.	• Abesser and Smedley (2008) provide a summary of average groundwater temperatures at a number of sites from the Carboniferous Limestone of the Derbyshire Dome. • Although the Derwent has been included in analysis of SW temperatures in English rivers (Hammond and Pryce, 2007; Garner et al., 2014), no systematic study of shallow groundwater temperatures in the catchment appear to have been undertaken. •	3		
Has there been previous work undertaken to model the impact of climate change on groundwater in the catchment?	Future Flows and eFLAG. Ward et al (2021) and light touch summary of peer-reviewed lit.	• Future flows site at Hucklow South (SK17/13 at [417700 377500]) none in the eFLAG project • No distributed modelling of the impact of climate change on groundwater appears in the peer-reviewed literature			2	
Has there been previous work on the temperature sensitivity of GWDTEs or groundwater-related surface water ecosystems.	Ward et al (2021) and light touch summary of peer-reviewed lit.		• Although the Derwent has been included in analysis of the effect of SW temperatures on SW ecosystems in English rivers (Webb and Walsh, 2004), no systematic study of the sensitivity of GWTEs to groundwater temperatures appear to have been undertaken.			1
Is there a 3D geological model and groundwater model of the catchment?	GIS: GW models	• The catchment lies within the BGS' Central England 3D Regional Geological Model. In addition, there is good understanding of the geology of the catchment.	• Groundwater model - East Midlands Yorkshire Model to the East but does not encompass the catchment (Whiteman et al., 2012).		2	

Table A2d West Midlands SWBs

W Midlands SWBs						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Are there i) temperature-sensitive groundwater bodies and ii) hydraulically connected GWDTEs and iii) surface waters in the catchment?	GIS: Rivers, Bedrock vulnerability maps, GWDTEs, Bedrock geology	i) ii) 278 GWDTEs iii)		3		
Is there unconfined Chalk in the catchment?	GIS: Bedrock/superficial geology		No			1
Is there a high baseflow river in the catchment?	GIS: Rivers, CAMELS GB		Wide range of baseflow in region but none very high		2	
Are there multiple opportunities for instrumentation of EA boreholes?	GIS: WISKI monitoring boreholes, NGLA	83 NGLA sites, 663 WISKI sites		3		
Are there opportunities for instrumentation of streams near to EA boreholes within the catchment?	GIS: WISKI surface water sites, watercourse	Probably but need more detailed analysis of sub-catchments		3		
Are automated data loggers capable of temperature monitoring already deployed in EA boreholes within the catchment?	GIS: WISKI monitoring boreholes, NGLA boreholes	100 sites with data loggers. Several sites within the West Midlands are on GWDTEs 60 sites with telemetry capability	Sites concentrated around abstractions.	3		
Are telemetered groundwater levels already being obtained from EA boreholes within the catchment?	GIS: NGLA boreholes, list from EA	83 sites in catchment. High density monitoring around Shropshire groundwater scheme increases possibility of dense network	Sites are mostly associated with monitoring of the Shropshire groundwater scheme and abstraction around Kidderminster. P/T capable sites limited to extreme south of GW Body area in Cotswolds	3		
Are there EA staff available to facilitate access to EA infrastructure in a timely manner during the design and the implementation phases of the pilots?	John Davis / Sue Forsyth		EA regional staff unable to attend pilot catchment selection meeting			1

W Midlands SWBs						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Sustainability and practicality of access during the Pilot phase?	GIS		The majority of the sites would not be within a day's drive using an electric vehicle and would require overnight stays within the study area. Sites within the southern part of the region may be within a short working day's drive using an electric vehicle.			1
Has there been previous research undertaken on groundwater temperature in the catchment?	Ward et al (2021) and light touch summary of peer-reviewed lit.	• A number of detailed studies of groundwater and related SW temperatures in the Tern catchment (Keery et al., 2007; Hannah et al, 2009; Krause et al 2011; 2012; Krause and Bloom, 2013)	• No temperature-related studies on the wider catchment	3		
Has there been previous work undertaken to model the impact of climate change on groundwater in the catchment?	Future Flows and eFLAG. Ward et al (2021) and light touch summary of peer-reviewed lit.	• Heathlanes OBH was included in the Future Flows analysis and is included in the eFLAG project • No distributed modelling of the impact of climate change on groundwater appears in the peer-reviewed literature • EA groundwater models may have been run to assess the impact of climate change on GW across the region			2	
Has there been previous work on the temperature sensitivity of GWDTEs or groundwater-related surface water ecosystems.	Ward et al (2021) and light touch summary of peer-reviewed lit.		• No systematic studies of the sensitivity of GWTEs to groundwater temperatures have been found in the peer-reviewed literature.			1
Is there a 3D geological model and groundwater model of the catchment?	GIS: GW models	• The catchment lies within the BGS' Central England 3D Regional Geological Model. In addition, there is good understanding of the geology of the catchment, particularly of the Chalk. • The EA have hydrogeological models of the RBDs (Whiteman et al., 2012).			2	

Table A2e Thames Gravels GWB

Thames Gravels GWB						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Are there i) temperature-sensitive groundwater bodies and ii) hydraulically connected GWDTEs and iii) surface waters in the catchment?	GIS: Rivers, Bedrock vulnerability maps, GWDTEs, Bedrock geology	i) Thames Gavels GWB ii) 7 GWDTEs iii) ?		3		
Is there unconfined Chalk in the catchment?	GIS: Bedrock/superficial geology		No			1
Is there a high baseflow river in the catchment?	GIS: Rivers, CAMELS GB	Partially in CAMELS-GB catchment 39001. Baseflow index 0.63, baseflow index CEH 0.59			2	
Are there multiple opportunities for instrumentation of EA boreholes?	GIS: WISKI monitoring boreholes, NGLA	1 NGLA site Bray No1 OBH (SU97/78A at [4910 1780]) 6WISKI sites		3		
Are there opportunities for instrumentation of streams near to EA boreholes within the catchment?	GIS: WISKI surface water sites, watercourse	Surface water WISKI sites ~5km from NGLA borehole			2	
Are automated data loggers capable of temperature monitoring already deployed in EA boreholes within the catchment?	GIS: WISKI monitoring boreholes, NGLA boreholes	4 active sites on BWS. 2 Instrumented sites. Two sites with PT/ loggers, I1 telemetered	Sites not associated with GWDTEs			1
Are telemetered groundwater levels already being obtained from EA boreholes within the catchment?	GIS: NGLA boreholes, list from EA	One site in catchment. Site is at upper end of catchment and likely to be representative of shallow waters in gravels and the Bray Pennyroyal Field (SSSI) GWDTE	Only one telemetered site		2	
Are there EA staff available to facilitate access to EA infrastructure in a timely manner during the design and the implementation phases of the pilots?	Nigel Hoad			3		
Sustainability and practicality of access during the Pilot phase?	GIS	Within a day's drive of BGS office using an electric vehicle		3		

Thames Gravels GWB						
Criterion	**Data or evidence**	**Pros**	**Cons**	**H**	**M**	**L**
Has there been previous research undertaken on groundwater temperature in the catchment?	Ward et al (2021) and light touch summary of peer-reviewed lit.		• A number of studies of groundwater heating/cooling in the gravels but not in the immediate GWB (Birks et al 2013 and references therein)			1
Has there been previous work undertaken to model the impact of climate change on groundwater in the catchment?	Future Flows and eFLAG. Ward et al (2021) and light touch summary of peer-reviewed lit.	• EA groundwater models may have been run to assess the impact of climate change on GWB	• None in the peer-reviewed literature			1
Has there been previous work on the temperature sensitivity of GWDTEs or groundwater-related surface water ecosystems.	Ward et al (2021) and light touch summary of peer-reviewed lit.		• None in the peer-reviewed literature			1
Is there a 3D geological model and groundwater model of the catchment?	GIS: GW models	• The EA have a hydrogeological model of the RBD (Whiteman et al., 2012), namely: Groundwater models: London Basin Mode, Mole Model, South West Chilterns Model	• There has been very little published on the hydrogeology of the Thames Gravels to the west of London (Naylor, 1974). Bricker and Bloomfield (2014) analysed the aquifer properties of the unit across the basin but not specifically the London Gravels GWB area. There are no 3D geological models of the gravels in the peer-reviewed literature.		2	

Table A3 (a-d) Details of candidate sites

Table A3a Berkshire Downs

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Notes & overall assessment (pros/cons) of OBH or sough and any issues
Ashdown Park OBH	428090	181600	No issues	0-10 m plain	80.6 m plumb	Ott PLS SDI-12 53.7 m sensor cable, 0-100m range	Relatively cool GW recharge in top of profile (10.1 °C) with increase in temp at ~20mbGWL. EA sensor set ~23mbGWL.	EA depth 92m BGS used lower hole on flange plate. Not listed in EA list of decom. sites **Scope for second sensor towards base of OBH in warmer section (10.8 °C) of the OBH at ~50mbGWL**
Ashridge Wood OBH	449410	177920	No issues	0-10 m plain	70.87 plumbed	Impress S12C 60.6 m sensor cable, 0-30 m range	Small linear increase in GW T from water table (10.24 °C) to ~15mbGWL (10.26 °C)	EA depth 69 Sensor has no cap Not listed in EA list of decom. sites **Relatively short interval for monitoring with limited GW T var. – no new instrumentation recommended.**
Chapel Farm OBH	444550	175900	No issues	0-10 m plain	33.63	Impress S12S 22.6 m sensor cable, 0-30 m range ~5m spare cable	Small decrease in GW T with depth below GWL from 10.38 °C at water tables to 10.27 °C about 18m below GWL	Isodaq Frog (telemetry) EA TD 32.4 m Not listed in EA list of decom. sites **Relatively short interval for monitoring with limited GW T var. – no new**

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Notes & overall assessment (pros/cons) of OBH or sough and any issues
								instrumentation recommended.
Eastridge Farm OBH	429950	172440	No issues	Casing to 13.7 m	97.3 m estimate using transducer cable length	Ott PLS SDI-12 80.3 m sensor cable, 0-100m range	Irregular depth profile with distinct step up in GW T at ~17.5 bGWL. Overall increase in GWT from 10.27 °C at GW table to 10.67 at ~30mbGWL	Diameter of borehole too narrow to plumb. No GWL dip as dip tape not long enough. Not listed in EA list of decom. sites **Relatively short interval for monitoring – no new instrumentation recommended.**
Faarn Combe OBH	431090	178050	No issues	0-10m plain	86.28 m plumb	Impress S12C 38.5 m sensor cable 0-40m range	Roughly constant GW T (10.45 deg.C) from GW table to ~45mbGWL then significant increase in GW T up to 11.07 °C at ~65 mbGWL	EA depth 115.82 m Not listed in EA list of decom. sites **Scope for second sensor towards base of OBH in warmer section (11.07 °C) of the OBH at ~65mbGWL**
Great Shefford OBH	438120	175470	No issues	12.5m plain casing	100.58	Impress S12C 1.90 m cable length 0-5 m range	EA transducer in cased interval at 1.9 mbGL. GW T in casing relatively cool rising from 9.6 to 10.3 °C with depth through cased interval. In uncased section increases in stratigraphic controlled(?) steps to 11 °C at 100m bGL.	28m of spare cable on EA line BGS could not plumb >100m due to limit on length of plumb line Listed as 561 in overall asset ranking in EA decom. list **Scope for two additional sensors one just below**

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Notes & overall assessment (pros/cons) of OBH or sough and any issues
								casing at ~20mbGL and a second at ~50mbGL
High Street Farm OBH	442100	171180	No issues	0-10 m plain	46.25	GEMS 9600 22.15 m sensor cable 0-30m range ~5 m unused cable	Very limited GW T range from 10.165 to 10.22 °C with tendency for warming with depth below GW table	EA TD 45.7 Listed as 2485 in overall asset ranking in EA decom. list **Relatively short interval for monitoring with limited GW T var. – no new instrumentation recommended.**
Hodcott 2 OBH	448250	182090	No issues	0-10 m plain	138	Impress S12S 31.58 m sensor cable 0-50 m range	Cool upper section with GW T at ~ 10.45 °C down to ~50mbGWL then steady increase in T to ~11 deg.C at ~100mbGWL	EA depth 138m Not listed in EA list of decom. sites BGS could not plumb >100m due to limit on length of plumb line **Scope for second sensor towards base of OBH in warmer section (11 °C) of the OBH at ~100mbGWL**
Lower Chance Fm OBH	451900	182730	No issues	0-55 m plain	85.94 m plumb	Ott PLS SDI-12 29.74 m sensor cable	Casing down to 55mbGL. GW T in casing slowly rises from ~10.2 °C at 10mbGL to 10.45 °C at 52 mbGL. EA transducer is in cased interval at 28.74 m bGL. GWT then increases more rapidly with depth to base of OBH with GW T of ~11.1 °C at 84m bGL	EA depth 88 m Not listed in EA list of decom. sites **Scope for two additional sensors one just below casing at ~55mbGL and a second at base of OBH at ~85mbGL**

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Notes & overall assessment (pros/cons) of OBH or sough and any issues
Marlston Farm OBH	453370	171890	No issues	0-12 plain	28.05	Impress S12S 9.46 m sensor cable 0-10m range	Casing down to 12mbGL. GW T in casing slowly falls from ~11 °C at 8mbGL to 10.95 °C at base of casing. EA transducer is in cased interval at 9.46mbGL. GW T continues to fall to ~ 10.75 deg. At 22.5 mbGL and then is aprox. constant to base of OBH at ~29 mbGL	EA TD 29m Not listed in EA list of decom. Sites **Scope for additional sensor at base of OBH at ~29mbGL.**
Mayfield Farm OBH	451190	179510	No issues	0-10 m plain	62 m plumb	Ott PLS 48.6 m sensor cable 0-40 m range	GW T increases v slightly from 10.25 °C from the top of GW table to 10.28 °C at ~17mbGWL. It then rises more rapidly to ~ 10.4 °C to the base of the OBH at about 23mbGWL	EA depth 69 m Not listed in EA list of decom. Sites **Scope for second sensor towards base of OBH in warmer section (10.4 °C) of the OBH at ~23mbGWL**
Oak Ash OBH	442730	177410	No issues	0-10 m plain	95.12 plumb	Impress S12C 68.3 m sensor cable 0-30 m range	Coolest GW T of the Berkshire Downs sites. Gradual increase in GW T from ~9.88 °C at GW table to 10 °C at~32.5 mbGWL	EA depth 95m Not listed in EA list of decom. Sites BGS unable to dip as dipper not long enough Not listed in EA list of decom. sites **Scope for second sensor towards base of OBH at ~32.5 mbGWL**
Peasemore OBH	445940	175510	No issues	0-13m plain	32.8 m (plumb)	Ott PLS SDI-12 22.3 m sensor cable 0-40 m range	V. Limited GW T range of 0.1 °C from GW table to ~25 mbGWL	EA depth 141.73 Not listed in EA list of decom. Sites

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Notes & overall assessment (pros/cons) of OBH or sough and any issues
								Note big disparity with EA TD and BGS plum – collapse? **Relatively short interval for monitoring (due to OBH collapse) and hence limited GW T range – no new instrumentation recommended.**
Sulham Brook OBH	464130	175920	No issues	0-7.7 plain	11.13 m plumb	GEMS 9600 4.65 m sensor cable 0-5 m range	Large increase in GW T from ~10.7 °C at GW table in casing to ~11.4 °C at ~8.2 m GWL. EA sensor in casing	EA depth 15 m Not listed in EA list of decom. Sites **Relatively short interval for monitoring but scope for second sensor towards base of OBH in warmer section (11.4 °C) of the OBH at ~8 to 10mbGWL**
Upper Lambourn OBH	431400	180670	No issues	0-10 m plain	100m plumb	GEMS 9600 29.8 m sensor cable 0-50m range	~constant GWT from GW table at ~12mbGL to ~50mbGL then GW T increases to ~11.25 °C at ~100mbGL	EA depth 126 m Not listed in EA list of decom. Sites Dual completion hole. BGS used outer **Scope for two additional sensors at ~70m and ~100mbGL**
Winterbourne Farm OBH	445020	171890	No issues	0-13m plain	28.61 m plumb	GEMS 9600 9.08 m sensor cable 0-10m range	EA sensor within casing. Limited range of GW T below casing with GW T increasing from ~10.1 °C at base of casing (13mbgl) to ~10.3 °C at ~27mbGL	EA depth 37.5 m Listed as 1582 in overall asset ranking in EA decom. list **Relatively short interval and limited GW T range –**

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Notes & overall assessment (pros/cons) of OBH or sough and any issues
								no new instrumentation recommended.

Table A3b Derwent

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Overall assessment (pros/cons) of OBH or sough and any issues
Rider Point	426170	356430	No issues	47 mm down to 100.16 m (slotted casing?)	100	GEMS 9500 41.89 m sensor cable 0-40m range	Limited range of GW T with small decline in T from ~9.5 °C at GW tables to ~8.8 °C at ~80mbGWL. GWL time series appears to show rapid up to 1 °C rapid changes in GW T at the EA sensor (41.89 mbGL) but no systematic correlation with GWLs at site so may be artefacts	EA TD 100m Not listed in EA list of decom. Sites Too narrow for BGS to plumb Temp now enabled by local EA H&T team EA records of sensor inconsistent with current instrumentation. **No new instrumentation recommended.**
Oddo House	421820	360710	No EA lease, remote site	1.5 m dia. well unlined to 33.5 m	29.75 m	None	No change in GW T from GW table to 4 mbGWT	EA 45.72m Not listed in EA list of decom. Sites Apparent borehole collapse too narrow to get dipper past 29.75 **No new instrumentation recommended.**

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Overall assessment (pros/cons) of OBH or sough and any issues
Dalehead Farm	420776	368997	Needs prior notice with land owner	47 mm dia. tube to depth of 100 m lined with (slotted?) plastic	100.16 m			Not visited. Not listed in EA list of decom. Sites **No new instrumentation recommended.**
Hillcarr Sough	425840	363720	No issues			Stage board (1m) with steps down to board.	T series data available	Water Quality monitoring at bridge 100m downstream(100l/s) Sough 0.6 to 0.7m deep, all shaded outlet. Stilling well could be attached to board or fixed by drilling into wall. **No new instrumentation recommended.**
Magpie Sough	417920	369610	No issues	N/A	N/A		T series data available	Completely shaded. Un-instrumented stilling well at site. **Recommend installation of sensor in stilling well**
Meerbrook Sough Outfall	432670	355240	Needs prior notice with water co.	N/A	N/A	No EA equipment on site. T measured at water co. intake a few 100m away. Water company ultrasonic sensor and stage board	T series data available	Completely shaded. **No new instrumentation recommended.**

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Overall assessment (pros/cons) of OBH or sough and any issues
Yatestoop Sough Outfall	426400	362580		N/A	N/A		T series data available	Not visited **No new instrumentation recommended.**
Mandale Sough outfall	419710	366110		N/A	N/A		T series data available	Not visited **No new instrumentation recommended.**
Well head Spring Middleton	419990	363260		N/A	N/A		T series data available	Not visited **No new instrumentation recommended.**

Table A3c Thames Gravels

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Overall assessment (pros/cons) of OBH or sough and any issues
Summerleaze			Site owned by quarry	2m casing	6.24 m plumb	Ott PLS 3.54 m sensor cable 0-4 m range 13 m spare cable	Increase from 10.7 at GW table to 11.2 °C at ~3mbGWL	EA TD 5.1m Not listed in EA list of decom. Sites **Relatively short interval for monitoring – no new instrumentation recommended.**
Bray No1			Prior permission needed from water company		12.52 m plumb	GEMS 9600 0-5 m range 5.8 m sensor cable Spare 10m cable	GW T constant at ~11.8 °C from GW table to ~7mbGWL	EA TD 13 Not listed in EA list of decom. Sites **Relatively short interval for monitoring – no new**

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Overall assessment (pros/cons) of OBH or sough and any issues
								instrumentation recommended.
Maidenhead D	489120	182000	EA fenced	0-6.5 plain 6.5-20m slotted 100mm dia casing	10 m plumb	Telemetered Ott PLS. ‘sig. spare cable’. Scope for lowering sensor 4 or 5 metres.	Increase from 11.2 at GW table to 11.7 °C at ~6.5mbGWL	Close to stream. Stream temp 5.6 °C and air temp 4.2 deg C. Not listed in EA list of decom. Sites **Relatively short interval for monitoring – possible scope for additional instrumentation below casing.**
Blackamoor Lane	489350	18610	No issues	0-8 plain, 8-18 slotted casing	18 m plumb	Ott Orpheus mini set within blank casing	Increase from 11.8 at GW table to ~12.5 °C at ~6mbGWL and then constant to ~15mbGWL	Not listed in EA list of decom. Sites **Relatively short interval for monitoring – no new instrumentation recommended.**
Cookham	488220	184090	No issues	No evidence of slotted casing, ‘possibly hand slotted at 0.5 to 0.75 m intervals	23 m plumb	Ott Orpheus mini and Water company Level Troll	GW T constant at ~11.8 °C from GW table to ~11.5mbGWL	Not listed in EA list of decom. Sites **Relatively short interval for monitoring – no new instrumentation recommended.**
Albany Park	502967	177054	No issues	Plain to 1.5 m then slotted 1.5 to 2.8 m	2.8 m	Water Company Level Troll at 2m	Constant at about 10.1 °C from GW table to ~3mbGWL	Very shallow water, manhole flooded. Not listed in EA list of decom. Sites **Relatively short interval for monitoring – no new instrumentation recommended.**

Table A3d London confined Chalk

Borehole Name	Easting	Northing	Access	Construction	Total depth	Current instrumentation	Summary of T time series and depth profiles	Notes & overall assessment (pros/cons) of OBH or sough and any issues
Ashley Green OBH	529329	179090	Prior approval from land owner	Unknown	80.6 m plumb	Unknown	N/A	T profile yet to be obtained
St Agnes Well OBH	526703	180682	No access was available	Unknown	70.87 plumbed	Unknown	N/A	No T profile measured

Figure A1. Photos of deployed infrastructure

Berkshire Downs - Ashdown

Berkshire Downs – Upper Lambourn

Berkshire Downs – Faarn Combe

Berkshire Downs – Great Shefford

Berkshire Downs – Oak Ash

Berkshire Downs – Hodcott 2

Berkshire Downs – Mayfield Farm

Berkshire Downs – Marlstone Farm

Derwent – Magpie sough

Central London confined Chalk – Asley Gardens

Thames Gravels – Maidenhead D