# BGS Karst Report Series: C4. Karst in the Chalk of the Chilterns and the Berkshire and Marlborough Downs

Environmental Change, Adaptation and Resilience Programme

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Keyworth, Nottingham British Geological Survey 2020

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# Introduction to the BGS Karst Report Series

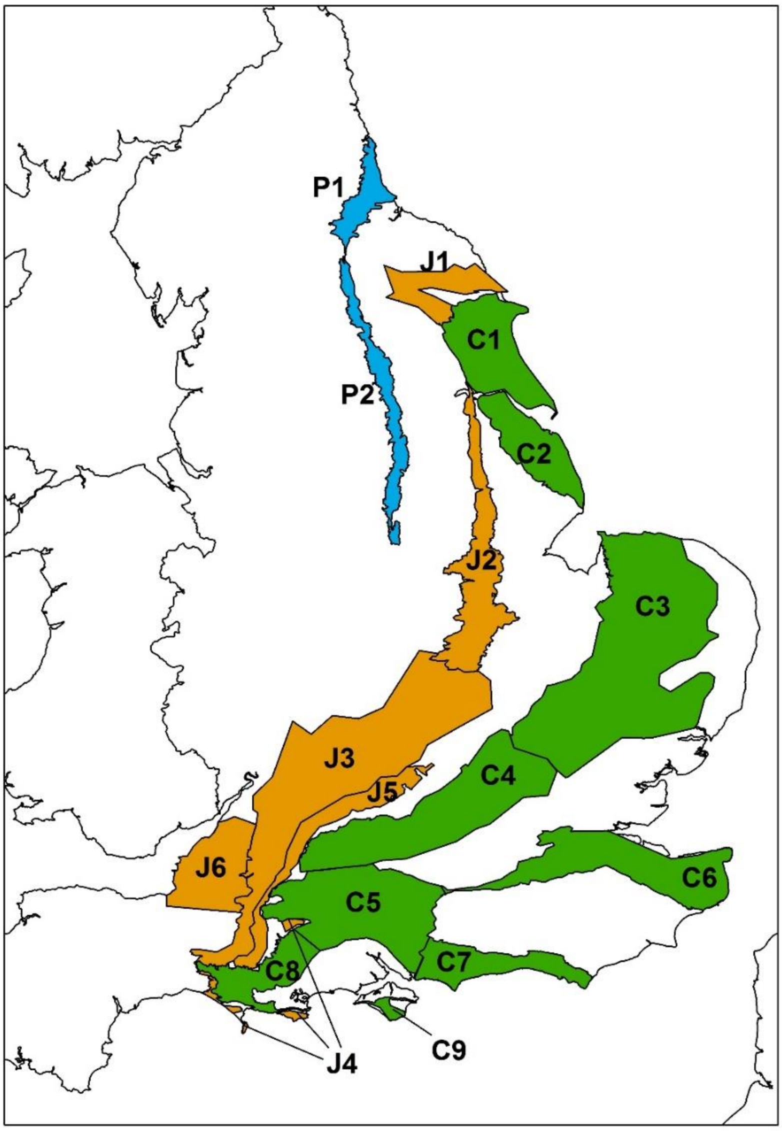
The BGS karst report series is focused on karst aquifers in England in which cave development is limited – The Chalk and the Jurassic and Permian Limestones. The series is the main output of the NERC funded Knowledge Exchange fellowship “Karst knowledge exchange to improve protection of groundwater resources” undertaken between 2015 and 2021.

The term “karst” applies to rocks that are soluble. In classical karst there are extensive caves; and there are large scale surface karst landforms such as dolines, shafts, river sinks, and springs. In the past the Chalk and the Jurassic and Permian Limestones of England were not considered karstic because they have limited cave development, and because karst features are small and have not been well documented. However, permeability in these aquifers is determined by their soluble nature and groundwater flow is predominantly through small-scale karstic solutional features comprising small conduits ~ 5-30 cm diameter and solutionally enlarged fractures (fissures) of ~0.5-15 cm aperture. There are some short caves in all three aquifers; they all have dolines, stream sinks and large springs; and rapid flow can occur over long distances. Karst is therefore an important feature of these aquifers.

The series comprises 17 reports which provide an overview of the evidence for karst in different areas of England. The Chalk and Jurassic and Permian Limestones are divided into these areas based on geology and geography. The Chalk is divided into 9 areas, primarily based on geography. The Permian limestones are divided into two areas, comprising a northern and southern outcrop. The Jurassic limestones have more variable geology and are divided into six areas. J1 covers the Corallian Limestone of Northern England. J2 covers the Lincolnshire Limestone of central England. J3 covers the Great and Inferior Oolites of Southern England. J4 covers three small areas of the Portland and Purbeck limestones in Southern England. J5 covers the Corallian Limestone of Southern England. J6 covers the Blue Lias of Southwest England and comprises several small outcrops within a large area.

Karst data are compiled from the British Geological Survey databases on karst, springs, and transmissivity; peer reviewed papers and reports; and through knowledge exchange between 2015 and 2020 with the Environment Agency, universities, water companies and consultants. The data are not complete and further research and knowledge exchange is needed to obtain a fuller picture of karst development in these aquifers, and to investigate the detail of local catchments. The reports provide an initial overview of the evidence for karst and demonstrate that surface karst features are much more widespread in these aquifers than previously thought, and that rapid groundwater flow is common. Consideration of karst and rapid groundwater flow in these aquifers will improve understanding of how these aquifers function, and these reports provide a basis for further investigations of karst to enable improved management and protection of groundwater resources.

The reports are structured to provide an introduction to the area and geology, evidence of karst geomorphological features in the area (caves, conduits, stream sinks, dolines, springs); evidence of rapid flow from tracer testing, and other hydrogeological evidence of karst. Maps of the area show the distributions of karst features, and there is a quick reference bullet point summary.




**Map of the locations of the Karst reports**

C1) Karst in the Chalk of the Yorkshire Wolds
C2) Karst in the Chalk of Lincolnshire
C3) Karst in the Chalk of East Anglia
C4) Karst in the Chalk of the Chilterns and the Berkshire and Marlborough Downs
C5) Karst in the Chalk of the Wessex basin
C6) Karst in the Chalk of the North Downs
C7) Karst in the Chalk of the South Downs
C8) Karst in the Chalk of Dorset
C9) Karst in the Chalk of the Isle of Wight
J1) Karst in the Jurassic Limestone Corallian Group of Northern England
J2) Karst in the Jurassic Lincolnshire Limestones of Central England
J3) Karst in the Jurassic Great and Inferior Oolites of Southern England
J4) Karst in the Jurassic Portland and Purbeck Limestones in Southern England
J5) Karst in the Jurassic Corallian Group Limestones of Southern England.
J6) Karst in the Jurassic Blue Lias Limestones of Southwest England.
P1) Karst in the northern outcrop of the Permian Limestones
P2) Karst in the southern outcrop of the Permian Limestones

# Introduction to Karst Data

This section provides background on each type of evidence for karst, the data sources used, and any limitations in the data. A glossary is provided at the end of the report.

*Stream sinks*

Stream sinks provide direct evidence of subsurface karst and rapid groundwater flow because there must be a network of solutional voids of sufficient size to transport the water away. Most stream sinks occur near to the boundary between the carbonate aquifer and overlying lower permeability geologies, with surface runoff from the lower permeability geologies sinking into karstic voids in the carbonate aquifer at the boundary or through more permeable overlying deposits close to the boundary.

Data on stream sink locations in the Chalk and Jurassic and Permian limestones are variable and although there are many records, the dataset is incomplete, and further surveys are likely to identify more stream sinks. Stream sink records are predominantly from the BGS karst database in which many were identified by desk study. Several stream sink field surveys have also been carried out, predominantly in areas of the Chalk in Southern England. Some additional records were obtained through knowledge exchange.

Most streams that sink have multiple sink points over distances of 10s to 1000s of metres. The sink point varies depending on flow conditions and also as some holes become blocked with detritus and others open up. Each individual sink point provides recharge into a solutional void in the underlying carbonate aquifer, and their locations therefore provide direct evidence of the locations of subsurface solutional features enabling rapid recharge. The sink points range from small holes in stream beds, to sink points located in karstic depressions of more than 10 m in depth and/or diameter. Some data sources report many/all individual sink points associated with a stream; whilst others report a single point for an individual stream irrespective of whether there are multiple sink points. The data presented here comprise all the sink point records that the studies report, but there are likely to be many more sink points in streambeds which have not yet been identified.

Further information on the discharge and nature of the stream sinks is generally sparse, but where available, information from reports and papers are summarised.

Some streams and rivers flowing over carbonate geologies have sections with substantial losses or which dry up in the middle of their course. These are also a type of karst stream sink providing recharge to solutional voids in the subsurface. Whilst some that sink into obvious holes in the riverbed have been identified, and there are some studies that provide evidence of river losses/drying, there has been no systematic study of the occurrence of karstic recharge through riverbeds in the Chalk, or Jurassic or Permian limestones. River flow data were not reviewed for these reports. The data presented are from a brief literature review, and there may be many other streams and rivers that provide point recharge into subsurface karstic features.

*Caves and smaller conduits*

Karstic caves (conduits large enough for humans to enter) occur in the Chalk and Jurassic and Permian limestones, providing clear evidence of the importance of karst in these aquifers. Caves were identified from literature review, predominantly from publications of the British Cave Research Association, and local and regional caving societies. Many chalk caves were identified by Terry Reeves of the Chelsea Speleological Society, who provided pictures and information about the caves, many of which are documented in the journal of the Chelsea Speleological Society.

Smaller conduits are observed in quarry walls and natural cliff outcrops, and in images of borehole walls. Conduits (~5 to >30 cm in diameter) and larger solutional fissures (apertures of > 2 cm) are commonly observed in images of abstraction and monitoring boreholes. However, there is no dataset on conduits, and they have generally not been studied or investigated, so it is not possible to assess their frequency or patterns in their distributions. Information on conduits from knowledge exchange and literature review are included, but the data are very limited in extent.

*Dolines*

Dolines provide direct evidence of karst, and may be indicative of rapid groundwater flow in the subsurface. They occur in the Chalk and Jurassic and Permian limestones. However, their identification can be challenging as surface depressions of anthropogenic origin (e.g dug pits, subsidence features associated with the collapse of old mines, dewponds) can appear similar to karst dolines. This is especially the case in the Chalk. The reports review the evidence for surface depressions in the area and discuss whether these are likely to be karstic or anthropogenic in origin.

Data on surface depression locations come from the BGS karst database in which they were identified by either desk study or during geological mapping. Other records of surface depressions were obtained through knowledge exchange and literature review, and studies of dolines in the area are summarised. In some areas there may be surface depressions/dolines that have not yet been identified.

*Dissolution pipes*

Dissolution pipes only occur in karstic soluble rocks and their presence is therefore evidence of karst. Their role in providing recharge into subsurface karstic features is poorly known although many of them appear to contain low permeability material and may be formed by in-situ bedrock dissolution and therefore may not be linked to larger dissolutional voids in the subsurface.

Dissolution pipes occur at very high densities in some areas, and are commonly encountered in engineering projects. Some data on dissolution pipes come from the National Cavities Database. This is a legacy dataset held by The British Geological Survey and Peter Brett Associates. It is comprised of data from a range of sources originally commissioned by the Department of the Environment and reported by Applied Geology Limited (1993). In some areas dolines and dissolution pipes are not distinguished in the National cavities database. Information from reports and papers with information on dissolution pipes in the area are summarised.

*Springs*

Large springs are indicative of connected networks of karstic voids to sustain their discharges. Data on spring locations were collated from the BGS karst and springs databases, and Environment Agency spring datasets. Further information on springs was obtained through knowledge exchange and literature review. The springs dataset presented in this report series is not complete and there are likely to be more springs that have not been identified. In England there are very few data on spring discharges and most springs are recorded as of unknown discharge. However, in most areas some springs with known discharges of > 10 or > 100 $l.s^{-1}$, have been identified. There are also some springs with no discharge data but which have been observed during field visits to be large (likely to be > 10 $l/s^{-1}$), or were used as monitoring outlets in tracer studies, and these have been recorded as "assumed large springs". There remains much work to be done to develop a useful dataset on the discharges and characteristics of springs in the Chalk and Jurassic and Permian limestones, but the data presented here provide an initial overview, and suggest that large springs are common in these aquifers.

*Tracer tests*

Tracer tests provide direct evidence of subsurface karstic flowpaths in which groundwater flow is rapid. The development of cave-sized conduits is not a pre-requisite for rapid groundwater flow, and in these aquifers where cave development is limited, the karstic flowpaths may comprise connected networks of smaller conduits and solutional fissures.

Tracer test data were compiled from literature review and knowledge exchange. It is probable that most of the successful tests that have been carried out in these aquifers have been identified.

*Other evidence of karst and rapid groundwater flow*

This section provides an overview of other evidence of karst from literature review and knowledge exchange; and includes evidence from borehole monitoring or other hydrogeological studies.

There is substantial evidence of karst from groundwater abstractions from these aquifers. Whilst all successful abstractions are likely to be supplied by connected networks of solutional voids, the higher the transmissivity, the more widespread and well developed the karstic networks are likely to be. Transmissivity data from the national aquifer properties manual (Allen et al., 1997; MacDonald and Allen, 2001) are presented.

Knowledge exchange with water companies highlighted that in many areas water supply abstractions and springs have some characteristics that are indicative of karst. In some areas abstractions have indicators of low residence time groundwater and/or connectivity with surface water; for example high coliforms, high turbidity, rapidly degrading pesticides, evidence of connectivity with the sea or surface rivers over long distances. These data are not presented to protect site confidentiality, but a general overview is provided where possible.

# Acknowledgements

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# Contents



**FIGURES**

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# 1 Introduction

## 1.1 AREA AND GEOLOGY

The C4 Chalk area extends from Devizes, Wiltshire in the Southwest to Stevenage, Hertfordshire in the Northeast (Figure 1). In the west of the area, the River Kennet and its tributaries flow towards the east to join the River Thames. The east of the area is drained by the Colne and Lee rivers and their tributaries (Figure 2).

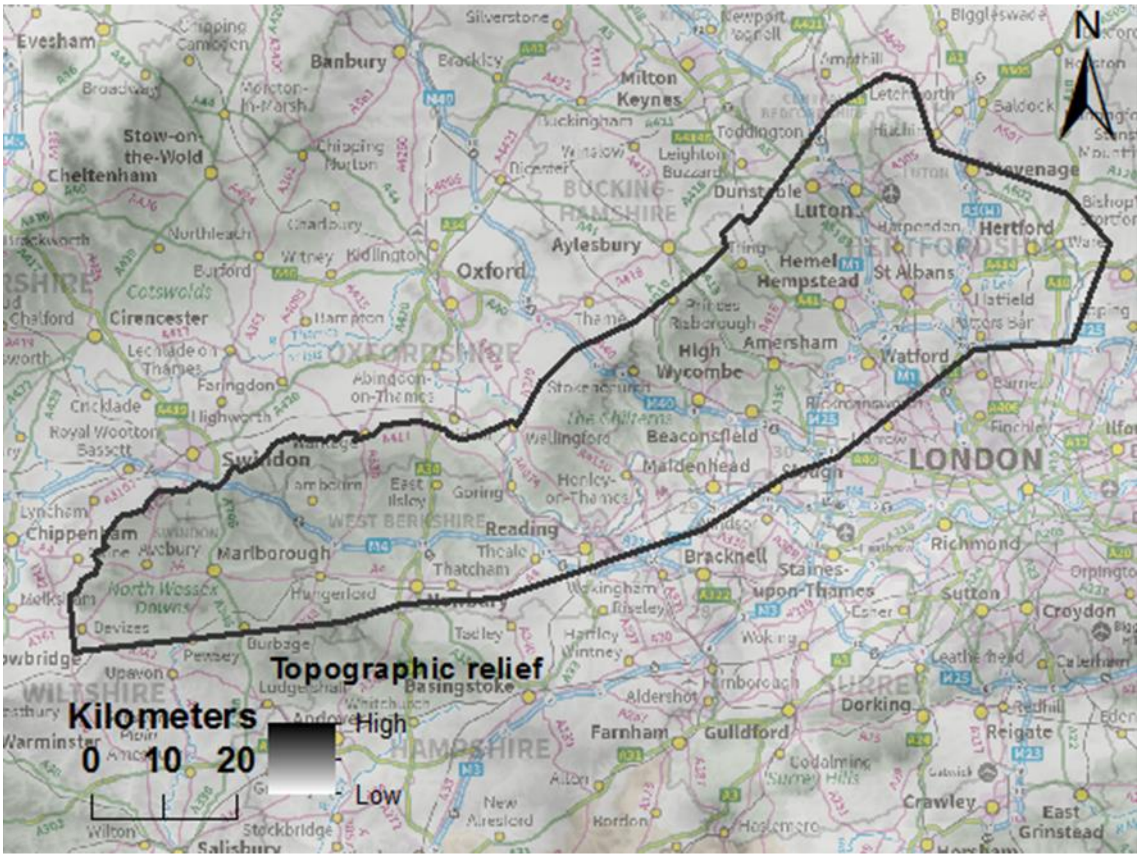


Figure 1. The C4 Chalk area.



The area comprises the Berkshire and Marlborough Downs and the Chiltern Hills, which form the northwest side of the London basin. The Upper Cretaceous Chalk Group dips gently towards the south and southeast where it is overlain by younger Palaeogene deposits of the Lambeth Group and overlying London Clay Formation (Figure 2). To the north and west, the Chalk is underlain by the Selborne Group which comprises the Upper Greensand Formation and the Gault Formation. The stratigraphy of the area is presented in Table 1. The area is bounded in the north and west by the steep Chalk escarpment, and by the Palaeogene outcrop to the south and east.

Superficial deposits are generally present (Figure 3). Alluvium, and sands and gravels occur in the river valleys; and Clay with Flints deposits are present on the interfluves. In the east of the area there are some glacial deposits (Till and glaciofluvial gravel), primarily in the River Lee catchment around Hertford. River terrace deposits occur along the major river valleys and through the Vale of St Albans.

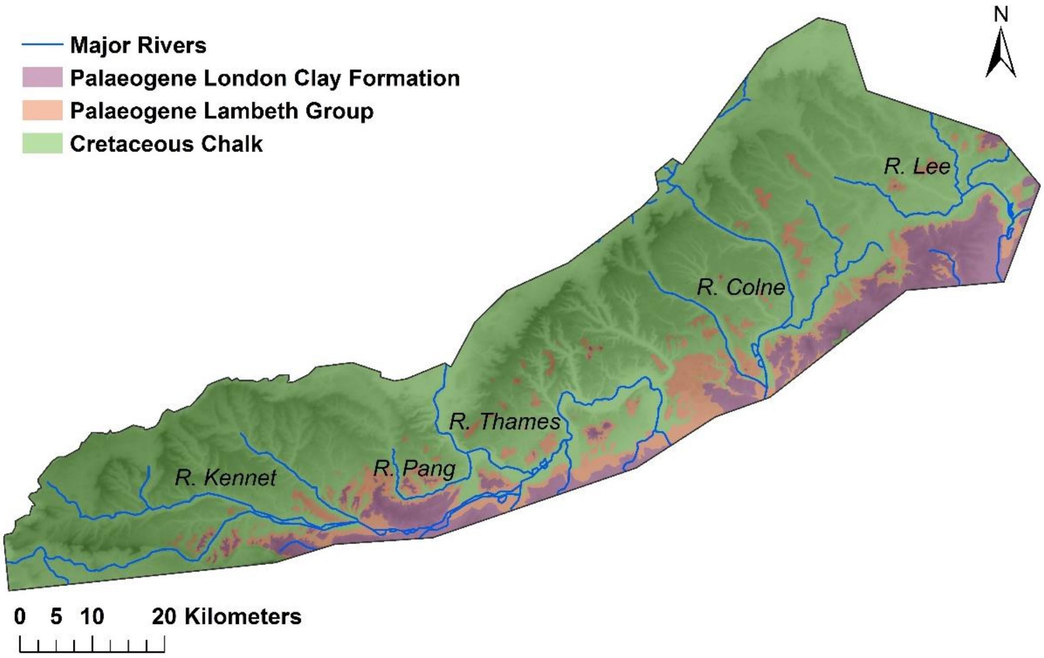


Figure 2. Bedrock geology and rivers in the C4 Chalk area.



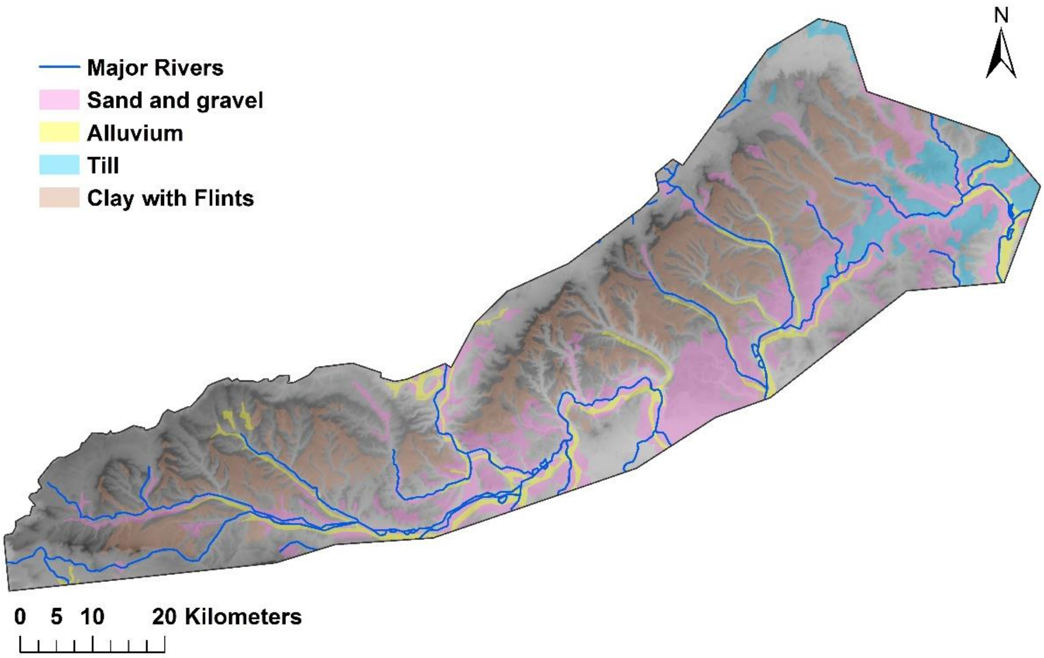


Figure 3. Superficial geology and rivers in the C4 Chalk area.

Table 1. The stratigraphy of the C4 Chalk area.

| Age | Group | Formation | Lithology |
|---|---|---|---|
| Palaeogene | Thames Group | London Clay Formation | Clay, some silt and sand and pebbles |
| | Lambeth Group | Reading Formation | Clay and sand |
| Upper Cretaceous | White Chalk Subgroup | Newhaven Chalk Formation | Soft to medium hard smooth white chalk with numerous marl seams and flint bands. |
| | | Seaford Chalk Formation | Firm white chalk with large nodular and tabular flints. |
| | | Lewes Nodular Chalk Formation | Hard to very hard nodular chalks with interbedded soft chalk and marls. |
| | | New Pit Chalk Formation | Firm and blocky white chalk with sporadic flint and numerous marls. |
| | | Holywell Nodular Chalk Formation | Hard nodular chalk with thin marls and often significant shell debris. |
| | Grey Chalk Subgroup | Zig Zag Chalk Formation | Pale grey blocky chalk with alternations of marl in the lower sections. |
| | | West Melbury Marly Chalk Formation | Soft grey and off-white chalk with mark and limestone. |
| Lower Cretaceous | Selborne Group | Upper Greensand Formation | Glauconitic sand and sandstones |
| | | Gault Formation | Clay and mudstone |

## 1.2 WATER PROVIDERS AND REGULATORS

Thames Water and Affinity Water are the main water providers in the C4 Chilterns Chalk area (Figure 4). Small parts of the area are supplied by Wessex Water, Anglian Water and South East Water. The western part of C4 Chilterns Chalk area mainly lies in the Thames Environment Agency area (Figure 5), with the eastern part of the area within the Hertfordshire and North London Environment Agency area.

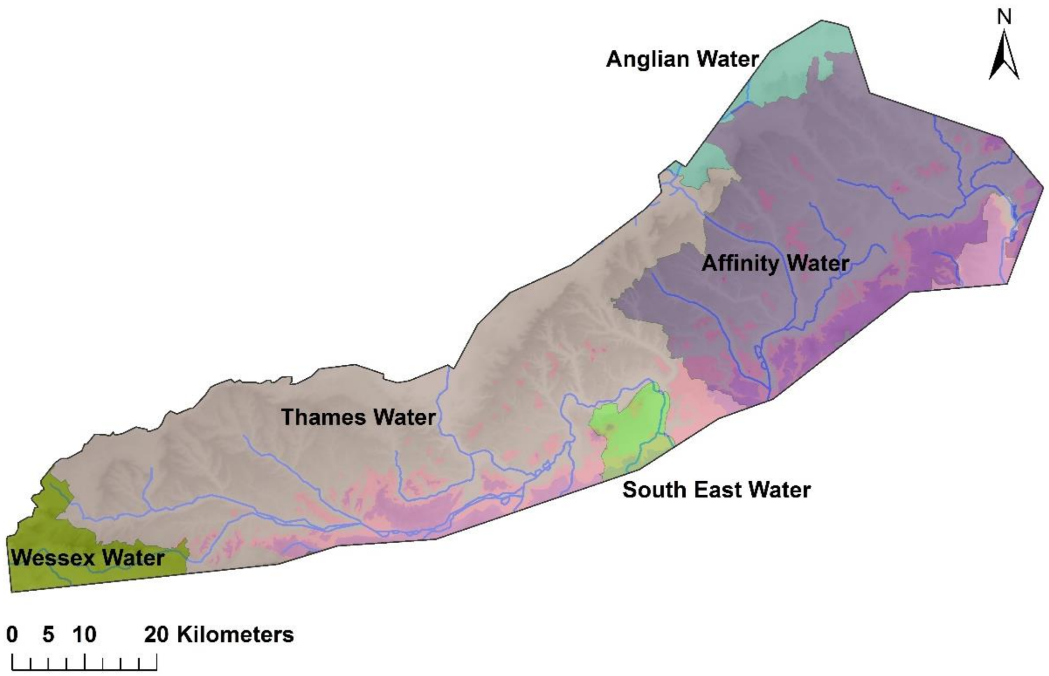


Figure 4. Water providers in the C4 Chalk area.



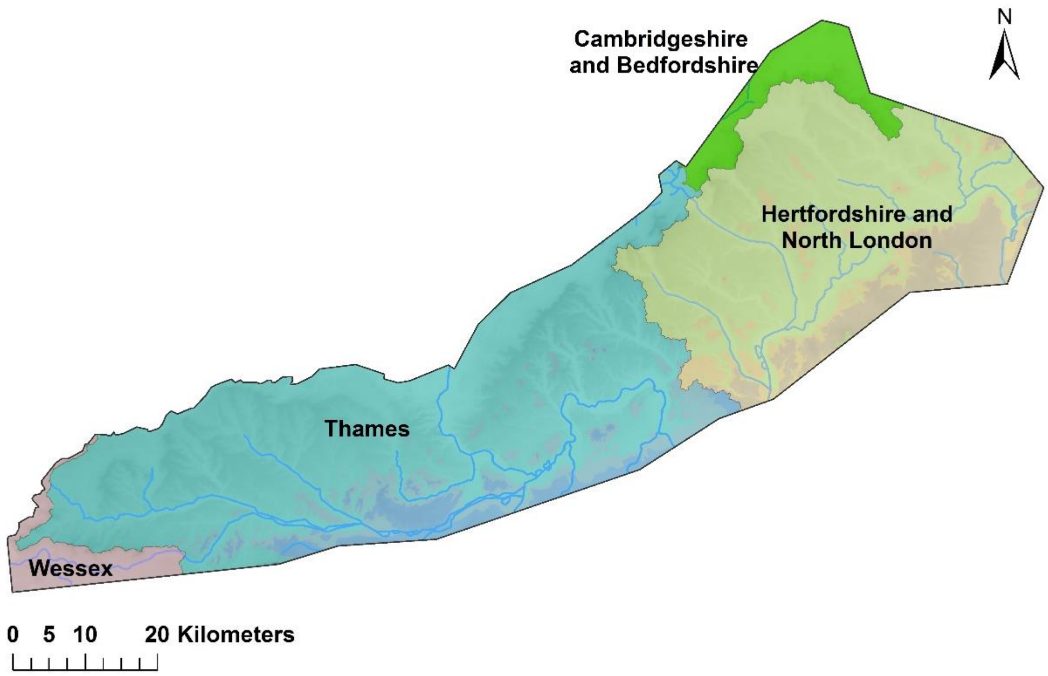


Figure 5. Environment Agency areas in the C4 Chalk area.

# 2 Karst Geomorphology

## 2.1 STREAM SINKS

There are hundreds of stream sinks recorded in the C4 Chalk area (Figure 6). Several field studies have been conducted where stream sinks were visited. These include 116 stream sinks in Berkshire (Maurice, 2009); 75 in Hertfordshire (Farrant et al., 2017); 23 in the Misbourne area (Farrant et al., 2018); and stream sinks visited in the Mimram (12) and Ver (7) catchments (Farrant et al., 2019). Some additional stream sinks are recorded in the BGS karst database, and 4 additional stream sinks were identified by the Environment Agency (Figure 6).

The stream sinks are generally concentrated near the Chalk-Palaeogene margin and there may be some additional stream sinks along this geological boundary that have not been recorded. There are also some stream sinks associated with drainage off the glacial till around Hertford and Bricket Wood near Watford. There are 9 larger rivers (generally on outcrop Chalk) where losses/dry sections (Grapes et al., 2005, Griffiths et al., 2006; Sefton et al., 2019) suggest they may provide point recharge into subsurface solutional features (Figure 6). More information on stream sinks in the area is provided below.

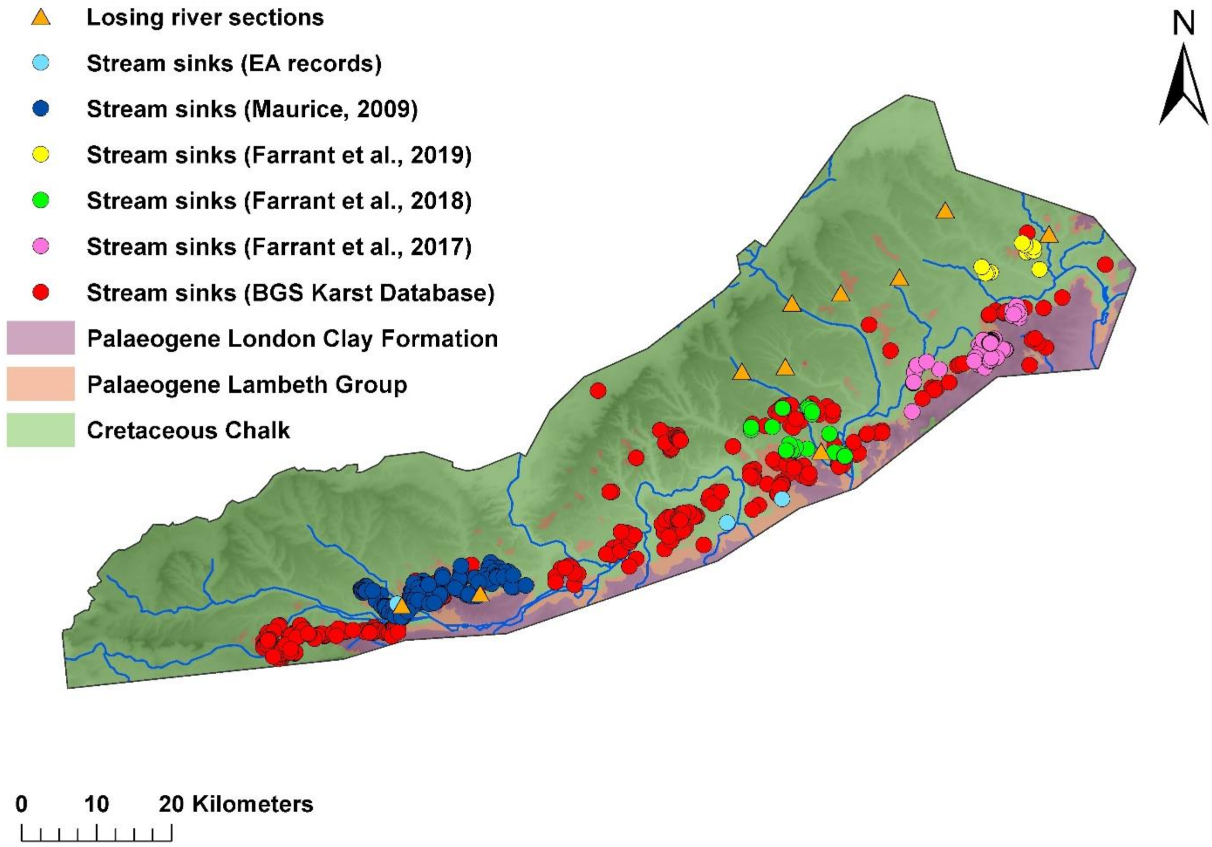


Figure 6. Stream sinks in the C4 Chalk area.



*Water End Swallow Holes*

The Water End Swallow holes (see Figure 9 for location) are the most significant chalk stream sink in England, and are a designated Site of Special Scientific Interest (SSSI) for their geological and biological importance (Waltham et al., 1997). Water from the Mimmshall Brook sinks into a series of more than 15 karst sinkholes - the exact sink points change in response to the amount of water flow, and as some sinks become blocked and others form. Walsh and Ockendon (1982) report that they have a mean flow of ~ 80 l/s, and the capacity to take up to 1000 l/s, before they back up and overflow into the Upper Colne valley. Wooldridge and Kirkaldy (1936) provide pictures and descriptions of the swallow holes in 1936. Walsh and Ockendon (1982) provide a description of the different sink points from observations between August 1969 and January 1970. Harold (1937) provides further descriptions of the swallow holes and also reports the number of days between 1927 and 1936 that the capacity of the swallow holes was exceeded and water overflowed into the Colne catchment (Table 2). Cavities have been entered, and there is some cave development beneath the swallow holes (Section 2.2.3).

Table 2. Number of days that the Water End Swallow Holes capacity was exceeded (from Harold, 1937).

| Year | No. days swallow hole capacity exceeded |
|---|---|
| 1927 | 44 |
| 1928 | 40 |
| 1929 | 31 |
| 1930 | 38 |
| 1931 | 21 |
| 1932 | 17 |
| 1933 | 14 |
| 1934 | 6 |
| 1935 | 29 |
| 1936 | 37 |

*Other stream sinks in Hertfordshire*

Other stream sinks close to Water End are mentioned by Kirkaldy (1950). Cook (2010) provides detailed annotated maps of stream sinks in the Hatfield area based on a field survey. Recently, Affinity Water commissioned the British Geological Survey to investigate the stream sinks in the North Mymms, Essendon and Upper Colne areas. A combination of desk study and a brief field survey was undertaken (Farrant et al., 2017). Twenty nine sinking stream catchments were identified; many with multiple sink points, so the geomorphology and hydrology of a total of 75 stream sinks are described. A new method of assessing the likely impact of the stream sinks on groundwater quality was developed and applied. During geological mapping 23 stream sinks were identified in the Misbourne area and their characteristics are described in Farrant et al. (2018). 17 of them were observed to sink into karstic depressions or blind valleys, while the remaining 6 sink through the stream bed or into marshy areas. During geological mapping in the Mimram and Ver catchments 19 stream sinks were identified and described (Farrant et al., 2019).

Whitaker (1921) provides information on stream sinks in Buckinghamshire and West Hertfordshire, the Mimmshall Brook area, and Eastern Hertfordshire. He also reports stream sinks around Lane End, Beaconsfield, Coleshill, Hodgemoor Wood, Cowcroft, Pollards Wood, Newlands, O'Connorvillle, Abbots Langley, and Ayot; as well as stream sinks in the valleys of the Ver, Mimram and Beane. Some of these stream sinks may be additional to those shown on Figure 6.

*Pang and Lambourn catchments in Berkshire*

A field survey of 128 stream sinks in the Pang and Lambourn catchments in Berkshire was undertaken by Maurice (2009) to identify potential tracer test sites, and record their characteristics, and some examples are shown in Figure 7.

Figure 7. Examples of stream sinks in Berkshire (from Maurice, 2009)

The stream sinks were classified into 7 categories: seepage sinks, ephemeral ponds, ditch sinks, pit sinks, doline sinks, partial sinks, and mature doline sinks. Five areas of stream sinks within the Pang and Lambourn catchments were identified, and an overview of the stream sinks in each of these areas was provided. These overviews, and more details about the classification system can be found in Maurice (2009), and there is further information on the stream sinks in Maurice et al. (2015).

The field survey found that the stream sinks were supplied by a mixture of small springs draining the Palaeogene strata, surface runoff, and agricultural and road drainage. Most stream sinks were observed to respond rapidly to rainfall and have no/little flow during dry periods (e.g. stream sink shown under high and low flow conditions in middle panel of Figure 7). Thirty-seven appeared to have quite substantial flows that, based on visual observation, were estimated to be several litres/second following rainfall. Visual estimates are very uncertain, and without more formal measurements it is unclear how much recharge is entering the Chalk through these stream sinks. However, field observations suggested that a very substantial proportion of the precipitation falling on the Palaeogene is likely to be recharging the Chalk aquifer at or near to the geological boundary.

Similarly during more recent fieldwork in Hertfordshire (Farrant et al., 2017; 2018; 2019), observations suggested that in addition to the obvious point recharge via stream sinks, recharge may also be concentrated more extensively near the geological boundary with precipitation entering the chalk via the basal sands in the Palaeogene. Figure 8 shows how stream sinks may evolve and develop near to the Chalk-Palaeogene boundary (from Maurice, 2009).

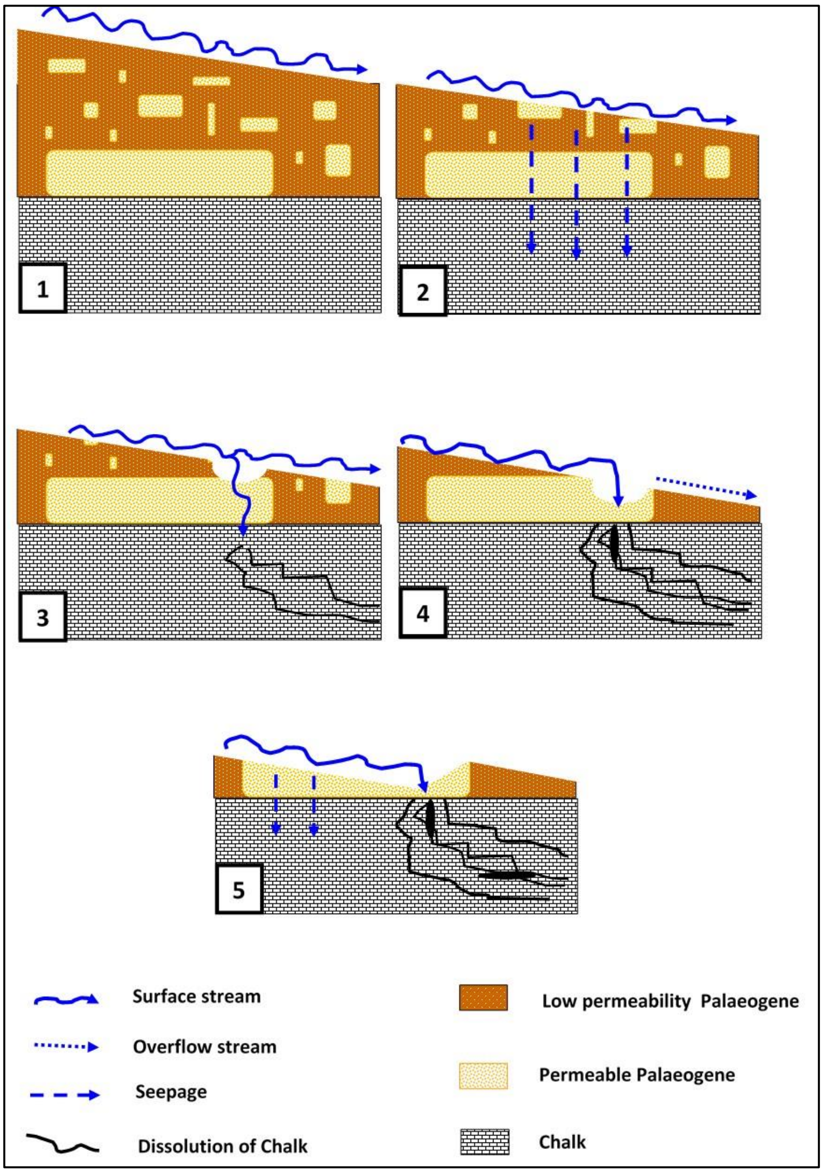


Figure 8. Geomorphological evolution of stream sinks where a surface stream flows over Palaeogene deposits overlying the Chalk (from Maurice, 2009)

*Chalk Rivers*

Rivers on the Chalk in the area may also contribute recharge into subsurface solutional features; and examples where losing/dry sections are reported are shown on Figure 6. The River Pang has a losing section around Bucklebury (Griffiths et al., 2006); and Grapes et al.

(2005) report that the River Lambourn loses water around Woodspeen. Sefton et al. (2019) show that the Rivers Gade, Ash, Misbourne, Ver, Beane, Rib, and Stort have sections which sometimes dry up completely indicating recharge through the riverbed upstream of these points.

## 2.2 CAVES AND CONDUITS

There are four recorded karst caves in the C4 Chilterns Chalk area. Three are associated with stream sinks, and one was intercepted during borehole drilling (Figure 9). It is likely that there are more small caves present in the area, particularly in association with the stream sinks.

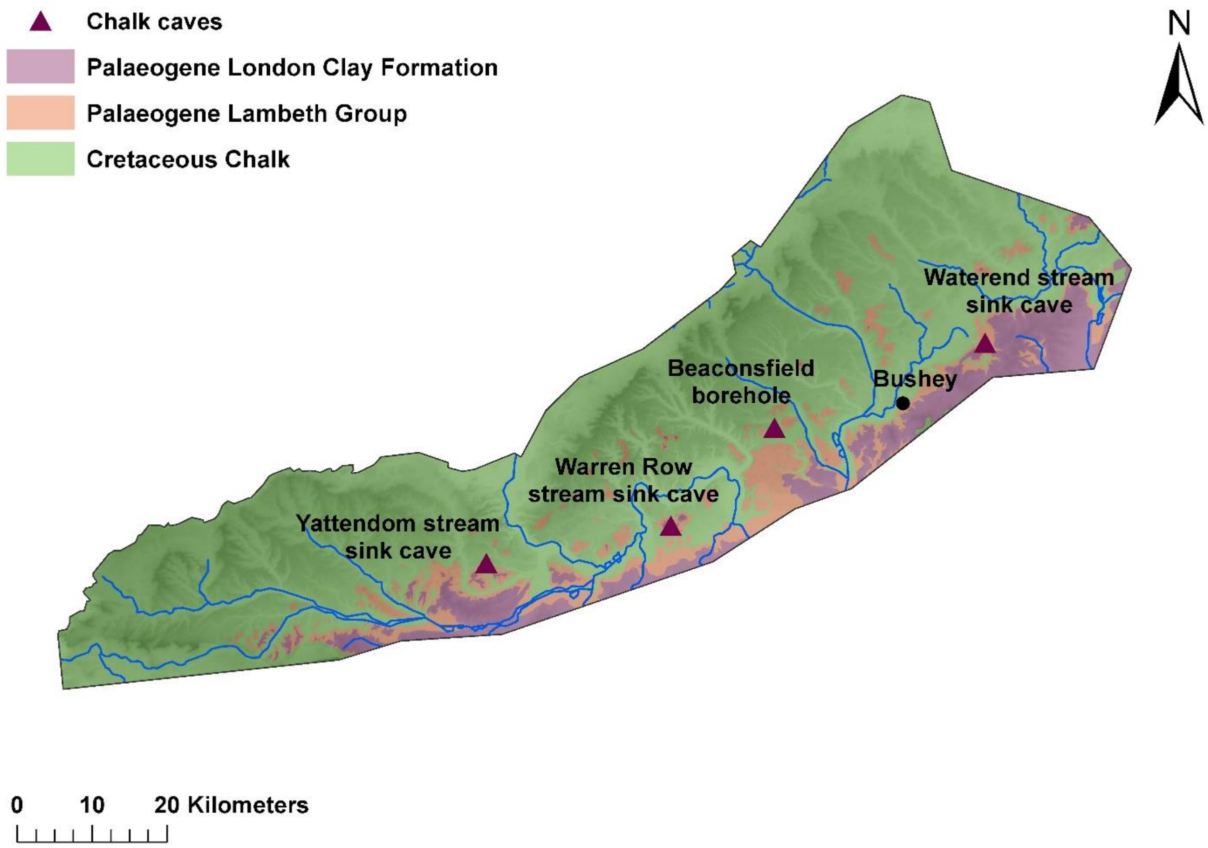


Figure 9. Caves in the C4 Chalk area.



### 2.2.1 Yattendon cave, Berkshire.

This is a cave formed by a stream sink. A stream draining the Palaeogene outcrop near Yattendon sinks into the Chalk. Unlike most stream sinks, the chalk is exposed. The stream has carved a narrow trench through the basal Palaeogene (or Clay-with-Flints) into the underlying Chalk, and sinks into the cave (Figure 10). The cave consists of a short stretch of vadose canyon to a point where the stream disappears down a vertical rift 30-40 cm wide and several metres deep. The cave is located just below a flint layer (Figure 11), and it is probable that it is developed in the upper part of the Seaford Chalk Formation.

Figure 10. Chalk cave at Yattendon, Berkshire (Photo by BGS)

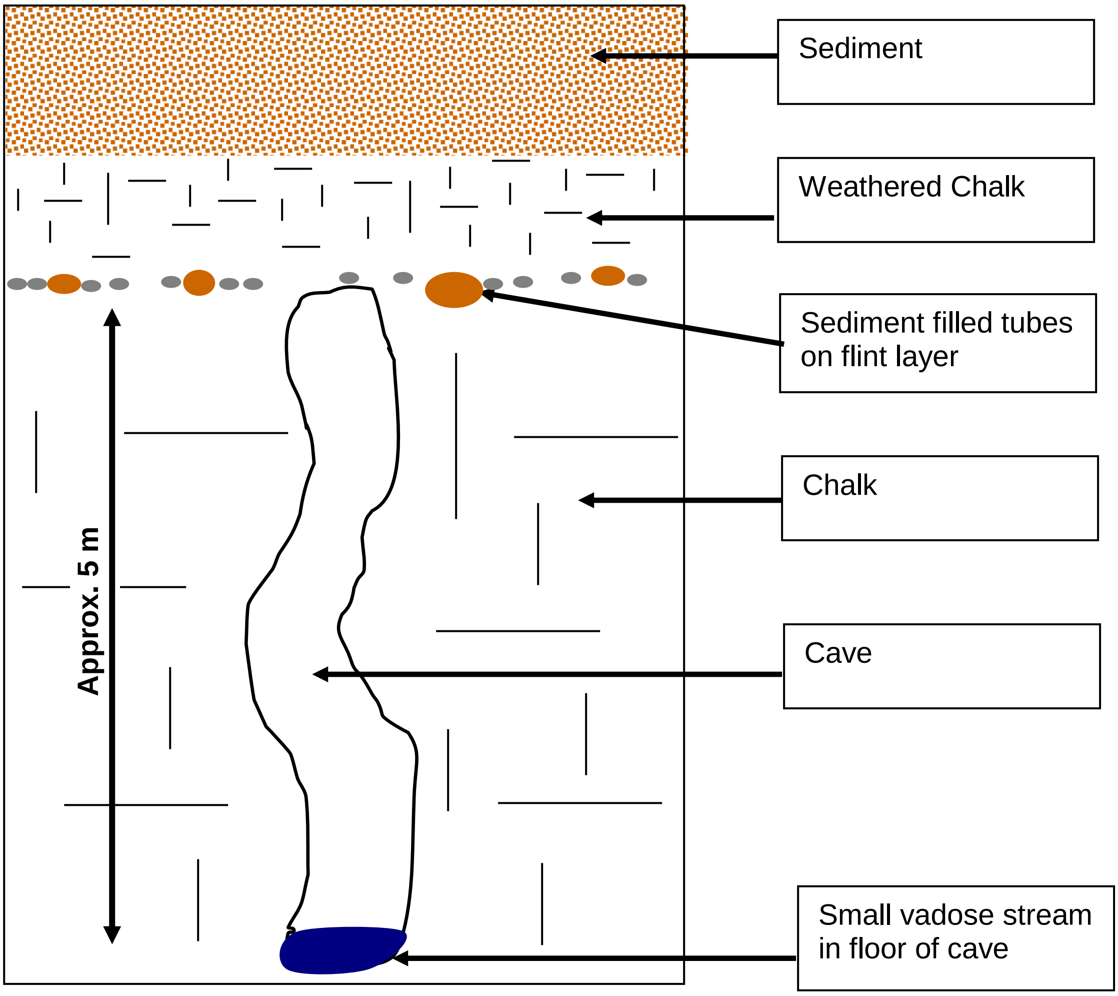


Figure 11. Schematic cross section of the Yattendon chalk cave (not to scale) from Maurice (2009)

### 2.2.2 Warren Row cave, Reading, Berkshire.

Warren Row cave is a stream sink cave near Reading explored by cavers in the late 1980's (CSS, 1990; Reeve, personal communication, 2017). An open stream cave in the base of a depression (Figure 12) was explored for about 20 m to a section which was too small to follow, but further passage could be seen beyond. The cave included small passages (Figure 13 and Figure 14) two short drops of about 1 to 2 m, and a chamber that was 5 m high (Figure 15 and Figure 16). The cave is also likely to be located in the upper part of the Seaford Chalk Formation.

Figure 12. Closed karst depression at Warren Row stream sink (photo courtesy of Terry Reeve)

Figure 13. Crawl in Warren Row stream sink cave (photo courtesy of Terry Reeve)

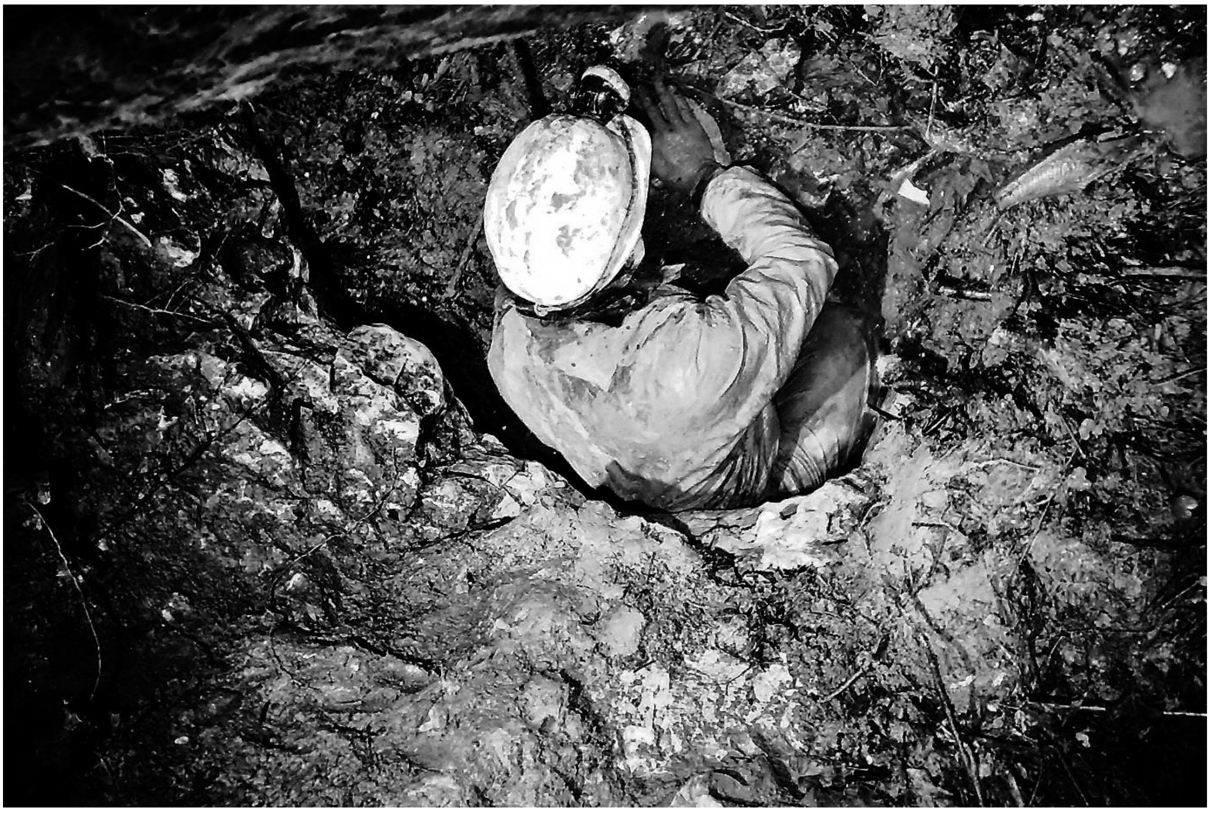

Figure 14. Entering a narrow passage in Warron Row stream sink cave (photo courtesy of Terry Reeve)

Figure 15. Chamber in Warren Row stream sink cave (photo courtesy of Terry Reeve)

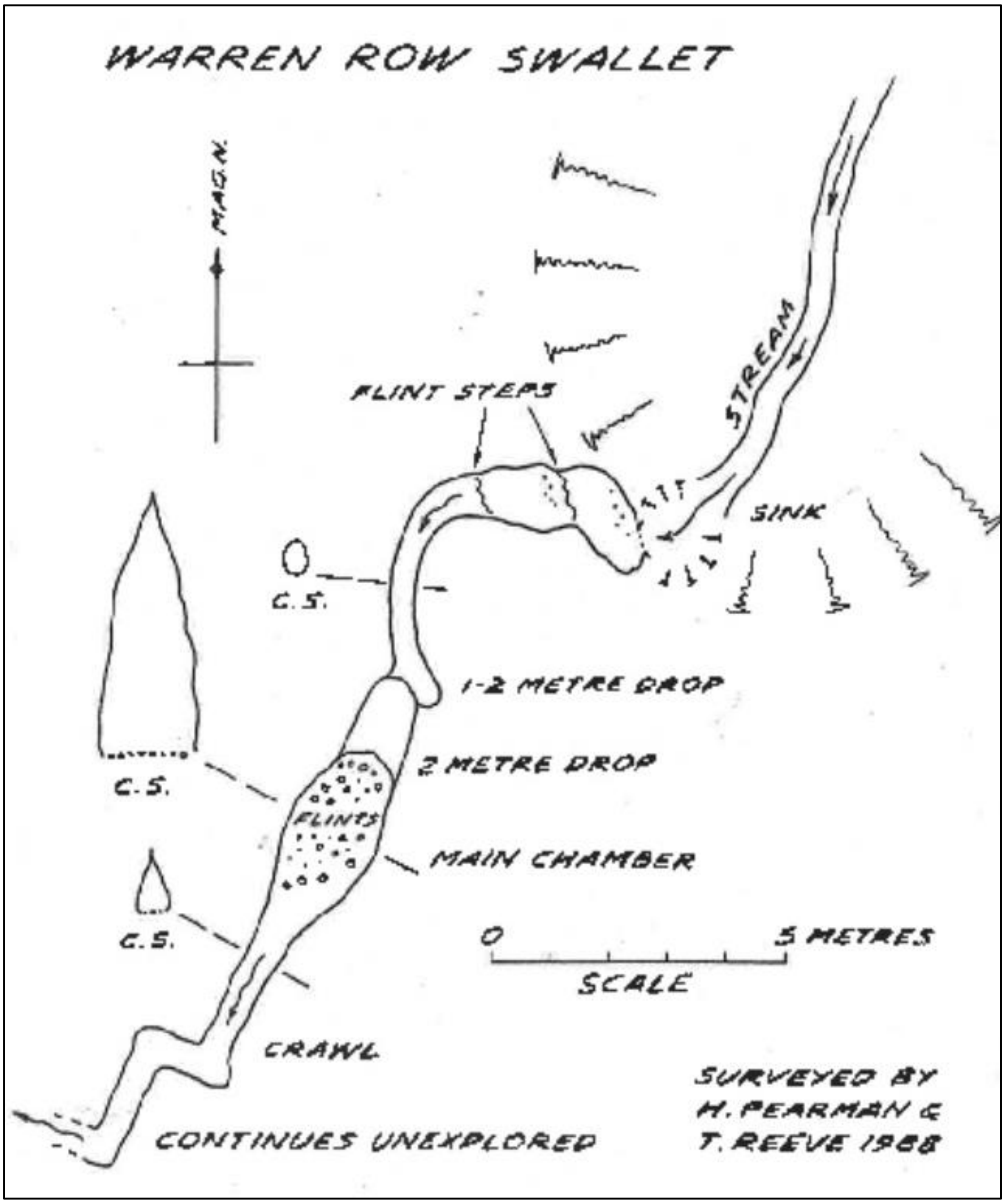


Figure 16. Survey of Warren Row stream sink cave courtesy of Terry Reeve, from CSS (1990)

### 2.2.3 Waterend swallet, South Mimms, Hertfordshire

The Waterend swallow holes are a complex of multiple stream sinks in which water from the Mimmshall Brook sinks into the Chalk (Section 2.1). The sink points vary depending on flow conditions, and new holes open up periodically due to collapse into the underlying cavities. Kirkaldy (1950) reports that three swallow holes collapsed in the year 1928, one which was about 11 m deep and 7 m diameter at the surface. Evans (1944) reports a collapse of about 12 m in depth, which may be the same event. Cave passages up to 10 m long have been observed within the Chalk beneath the swallow holes (Reeve, personal communication, 2017; CSS,1990). A 3 m deep hole with overhanging sides was formed by a sudden collapse and explored by cavers some years ago (Reeve, personal communication, 2017; Figure 17). This collapse was about 1.5 m wide at the top, and the base was 3 m wide and floored by chalk rubble. The caves beneath Water End are likely to be located in the upper Lewes Nodular Chalk Formation or the lower Seaford Chalk Formation.

Figure 17. Waterend Swallet entrance (photo courtesy of Terry Reeve)

### 2.2.4 Beaconsfield Borehole

In 1911 two boreholes were drilled near Beaconsfield (BGS Single Onshore Borehole Index record SU 99SW15). The record reported that the site was “over the channel of an old karst swallowhole”. It is not clear whether this is referring to a doline or a stream sink. During drilling of the first borehole, the drilling tool suddenly dropped into a large cavity at a depth of about 54 m, and the tool was lost. A second borehole was drilled about 3.5 m away. It passed through about 12 m of Clay with Flints before entering the Chalk in what is likely to be the Seaford Chalk Formation. At about 30 m the tool dropped 3 m through an open cavity, and then passed through “soft detritus” before reaching Chalk bedrock again. The description suggests that the borehole may have intersected a sediment floored karst cave. The water level in this second borehole was at 50.5 m suggesting that this cave is in the unsaturated zone. Both the cavities are likely to be in the lower part of the Lewis Nodular Chalk Formation, and may be associated with the Chalk Rock hardground.

Homersham (1850) also describes cavities within the Chalk at Bushey Meadows (Figure 9) and at many other points along the Colne valley, which were intercepted during borehole drilling. They are described as “large faults, fissures or cavities varying from 12 inches to 12 feet in depth” found at a depth varying from 100 to 200 feet beneath the surface”.

### 2.2.5 Smaller Conduits

Many sediment filled conduits (up to 1 to 2 m wide) have been observed in Kensworth Quarry in the Ver catchment near Dunstable (Farrant et al., 2019; Figure 18). These are associated with Marls in the New Pit Formation at depths of 50 to 55 m below the surface.

Open conduits with diameters ~ 0.1 m have been observed in many water level monitoring boreholes and a quarry in Berkshire (Waters and Banks, 1997; Maurice, 2009; Maurice et al., 2012; Maurice et al., 2015; Figure 19). Conduits are also commonly observed in images of abstraction boreholes in the C4 Chalk area. It is likely that conduits too small for humans to enter occur frequently, and several studies in the area suggest that these are likely to be associated with flint layers, marls, and hardgrounds (Schurch and Buckley, 2002; Maurice et al., 2012).

Figure 18. Sediment filled conduits in Kensworth Quarry


Figure 19. Conduits in the C4 Chilterns Chalk karst area

## 2.3 DOLINES AND DISSOLUTION PIPES

Dolines and dissolution pipes may be common in areas where the Chalk is overlain by thin Palaeogene or superficial deposits. Identification of dolines is difficult because there are also many man-made pits, which appear as surface depressions and have very similar characteristics. Dissolution pipes may have no surface expression, but are exposed by engineering works and quarrying. Figure 20 shows the distribution of surface depressions recorded in the BGS karst database (as of 2020) and surface depressions/dissolution pipes recorded in the cavity database (Applied Geology Limited, 1993). Dissolution pipes and surface depressions are not distinguished in the cavity database.

It is difficult to assess the number of dolines in the area as although some of the surface depressions may be karst dolines, many may be man-made surface pits, or subsidence features associated with the collapse of old deneholes (shafts associated with underground chalk mining). Shallow subsurface dissolution pipes are encountered with very high densities during construction projects, and it is likely that they occur fairly ubiquitously where superficial cover is present, especially beneath Clay-with-Flints and River Terrace deposits.

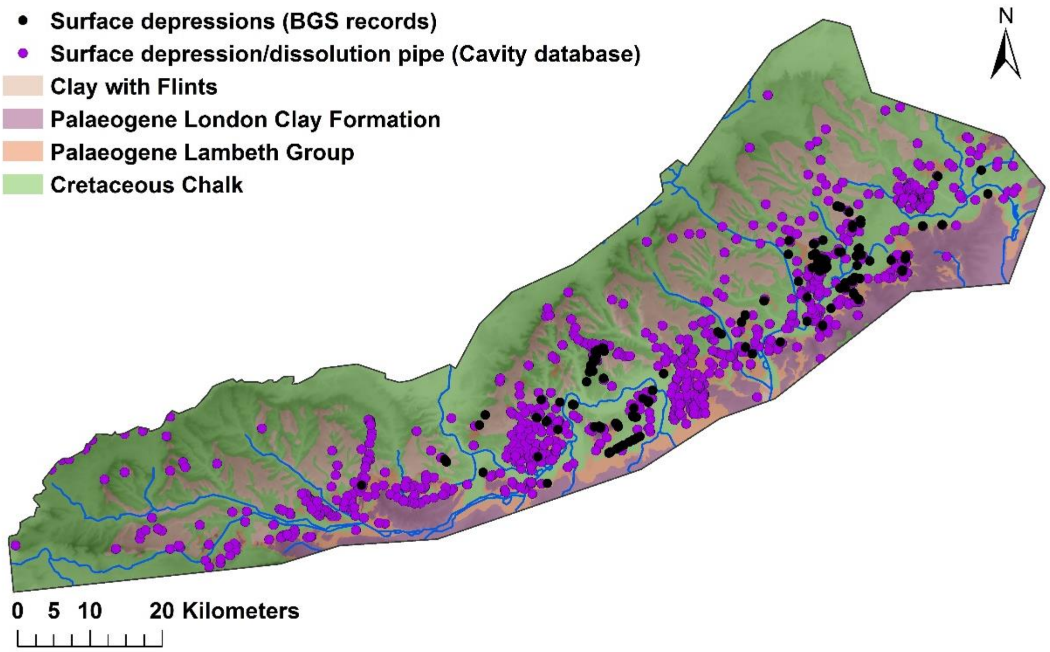


Figure 20. Surface depressions and dissolution pipes in the C4 Chalk area.



There have been several studies of solution features in the C4 Chalk area:

- Dissolution pipes in the Castle Lime works Chalk pit near South Mimms are described by Kirkaldy (1950); and were investigated in detail by Thorez et al. (1971). Waltham et al. (1997) also provide a description and picture of these solution pipes.
- Walsh et al. (1973) describe solution pipes at Kensworth Quarry near Dunstable.
- West and Dumbleton (1972) describe “swallow holes” during construction of the M40 near High Wycombe and Beaconsfield, and the descriptions suggest that they are likely to be dolines or dissolution pipes rather than stream sinks.
- Edmonds (1983) considers the density of dolines, dissolution pipes and stream sinks in different areas of the Chalk, and reports that the density of these karst solution features in the Chilterns area is 21-30 per 100 square kilometres.
- Edmonds (2001) undertook geomorphological mapping of karst features in the West Reading area and produced a subsidence risk map.
- Gibbard (1985) gives details of a number of chalk dissolution features which occur within the C4 Chilterns chalk area, as well as further references.
- Farrant et al. (2018) note that several deep dissolution features were revealed during the construction of the M25, including a 37.5 m deep and 40 m wide feature at Denham. A large doline at Denham is described by Gibbard et al. (1986).
- Worsley (2016) describes karst solution pipes in the Goring Gap.

## 2.4 SPRINGS

Springs are common in the C4 Chalk area, and many have large flows. Some springs have geological controls, being associated with particular lithological horizons such as the Chalk Rock, the Tottenhoe Stone, and the ‘Melbourne Rock’ (Woodwood et al., 1909; Whitaker, 1921). Many springs also occur in association with the boundary between the Chalk and the underlying Upper Greensand Formation at the base of the Chalk scarp scope (Whitaker, 1921).

Springs known or assumed to have larger discharges are shown on Figure 21. It is likely that there are additional substantial springs. Figure 22 shows records of springs in the Chalk held by the BGS and Environment Agency. Environment Agency records are springs used for water quality sampling, and some additional records of springs from Hertfordshire compiled by the Environment Agency from Whitaker (1921). The latter include records of watercress beds assumed to be fed by Chalk springs. The discharge of the springs shown in Figure 22 is not known.

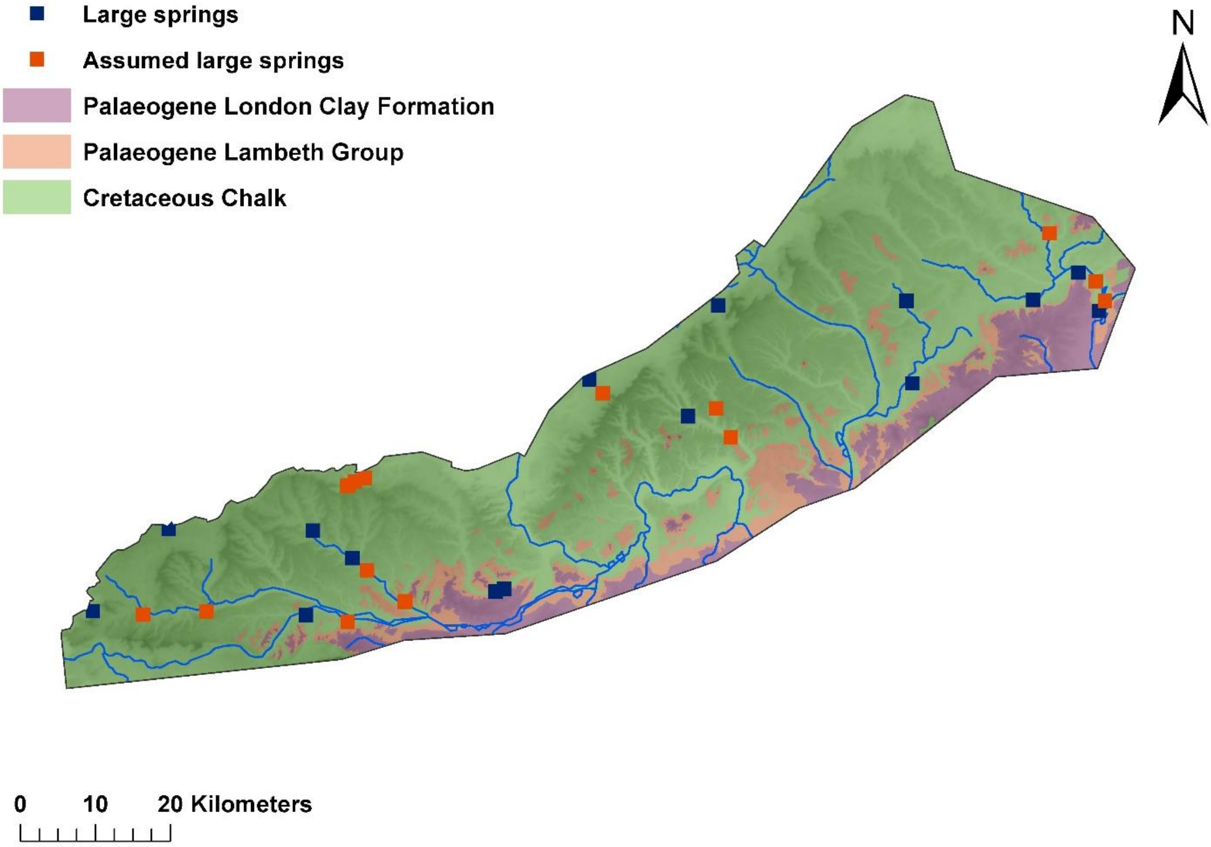


Figure 21. Large springs in the C4 Chalk area.

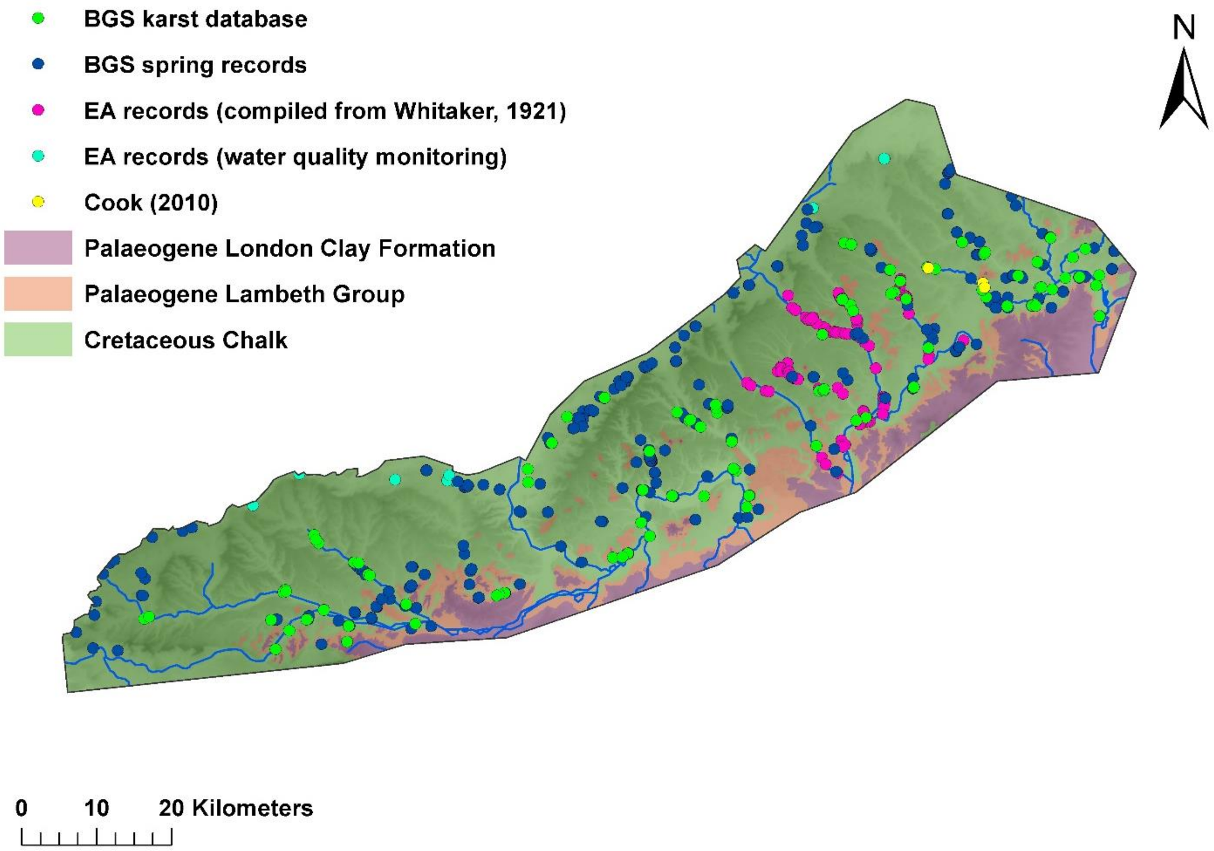


Figure 22. Chalk springs with unknown discharge in the C4 Chilterns Chalk area.



There have been few studies of Chalk springs and therefore their flow characteristics are poorly known. At least five springs in the C4 Chilterns Chalk karst area have been observed to have high turbidity following rainfall, suggesting their connectivity with stream sinks. These are the Blue Pool springs; springs at Hungerford (Figure 23), and Bagnor in Berkshire; and Arkley Hole and Chadwell springs in Hertfordshire.

Figure 23. Turbidity following rainfall at springs near Hungerford. Photos courtesy of the Environment Agency

There have been some investigations of springs in Berkshire. Observed turbidity following rainfall at the Blue Pool spring is reported by Banks et al. (1995) and Maurice (2009), but no turbidity measurements have been made. The Blue Pool has a flow of ~ 200 l/s and appears to maintain a relatively constant discharge. Sporadic flow measurements which have been made at the Blue Pool springs are discussed in Maurice et al. (2006) and Maurice (2009). Grapes et al. (2006) provide spring flow data for the Lynchwood Springs in the Lambourn catchment. The flow varied seasonally from 0 to 690 l/s with an average of 170 l/s (Grapes et al., 2006). No data are available to determine whether the spring discharge varies on short timescales in response to rainfall. Lynchwood Springs form the ephemeral head of the River Lambourn (Figure 24). The springs are 7 km upstream of the perennial head of the River Lambourn and they become active very rapidly. This type of river head migration to springs at specific points is characteristic of karst areas where the capacity of a conduit system is exceeded under high flow conditions resulting in re-activation of ephemeral conduits or fissures which are discharged through the ephemeral higher springs.

Monthly flow gauging of 5 springs in the Pang and Lambourn catchments was undertaken by Bell et al. (in preparation) between April 2012 and November 2013, and logged stage measurements were made at two of the springs, including the Blue Pool in 2013.

Figure 24. Pool with upwellings (left) and fissure outflow at Lynchwood springs

Springs in Hertfordshire are described in detail by Whitaker (1921) and Cook (2010). Arkley Hole is a major karst spring with flows of 10-160 l/s reported from spot gauging, and a rapid increase in flow and turbidity following rainfall events (Cook, 2010). Cook (2010) also describes several large springs in the Lea Valley, including Chadwell springs which were reported to have flows of up to 230 l/s. Chadwell and Arkley Hole springs act as estavelles, becoming a swallow hole under low water level conditions (Cook, 2010).

A large number of Chalk springs are described by Whitaker (1921) in “The water supply of Buckinghamshire and Hertfordshire”. Some springs were reported by Whitaker (1921) to have reduced flows or to have dried up. Many are described as “strong” springs but no discharge is reported. Emmas Well springs have highly variable discharges (Whitaker, 1921; Cook, 2010). Flow rates for some large Chalk springs that are reported by Whitaker (1921) are listed in Table 3. Whitaker (1921) also reports monthly discharge data for Chadwell spring from 1889 to 1896 and an average flow from 1881 to 1903. These data suggested that the discharge of Chadwell Springs during this period varied from about 25 l/s to 250 l/s. Whitaker (1921) describes Chadwell Springs extensively, and also reports previous flows in the 1850s of more than 330 l/s.

Cook (2010) reports that there are springs at Wheathampstead (NGR TL148149), Brocket Park (NGR TL221129), and Lemsford (NGR TL223123).

Woodward et al. (1909) note that there are springs present at Houghton Regis, Leagrave, Limbury and Biscot.

There are a number of significant springs which discharge from the base of the Chalk scarp slope in the northwest of the area (Figure 21 and Figure 22). Daily discharge data from 1963 to 2016 are available from the National River Flow Archive (2020) for Wendover springs. These scarp slope springs had a mean flow of 82 l/s over this period, with a maximum of 255 l/s and a minimum of 17 l/s. Other examples of scarp slope springs are three which emanate from the Chilton stone limestone bed to form the headwaters of the Letcombe Brook near Wantage (Mott MacDonald, 2012).

Table 3. Spring discharges reported by Whittaker (1921)

| Location | Reported discharge | Notes from Whittaker (1921) |
|---|---|---|
| Otterspool | 16 l/s (previously 53 l/s) | Reported to be connected to stream sinks |
| Well Head spring, Wendover | 84 l/s | Several springs over several kilometres. |
| Between Amwell and Rye House | 420 l/s | Colour changes in wet weather |
| Between Hoddesdon and Broxbourne | 315 l/s | This is flow in dry periods |
| Chadwell spring | 25 to 330 l/s | Flow is variable, turbidity following rainfall |

# 3 Tracer Tests

Tracer tests have been carried out using tracer injections into karst stream sinks, soakaways, and boreholes (Figure 25, Table 4). The karst features in the key areas where tracer tests have been conducted are shown in more detail in Figure 26. The arrows in Figure 26 present a schematic representation of the connections identified in the tracer tests, the actual positions and structure of the conduit networks remain unknown. One tracer test has been conducted in the unsaturated zone (Lawrence et al., 1996).

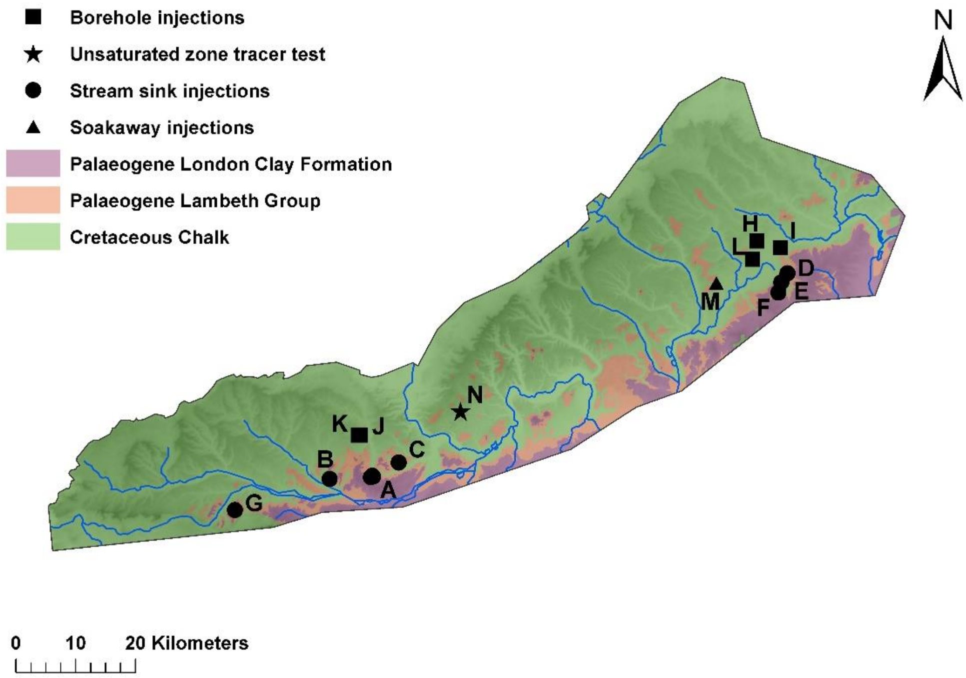


Figure 25. Tracer tests in the C4 Chilterns Chalk area.

Table 4. Tracer tests in the C4 area.

| | Test type | Injection site | Distance to outlet (m) | Velocity (m/day) based on first arrival | Recovery (%) | Reference |
|---|---|---|---|---|---|---|
| A | Stream sink to spring | Holly Lane stream sink | 4700 | 6836 | 7.7 (assumed) | Banks et al. (1995) |
| A | Stream sink to spring | Tylers Lane stream sink | 4400 | Unknown | Unknown | Banks et al. (1995) |
| A | Stream sink to-spring | Smithcroft copse sink | 5100 | 5641-6100 | 0.87-25.5 | Maurice (2009) |
| B | Stream sink to spring | Cromwells sink | 1250 | 638 | $< 7x10^{-6}$ | Maurice (2009) |
| C | Stream sink to spring | Mirams copse sink | 1600 | 4324 | $< 5x10^{-5}$ | Maurice (2009) |
| D | Stream sink to spring | Water end, mymmshall brook | 8090-16340 | 3208-5171 | 0.77-4.29 | Harold (1937), Cook (2010) |
| D | Stream sink to borehole | Water end, mymmshall brook | 3200-16600 | 1770-4717 | 0.77-4.53 | Harold (1937), Cook (2010) |
| E | Stream sink to spring | Welham green bourne | 15080-16340 | 5095-5601 | Unknown | Harold (1937), Cook (2010) |
| E | Stream sink to borehole | Welham green bourne | 16340-16586 | 5602-5832 | Unknown | Harold (1937), Cook (2010) |
| F | Stream sink to spring | Water end, catherine bourne | 11400-18960 | 1900-3160 | Unknown | Harold (1937), Cook (2010) |
| F | Stream sink to borehole | Water end, catherine bourne | 2921-19490 | 2921-3139 | Unknown | Harold (1937), Cook (2010) |
| G | Stream sink to spring | Dell stream sink | 3300 | 5700 | 7.5 | Brauns et al. (2017) |
| G | Stream sink to borehole | Dell stream sink | 4000 | 4200 | 9.2 | Brauns et al. (2017) |
| H | Borehole to boreholes/springs | *Harefield House | 9600-20000 | 55-805 (unspecified velocity) | Unknown | Cook (2010) |
| I | Borehole to borehole/springs | *Comet Way | 5650 - 16200 | 449-1327 (unspecified velocity) | Unknown | Cook (2010) |
| J | Borehole to borehole | BB – South | 70 | 2800-6720 | Unknown | Ward et al. (1998) |
| K | Borehole to Borehole | BB – West | 284 | 1136 | 14 | Ward et al. (1998) |
| L | Borehole to Borehole | MLS23 | 24 | 17-36 | 0.025-0.15 | Bottrell et al. (2010) |

| | | | | | | |
|---|---|---|---|---|---|---|
| M | Soakaway-borehole | M1/M25 junction | 3000 | 120-2580 | 0.000002 | Price et al. (1992) |
| N | Unsaturated zone injection | Sonning Common | 20 - 25 | >10 | Unknown | Lawrence et al. (1996) |
| O | Borehole to borehole | Trumpletts A and B | 32,54 | 3300,19400 | 79,99 | Mathias et al. (2007) |

*Positives from these tests remain uncertain due to low tracer concentrations and low sampling frequency

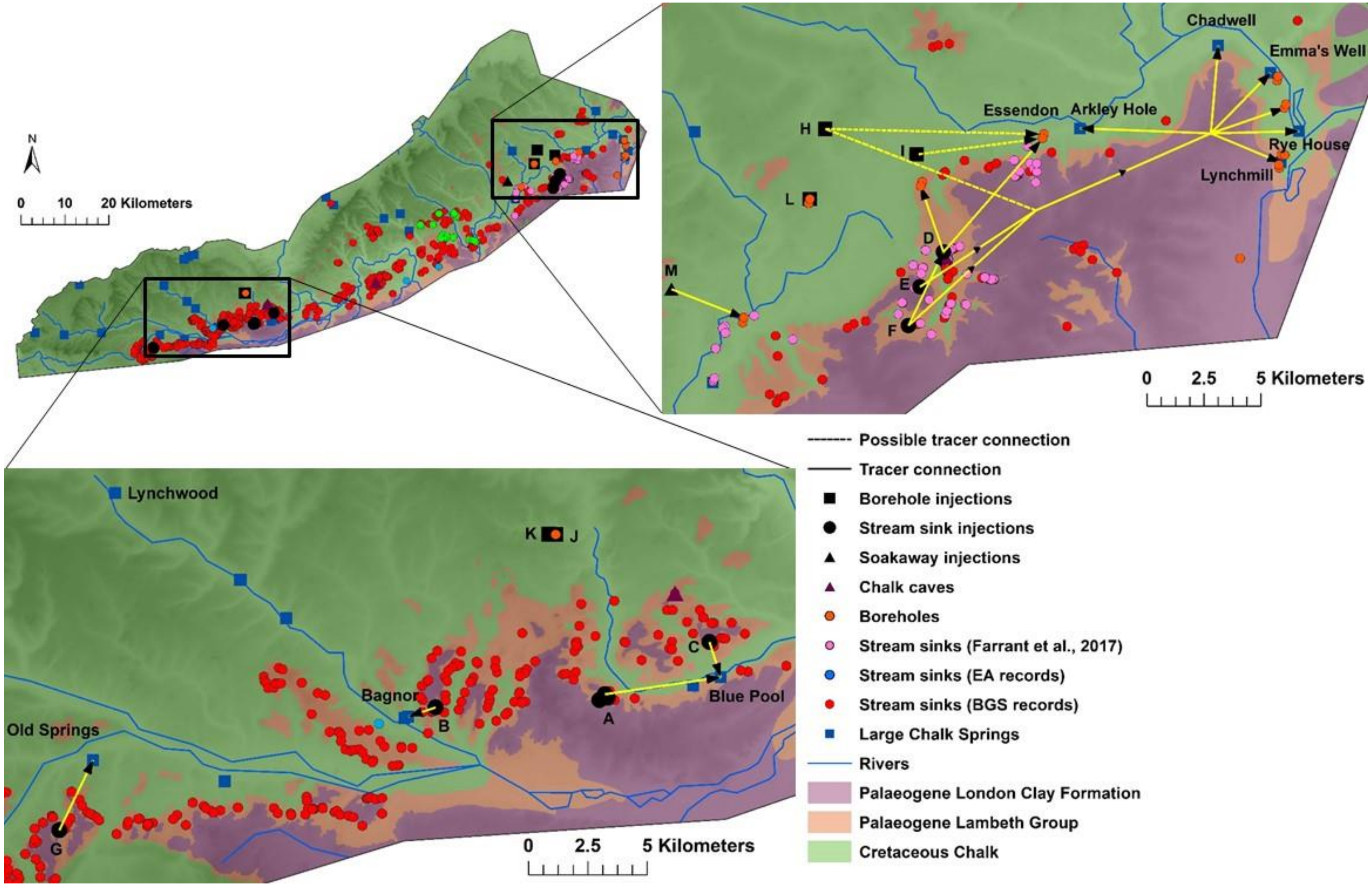


Figure 26. Surface karst and tracer test connections in the C4 Chalk area.

### 3.1 STREAM SINK TRACER TESTS

Tracer testing has proven connections between four stream sinks and the Blue Pool spring (Banks et al., 1995; Maurice et al., 2006, Maurice et al., 2010) near Newbury (Tests A and C in Table 4). The tests were carried out over distances of 1.6 to 5.1 km, and all proved very rapid groundwater flow of 4.3 to 6.8 km/day (based on time to 1$^{st}$ arrival of tracer). From three stream sinks, attenuation was low, with recovery of up to 25 % of the injected tracer. However, in one test there was extremely high attenuation and/or dilution of tracer, which resulted in very little tracer recovery. Tracer testing between a stream sink and springs at Bagnor in Berkshire also revealed rapid groundwater flow of 0.6 km/day over 1.2 km, combined with very high attenuation/dilution (Maurice et al., 2010). Tracers injected into one stream sink in the Bagnor catchment and one stream sink in the Blue Pool catchment were not detected.

An early tracer test from a stream sink to springs at Hungerford reported tracer arrival “at about the time expected” (Codrington, 1864). More recent tracer testing from a stream sink to these springs (Test G in Table 4) revealed rapid groundwater flow of 5.7 km/day over 3.3 km, combined with low tracer attenuation/dilution (Brauns et al., 2017).

In Hertfordshire, in the Water End area, tracer testing from stream sinks on the Catherine Bourne, the Mimmshall Brook, and the Welham Green Bourne have proved rapid groundwater flow of between 1.8 and 5.8 km/day over distances of up to 19.5 km (Harold, 1937: Cook 2010; Tests D, E and F in Table 4). These tracer tests are reviewed in Farrant et al. (2017), and some of the tracer test connections are shown in Figure 26 and Figure 27.

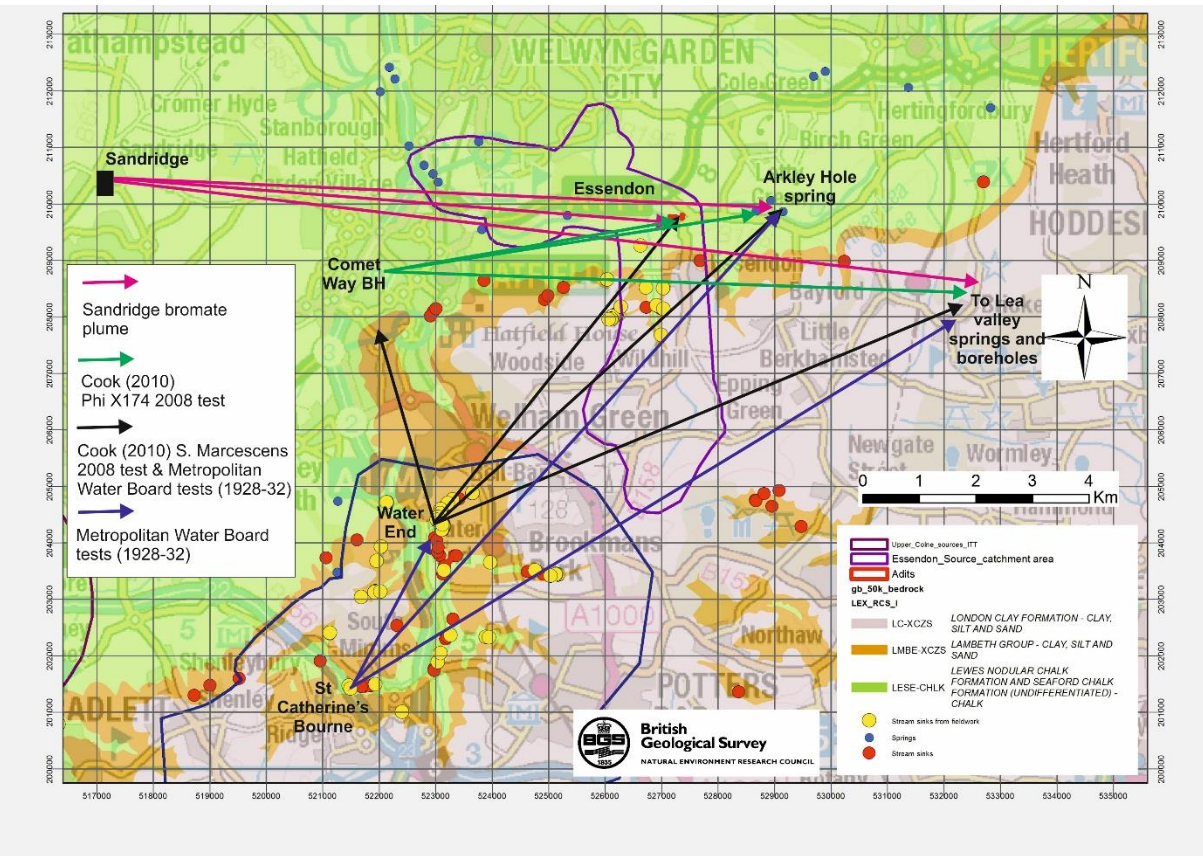


Figure 27. Some tracer test connections in Hertfordshire, from Farrant et al. (2017), adapted from Cook (2010)

## 3.2 SOAKAWAY TRACER TESTS

Tracer was injected into a soakaway at the M1/M25 interchange near Bricket Wood in Hertfordshire (Price et al., 1992; Test M in Table 4). Tracer was detected 3 km away, with a groundwater velocity of more than 2 km/day, combined with very high attenuation/dilution of tracer. Details are in Price et al. (1992), and the tests are reviewed in Farrant et al. (2017).

## 3.3 BOREHOLE TO BOREHOLE TRACER TESTS

Tracer testing was carried out from two observation boreholes to a pumping borehole at Banterwick Barn in Berkshire (Ward et al., 1998; Tests J and K in Table 4). The boreholes were 70 and 284 m from the pumping borehole. Breakthrough of dye tracer from the closest borehole was extremely rapid, less than 15 minutes in one test, and 32-42 minutes in a second test; indicating groundwater velocities of > 6.7 km/day and 3.1 km/day. Tracer injected into the more distant borehole arrived in 6 hours indicating a groundwater velocity of 1.1 km/day, with a tracer recovery of 14%, suggesting low attenuation and dilution.

Dye tracer tests have also been conducted from two monitoring boreholes to one abstraction borehole at Trumpletts Farm in the Pang catchment in Berkshire (Matthias et al., 2007; Test O in Table 4). These tests were over relatively short distances (32-54 m) but the velocities and recoveries were very high (Table 4). Tracer from the injection borehole 54 m away arrived at the abstraction borehole in less than 5 minutes indicating a velocity of > 19 km/day. These tests have been repeated on two occasions by BGS using DNA and dye tracers; and fluorescent microspheres, giving similar results (unpublished data).

Bacteriophage tracer tests to an abstraction borehole in Hertfordshire from observation boreholes at Comet Way and Harefield House suggested possible connections over distances of 5.7 and 9.6 km (Cook, 2010; Tests H and I in Table 4). Tracer from these boreholes was also apparently observed 5.7 to 20 km away at springs and boreholes in the Lee valley. However, tracer concentrations at all monitored sites were at, or near background concentrations, and the sampling frequency was low therefore positives from these observation boreholes are not conclusive.

Bottrell et al. (2010) conducted a tracer test in the Hertfordshire Chalk from different levels in an observation borehole to a pumped borehole 24 m away (Test L in Table 4). Groundwater velocities were 0.02 to 0.04 km/day.

## 3.4 SINGLE BOREHOLE DILUTION TESTS

Single Borehole Dilution Tests carried out in the area reveal distinct flow horizons, and rapid flows through boreholes.

Tests were carried out in 26 boreholes in the Pang and Lambourn catchments in Berkshire (Maurice, 2009; Maurice et al., 2012). These revealed rapid dilution suggesting connectivity with karstic networks of solutional fissures and conduits. Sixteen boreholes had one or more sections with tracer efflux times of < 12 hours, including 10 in areas away from the Chalk-Palaeogene margin (Maurice, 2009).

Single borehole dilution tests in Harefield House and Comet Way observation boreholes demonstrated rapid dilution (less than 8 hours) with estimated specific discharges of ~1 to 10 m/day (Fitzpatrick, 2008). A borehole dilution test in Berkshire demonstrated dilution within a few hours in the upper part of the borehole (Loveless et al., 2016).

## 3.5 HERTFORDSHIRE BROMATE PLUME

A subsurface bromate plume originating from a pollutant source at Sandridge has impacted springs and boreholes in the Lee valley demonstrating a connected groundwater flowpath across catchments, and over a distance of more than 20 km (Figure 27). More information on this can be found in Cook (2010) and Cook et al. (2012)

### 3.6 UNSATURATED ZONE TRACER TEST

An unsaturated zone tracer test was carried out in Berkshire the 1990s (Lawrence et al., 1996). The following description is from Lawrence et al. (1996). A 25 m borehole, cased to 20 m, was drilled to sample the saturated zone. Approximately 1 m of topsoil was removed from an area of 7 m by 7 m surrounding the borehole. Three types of tracers were applied to the surface with irrigation before and after application. The tracers applied were: lithium bromide, bacteriophage and three different sized microspheres (1, 6 and 10 µm particle diameter). Two 10 m boreholes were drilled within the site for core sampling to sample the unsaturated zone. All the tracers (except the 10 µm beads) were detected at low concentrations at the water table (located at approximately 25 m depth). The bacteriophage was detected 2 to 3 days after injection; the 1 and 6 µm beads were detected 1 day after injection; and the lithium bromide was detected 3 days after injection. Core samples obtained 6 months later contained 1, 6 and 10 µm beads throughout both boreholes, but concentrated at particular horizons and with considerable variability in particle numbers at different depths and between the two boreholes. The core samples showed that the 10 µm beads had migrated at least 10 m through the unsaturated zone. The core sampling demonstrated substantial retention of the tracers within the unsaturated zone. Overall, the study demonstrated a combination of rapid flow through 20 to 25 m of unsaturated zone combined with very high attenuation.

# 4 Other Evidence of Karst and Rapid Groundwater Flow

Abstraction boreholes within the C4 Chilterns Chalk area provide some additional evidence of karst processes. Pumping test data (Allen et al., 1997; MacDonald and Allen, 2001) show that some sites have high transmissivities of >1000 $m^2$/day, and a small number have very high transmissivities > 5000 $m^2$/day (Figure 28). Some of the highest transmissivities in the area occur away from the Palaeogene-Chalk boundary and area of stream sinks, suggesting connected networks of solutional fissures and conduits occur in these areas.

In some boreholes in the C4 area there are fissures/conduits in the unsaturated zone which provide substantial inflows above the water table. Piezometers at different depths in monitoring boreholes can have different water levels demonstrating the presence of distinctive water bodies at different levels in the aquifer (Karapanos et al., 2020). Some abstraction sites have high turbidity and coliform counts and/or rapidly degrading pesticides (Lawrence et al., 1996; Farrant et al., 2017). High turbidity that is not produced directly from the Chalk bedrock but is due to sediments derived from Palaeogene or superficial geologies is indicative of connectivity with surface karst features (especially stream sinks), or re-activation of sediment within subsurface conduits. Coliform counts or rapidly degrading pesticides are indicative of short residence time groundwater, suggesting rapid flow and recharge process that are likely to be associated with karstic pathways.

Karst features in the Hermitage-Curridge area in Berkshire are discussed in detail in Edmonds (2008) as part of a proposal for improved groundwater vulnerability mapping for the Chalk karst aquifer of Southern England.

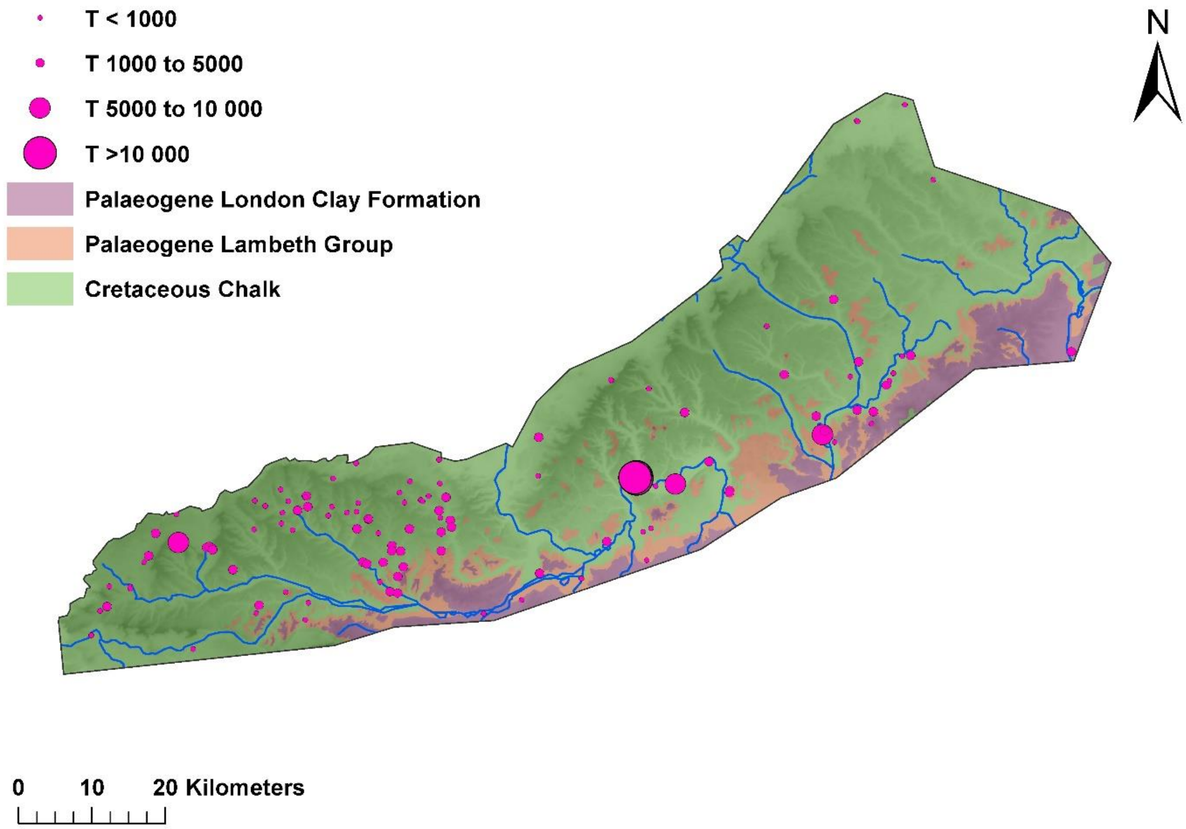


Figure 28. Transmissivity from pumping tests in the C4 Chalk area



# 5 Summary

- There is clear evidence of karst in the C4 Chalk area with caves, dolines, stream sinks and large springs present.
- Surface karst is extensive with hundreds of stream sinks located along the Palaeogene-Chalk boundary along the southern side of the area.
- Visual observations during field surveys suggest that much of the precipitation falling on the Palaeogene outcrop may recharge the Chalk at or near the geological boundary, either via the karstic stream sinks or in some cases via the basal sands in the Palaeogene.
- The largest chalk stream sink in England, with an estimated mean flow of 80 l/s, occurs at Water End in Hertfordshire.
- At three of the stream sinks, short karst caves have been observed, and it is possible that similar features are present beneath many other stream sinks where the chalk is concealed by the overlying sediments.
- Several chalk rivers away from the Chalk/Palaeogene margin have losing/dry sections suggesting they make contribute point recharge into subsurface karstic voids.
- An unsaturated zone tracer study demonstrates rapid groundwater flow to the water table at ~25 m in 1 to 3 days, but combined with very high attenuation.

- Tracer tests have demonstrated rapid groundwater flows of several kilometres per day from stream sinks, boreholes, and a soakaway. Tracer tests were conducted over distances of several kilometres, with rapid flow observed over distances of more than 15 km in Hertfordshire.
- Attenuation of tracer is low in the Hertfordshire tests, and also in some tests from stream sinks in Berkshire. High attenuation in other reported tests suggests that there is considerable dilution and/or attenuation through dispersion and diffusion.
- The frequency and extent of rapid groundwater flowpaths may increase from (1) areas in the north away from stream sinks to (2) areas with stream sinks in the west of the area to (3) areas with stream sinks in the east of the area.
- However, large springs, high transmissivity and rapid tracer dilution show that there are integrated networks of solutional fissures and conduits in areas away from the Chalk-Palaeogene boundary, and there is potential for rapid groundwater flow throughout the C4 Chilterns Chalk area.

# Glossary

**Cave:** A subsurface solutional conduit large enough for humans to enter (usually > ~ 0.5 m wide).

**Conduit:** A subsurface solutional void which is usually circular or cylindrical in cross section. In these reports the term is used predominantly for conduits which are too small for humans to enter (~0.05 to 0.5 m wide).

**Doline:** A surface depression formed by karst processes.

**Dissolution pipe:** A sediment filled solutional void in the subsurface, often with no surface expression.

**Dissolution tubules:** Networks of small cylindrical solutional voids ~ 0.5 cm in diameter found in chalk.

**Estavelle:** A karst feature in a stream or river which acts as a spring under high water levels and a sink under low water levels.

**Fissure:** An enlarged fracture with aperture of ~ 0.5 to ~15 cm, and a planar cross-sectional shape. In these reports the term is used for fractures that are enlarged by dissolution. Those developed on bedding partings may extend laterally both along strike and down dip.

**Inception horizon:** Lithological horizon which favours dissolution and the development of fissures, conduits and caves.

**Karst:** Term applied to rocks which are soluble and in which rapid groundwater flow occurs over long distances. The development of subsurface solutional voids creates characteristic features including caves, dolines, stream sinks, and springs.

**Scallop:** Small-scale dissolution features on cave walls caused by the flow of water which indicate the direction and relative speed of groundwater flow.

**Sinkhole:** Term widely used for surface depressions. These may be karstic in origin and synonymous with dolines, but can also arise from surface collapse into anthropogenic voids such as mines and pits. This term is not used for surface depressions in these reports due to the confusion arising from sinkholes of both karstic and anthropogenic origin. The term has also been used for the actual hole into which water sinks into karstic voids in the subsurface through the base of a stream or river, and may be used in this context in these reports.

**Stream sink:** A stream which disappears into solutional voids in a karst rock. The stream may fully sink into a closed depression or blind valley or may partially sink through holes in the stream bed. The term is used in these reports in preference to sinkhole which can be confused with dolines or depressions caused by collapse into anthropogenic voids.

**Surface depression:** The term used in these reports for all surface depressions where it is unclear whether they are karstic or anthropogenic in origin.

**Swallow hole:** Another term for stream sink, although it has been used in the past for dry dolines that do not contribute surface runoff to the aquifer, and therefore the term stream sink is generally used in these reports, as the presence of an active stream recharging the aquifer is directly inferred.

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