British Geological Survey

BGS Karst Report Series: J3. Karst in the Jurassic Great and Inferior Oolite Groups of southern England

Environmental Change, Adaptation and Resilience Programme

Open Report OR/23/002

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Maurice, L.D., Farrant, A.R., and Mathewson, E.

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British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG

Tel 0115 936 3100

BGS Central Enquiries Desk

Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales

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email bgslondon@bgs.ac.uk

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

Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB

Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw,
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Tel 01232 666595
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Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

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Executive summary

This report documents the evidence for karst and rapid groundwater flow in the Great and Inferior Oolite group aquifers of southern England. It is part of the BGS karst report series on those karst aquifers in England in which cave development is limited – principally the Upper Cretaceous Chalk and the Jurassic and Permian limestones. The term "karst" applies to rocks that are soluble. In classic karst there are extensive caves and large-scale surface karst landforms such as dolines, shafts, stream/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 usually small and have not been well documented. These reports provide data and information on karst in each area. Karst data are compiled from the British Geological Survey databases on karst, springs, and transmissivity; reports and peer reviewed papers; from geological mapping; and through knowledge exchange with the Environment Agency, universities, water companies, consultants and cavers.

This report shows that there is considerable evidence that the Inferior and Great Oolite group aquifers of southern England are karstic, but with substantial differences to the classical karst of the Carboniferous limestones where karst is much more obvious. Dissolution pipes appear to be absent or rare, perhaps due to the limited unconsolidated cover in the J3 area. There are records of dolines, but the dataset is incomplete and there has been little work on dolines in this area. There is little evidence of cave development, although some short caves have been observed in the Inferior Oolite Group. Smaller conduits (~10 to 30 cm) have been observed in underground stone quarries and at spring outlets. Information on karstic conduits from boreholes and outcrops have not been collated for this report, and it is unclear how commonly they occur. Hydrogeological studies of the area suggest that solutional fissures are very common. Small stream sinks are also common in some areas, and may be present in others as there has been no systematic survey. Rivers have highly karstic characteristics, with some big losses as they pass over the Great and Inferior Oolite group aquifers, sometimes via distinctive "swallow holes". Many are fed by large springs and commonly exhibit karstic bourne behaviour. More than 5000 springs have been recorded in the Great and Inferior Oolite group limestones. Discharge data are sparse. Many appear to be small with maximum flows of ~ 1 l/s but there are also 32 with large recorded flows of > 10 or > 100 l/s, and it is likely that there are many more large springs, and also that flows in the natural spring outlets have been greatly reduced by the exploitation of groundwater for supply. Tracer tests by Smart (1977a,b) in the By Brook catchment have demonstrated very rapid groundwater flow over distances of several kilometres, with velocities based on first arrival of tracer of up to 10 km/day, and velocities based on peak tracer concentrations ranging from 0.2 to 5.2 km/day (mean of 2.03 km/day). Tracer recoveries were high (5 to 95%), but breakthrough curves had extensive tailing suggesting attenuation and dilution along the flow paths. Other evidence of karst includes: some high transmissivities, some high borehole yields, rapid aquifer responses to rainfall, and responses to pumping over long distances. The Great and Inferior Oolite group aquifers appear to comprise extensive networks of solutional fissures and conduits, with many flow paths enlarged to a small degree, rather than a small number enlarged to form cave networks. Further investigation of karst (e.g. dolines, stream sinks, spring discharges, tracer tests, water quality indicators of rapid flow) would enable improved conceptualisation of the Inferior and Great Oolite group aquifers, and would be useful to assist with the protection and sustainable management of groundwater resources.

Acknowledgements

We thank Pete Smart for very useful discussions on karst in this area, and providing additional information on the tracer tests that he conducted in the 1970s. For discussions on hydrogeology/karst in this area we thank Gill Davies and Craig Hampton from the Environment Agency; and Simon Starling and Mike Jones from Thames Water. We thank Jonathan Paul from Royal Holloway, University of London for providing spring location data; and the Environment Agency for providing locations of their spring water quality monitoring sites. We thank Tim Rose and Peter Glanvill for providing pictures of Walditch Cave, and the University of Bristol Spelaeological Society for permission to use a picture of Cloford Quarry Cave. At BGS we thank Chris Jackson for reviewing the report; Vanessa Banks, who led much of the work on the BGS Karst database; and Carole Sharratt for assistance with report formatting. This work was partially carried out under the Natural Environmental Research Council (NERC) Knowledge Exchange Fellowship Scheme, grant ref NE/N005635/1.

We acknowledge the important contribution of Charlie Self (05/11/51 to 04/02/16, geologist, and caver in the University of Bristol Speleological Society), to the understanding of the non-karstic mass movement caves in the Cotswolds area.

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Introduction to the BGS Karst Report Series

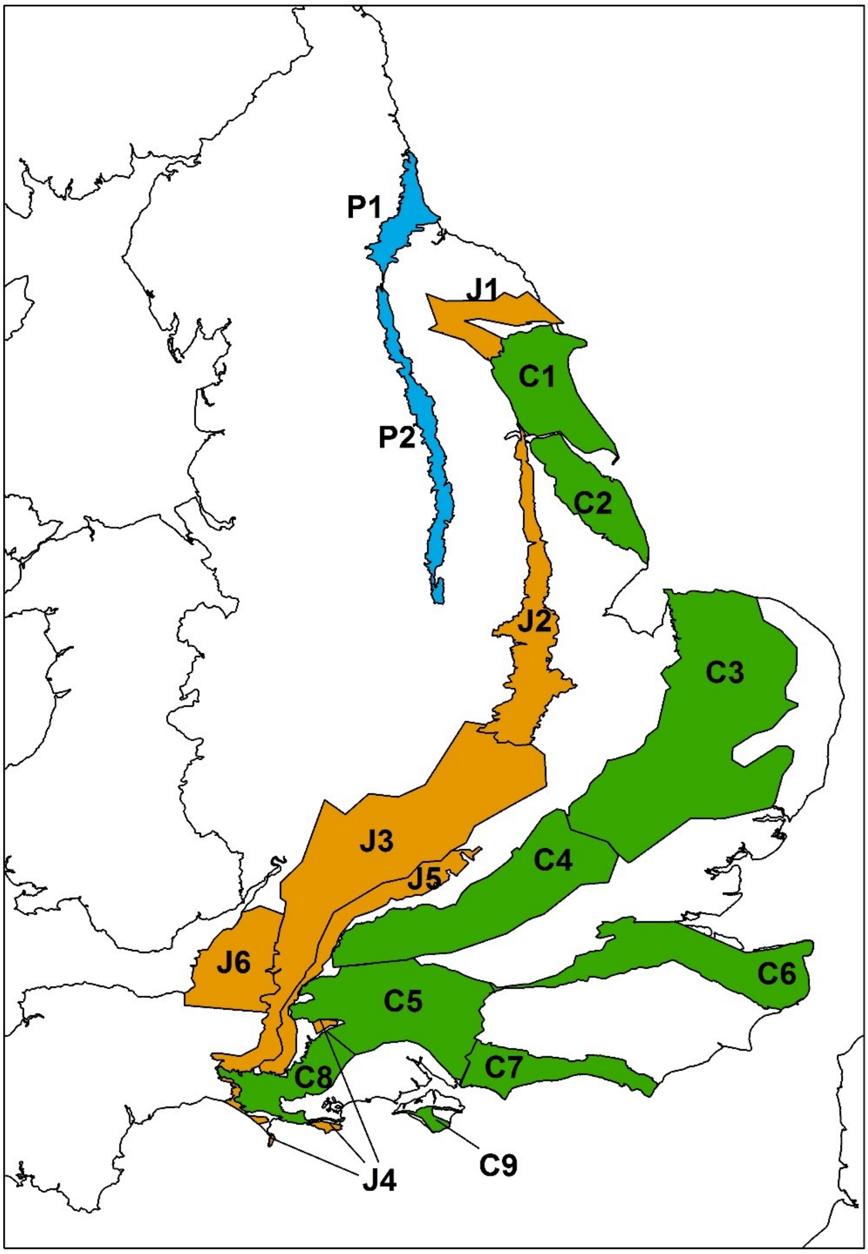
The BGS karst report series is focused on karst aquifers in England in which cave development is limited – the Chalk and the Jurassic and Permian limestones. The series is the main output of the NERC funded Knowledge Exchange fellowship "Karst knowledge exchange to improve protection of groundwater resources" undertaken between 2015 and 2022. This series is the first systematic review of karst features across these aquifers and provides a useful basis for future karst and hydrogeological studies.

The term "karst" applies to rocks that are soluble. In classical karst regions 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 usually 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 to >30 cm diameter and solutionally enlarged fractures (fissures) of ~0.5 to >2 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 will comprise 17 reports which provide an overview of the evidence for karst in different areas of England. The Chalk is divided into nine regions, primarily based on geomorphology and 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 Group of Northern England. J2 covers the Lincolnshire Limestone Formation of central England. J3 covers the Great Oolite Group and Inferior Oolite Group of Southern England. J4 covers three small areas of the Portland and Purbeck limestones in Southern England. J5 covers the Corallian Group limestones of Southern England. J6 covers the Blue Lias limestones of south-west 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; geological mapping; and through knowledge exchange between 2015 and 2022 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 full picture of karst development in these aquifers, and to investigate the detail of local catchments. The reports nonetheless provide an overview of the currently available 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 highlight the need for further investigations of karst to enable improved management and protection of groundwater resources.

The reports are structured to introduce the area and geology, evidence of karst geomorphological features in the area (caves, conduits, stream sinks, dolines and 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 Corallian Group limestones of northern England
J2) Karst in the Jurassic limestones of Central England
J3) Karst in the Jurassic Great and Inferior Oolite groups 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 south-west 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 in the BGS karst report series

This section provides background on each type of evidence for karst, the data sources used, and any limitations in the data. This introduction is general to all the BGS karst reports and further specific information on data sources is provided within the individual reports where applicable. 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 they are indicative of a network of solutional voids of sufficient size to transport the water away through the aquifer. Most stream sinks occur near to the boundary between the carbonate aquifer and adjacent 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 additional stream sinks. Stream sink records are predominantly from the BGS karst database in which many were identified by desk study and geological mapping. 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 seepages through alluvial sediments in the stream bed, 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.

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 solutional fissures (apertures of ~ 0.5 to > 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 is 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 (a form of buried doline) 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 understood. 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, but some may be associated with open solutional fissures.

Dissolution pipes occur at very high spatial densities in some areas, and are commonly encountered in civil engineering projects. Some data on dissolution pipes come from the Natural Cavities database. This is a legacy dataset held by the British Geological Survey and Peter Brett Associates. It comprises data from a range of sources originally commissioned by the Department of the Environment and reported by Applied Geology Limited (1993). 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 that provide flow 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 than have 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 large known discharges of > 10 or > 100 l/s, 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), or that are likely to be large because they were used as monitoring outlets in tracer studies. 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 flow paths 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 flow paths 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 & 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 groundwater with low residence time and/or connectivity with surface water; for example coliforms, turbidity, detection of rapidly degrading pesticides, evidence of connectivity with the sea or surface rivers over long distances. To protect site confidentiality these data are not presented specifically, but a general overview is provided where appropriate.

1 Introduction

1.1 AREA/GEOLOGY

The large J3 area forms a north-east to south-west strip from Northampton to the coast near Weymouth (Figure 1). The focus of this report is the karst in the Jurassic aged Inferior and Great Oolite group limestone aquifers that underlie much of the Cotswold Hills, and also extend south into the Wessex basin, and north into the Northampton area. Throughout much of the J3 area, the land broadly slopes towards the south-east with the higher ground in the west of the area (Figure 1). The area is dissected by deep river valleys (Bricker et al., 2014). In the north of the J3 area the River Nene and the Great Ouse and their tributaries drain north-east to the Wash. In the middle of the area there are several major tributaries of the Thames, including the rivers Cherwell, Evenlode, Windrush and Churn, which drain towards the south-east. The Chelt, which flows north-west, is a tributary of the River Severn. The headwaters of the River Avon (Bristol) drains east, then south before turning west to the Severn Estuary (Figure 2). There are three River Fromes within the J3 area. The most northerly River Frome is near Stroud, to the west of the River Churn. The most southerly River Frome rises in Somerset and flows in a generally northerly direction to join the River Avon. The Bristol Frome also rises in the Cotswolds and flows towards Bristol (not shown on Figure 2 for clarity). There are also many dry valleys associated with the Inferior and Great Oolite group limestones (Richardson, 1930a; Goudie and Parker, 1996; Neumann et al., 2003; Owen et al.,2005; Paul, 2014).

The area is geologically complex with thin and variable geological units, and extensive faulting (Figure 2). There is a particularly high density of mapped faults in the Cotswolds area in the headwaters of the River Thames where many of the faults have a broadly north-west to south-east orientation (Figure 2). Further south, in the Frome and Avon catchments many of the mapped faults have a south-west to north-east orientation, and in the far south of the J3 area there are high densities of faults that are west-north-west to east-south-east or in some cases broadly west to east orientated. The faults in the Cotswolds are normal faults and generally dip at 60° (Maurice et al., 2008).

The stratal dip in the area is generally around 0.5° to 1.5° towards the south or south-east (Neumann et al., 2003). The oldest rocks in the area therefore generally outcrop in the north and north-west. These are the Lias Group mudstones, sandstones and ferruginous limestones which underlie the Jurassic Inferior Oolite Group limestones, and are included in Figure 2. The Bridport Sand Formation is present at the top of the Lias Group (Table 1). The Jurassic limestones comprise the Inferior Oolite Group and the Great Oolite Group (Table 1). The detail of the geology of these units is described in Green (1992). The Inferior Oolite Group has a very variable thickness, with the thickest deposits in the north-west, as seen in the Isopach map in Green (1992). Allen et al. (1997) report that the Inferior Oolite Group limestones in the Wessex area to the south of the Cotswolds are finer grained and more marly than those in the Cotswolds. The Inferior Oolite Group outcrops on the scarp faces in the west of the J3 area, with the overlying Great Oolite Group outcropping over much of the area (Figure 2).

The Great Oolite Group is stratigraphically complex with lower permeability marls and mudstones interbedded with the limestones, and geographical variations in the presence and thicknesses of the different units (Table 1). For example, in the most southerly parts of the J3 area, to the south of the Mendip Hills, the limestones of the Great Oolite Group are replaced by the Frome Clay Formation (Green, 1992). The Great Oolite Group geology is described in detail in Green (1992), who also provides cross sections showing how the thicknesses and lithology of the Great Oolite Group varies on a regional scale. The main limestones of the Great Oolite Group are overlain by the Forest Marble Formation which comprises both limestones and mudstones. This is overlain by the limestones of the Cornbrash Formation. The Great Oolite Group is overlain by the sandstones, mudstones and siltstones of the Ancholme Group, which are in turn overlain by the Selborne Group sandstones and mudstones, which are included in Figure 2 for completeness, but only outcrop in very small areas in the very south of the area. The geology presented in Figure 2 is from the BGS 1:50,000 geological mapping.

The Inferior and Great Oolite group aquifers are not synonymous with the stratigraphical terms (Rushton et al., 1992). The Inferior Oolite Group is in hydraulic continuity with the underlying permeable Bridport Sand Formation (Rushton et al., 1992; Allen et al., 1997), and these units are commonly considered a single aquifer. In this report the term “Inferior Oolite aquifer” is used in this way, although the karst occurs in the Inferior Oolite Group limestones, and not in the Bridport Sand Formation. The Inferior Oolite and Great Oolite group aquifers are separated by the low permeability Fuller’s Earth Formation. Rushton et al. (1992) note that the top of the Great Oolite Group aquifer is difficult to define, with the Forest Marble Formation and the Cornbrash Formation having spatially variable composition and permeability, with some lower permeability layers that can confine the aquifer, as well as the permeable limestone layers. For the purposes of this report, the term “Great Oolite Group aquifer” includes the Forest Marble and Cornbrash formations, although where it is clear which formation a particular karst feature is in, then this is indicated. Local stratigraphical variations will have a bearing on the distribution of karst and should be considered in local assessments of karst.

Allen et al. (1997) report that the Inferior and Great Oolite group aquifers have similar hydraulic characteristics with high transmissivity and low storage. Although these are generally separate aquifers, in some areas they are in hydraulic continuity where the Fuller’s Earth Formation clays are thinner or more fractured, and/or due to the hydraulic gradients induced by pumping (Allen et al., 1997). In some parts of the eastern Cotswolds, where the clays are particularly thin, water levels in the Inferior and Great Oolite group aquifers are the same, indicating a single aquifer response; and where the clays are thicker in the west there can still be some leakage between the aquifers (Allen et al., 1997). There are also faults with throws of 30 to 50 m which result in horizontal connectivity between the Inferior Oolite Group and the Great Oolite Group in some places (Allen et al., 1997), although Bricker et al. (2014) note that there are few cases where this occurs.

The Great and Inferior Oolite group limestones are highly fractured (Figure 3 and Figure 4). An extensive survey of fractures in the Cotswolds (3660 fractures from 80 locations) was carried out by Hancock (1968). He provides many details and shows that there are six major joint sets (four normal to the bedding surfaces, and two inclined to the bedding) and nine other directions of non-systematic jointing. The spacing of well-developed joints that extend laterally for more than 1 metre is about 0.5 to 1 m (but up to 3 m), whilst minor joints are generally spaced less than 20 cm apart (Hancock, 1968).

As well as karstic solutional enlargement of fractures, there are many “Gull fissures” which are fractures enlarged by mass movement processes. Hancock (1968) notes that these are well developed where rocks are cambered and also close to the scarp slope in the west, and can range from open “fissures” of 1-2 cm to 10 cm, to major Gulls more than 1.5 m wide. Gull caves in the area are described by Self and Boycott (1999, 2004, 2005, 2011), Self and Farrant (2013), and Farrant and Self (2016), and are discussed in Section 2.1.2.

Some areas of more extensive landslip deposits occur south of Gloucester and south-east of Bristol; as indicated on Figure 5 which shows the superficial geology in the J3 area from the BGS 1:625k mapping. The landslip areas are mostly concentrated around Stroud and Bath, and where there is over-deepening of valleys due to river capture. Superficial deposits are not very extensive in the J3 area, with the exception of the north-east where there are glacial till deposits on the interfluves (Figure 5). Throughout the area, there are some alluvium and river terrace deposits in river valleys, with river terrace deposits most prevalent in the Thames valley.

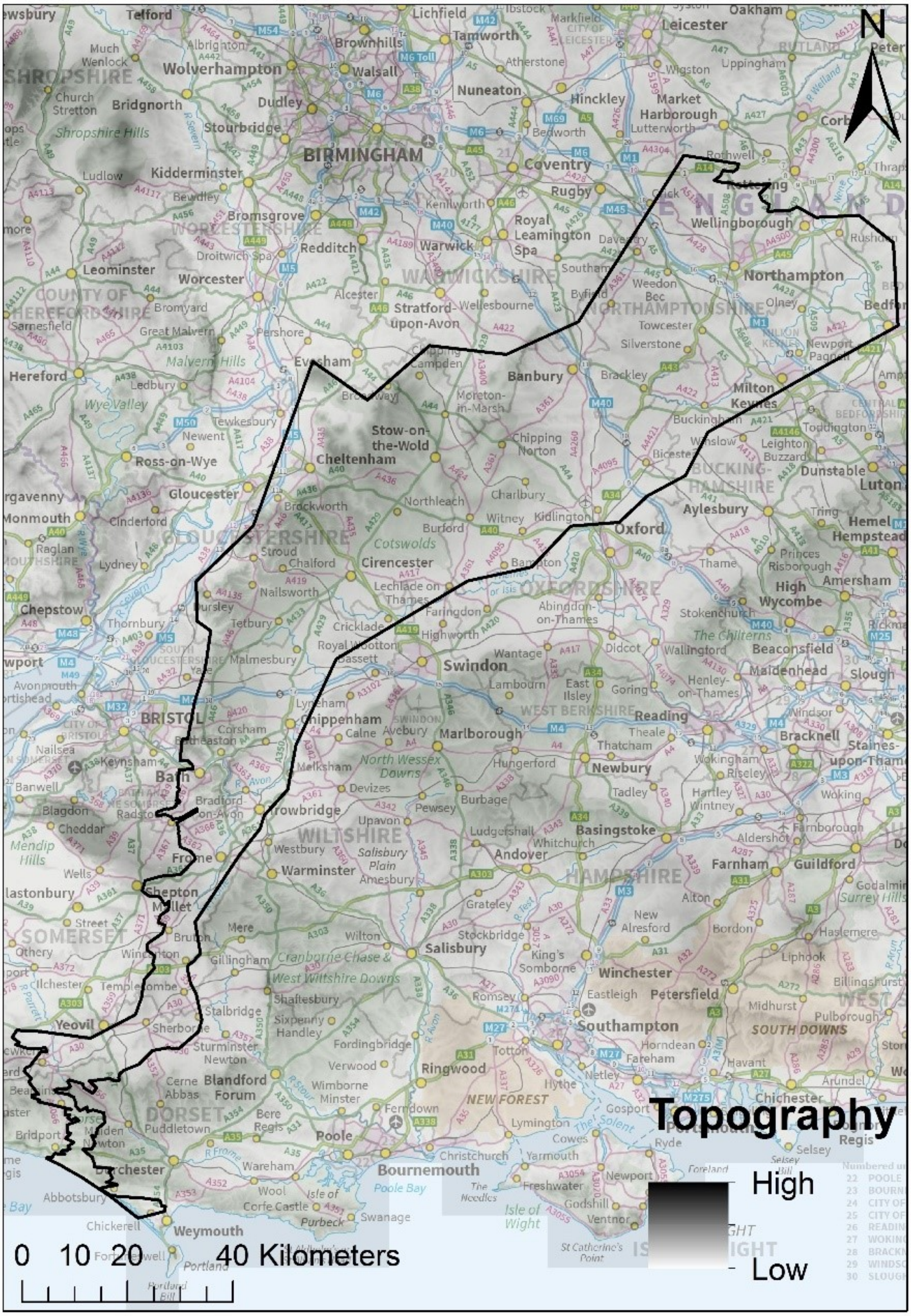


Figure 1. The J3 Jurassic limestone area.

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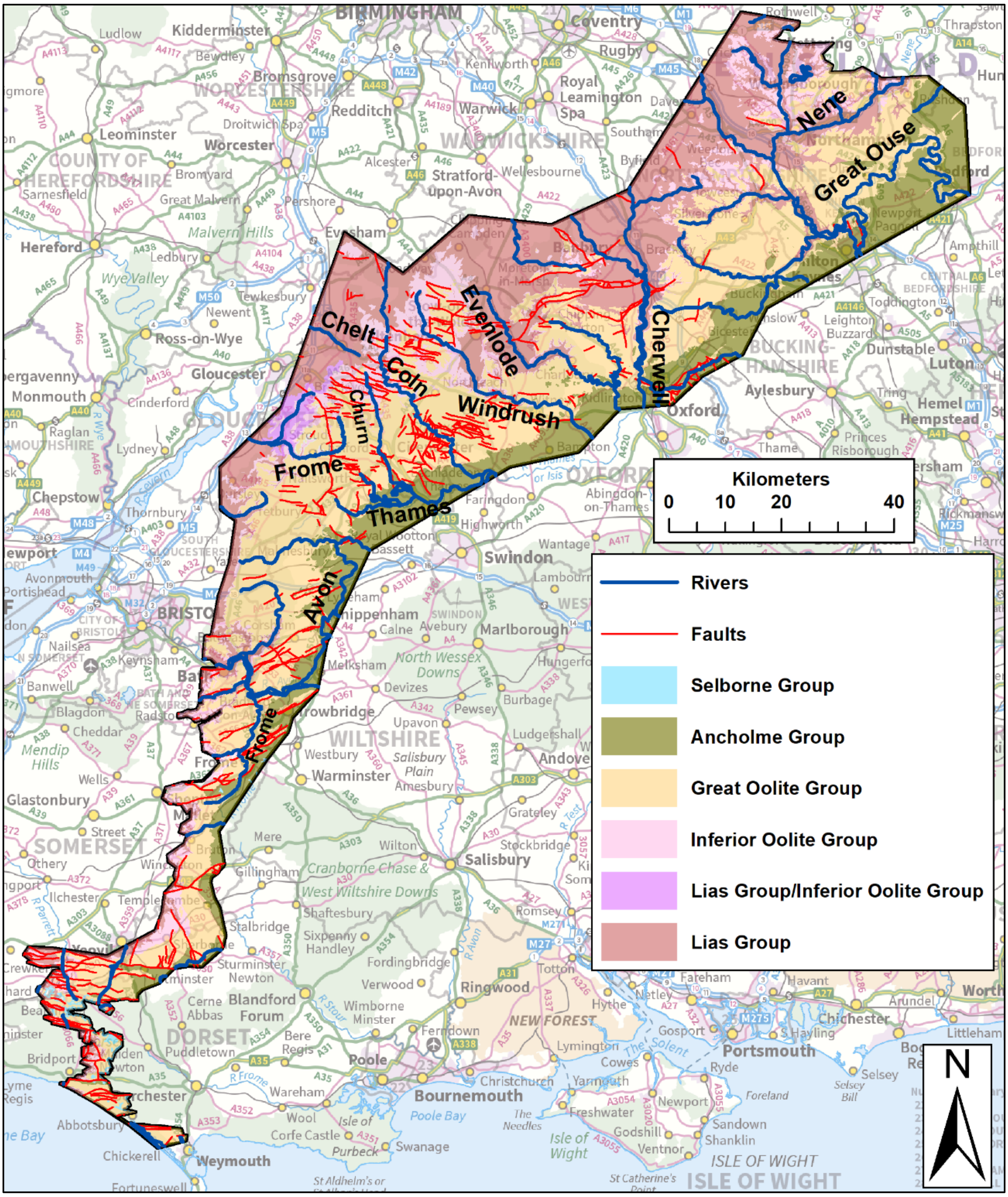

Figure 2. Bedrock geology and major rivers.

Table 1. Basic stratigraphy in the J3 Jurassic Limestone area.

Group	Formation	Lithology	Thickness
Selborne Group	Upper Greensand Formation	Sandstone	0-75 m
	Gault Formation	Mudstone	90-110 m
Ancholme	Oxford Clay Formation	Mudstone	23 m
	Kellaways Formation	Sandstone, siltstone and mudstone	8-12 m
Great Oolite Group	Cornbrash Formation	Limestone	2-6 m
	Forest Marble Formation	Limestone and mudstone	10-25 m
	North		
	White Limestone Formation	Limestone and mudstone	15-39 m
	Hampen Formation	Limestone, mudstone and marlstone	1-20 m
	Taynton Limestone Formation	Limestone	0-15 m
	South		
	Chalfield Oolite Formation	Limestone	0-50 m
	Athelstan Oolite Formation	Limestone	30 m
	Throughham Tilestone Formation	Limestone	5 m
	Far South		
	Frome Clay Formation	Mainly mudstone	20 to 50 m
	Fuller's Earth Formation	Limestone and mudstone	10-48 m
	Chipping Norton Limestone Formation	Limestone	0-5 m
Inferior Oolite Group	Salperton Limestone Formation	Limestone	8-20 m
	Aston Limestone Formation	Limestone	0-15 m
	Birdlip Limestone Formation	Limestone, sandstone and mudstone	0-65 m
Lias Group	Bridport Sand Formation	Sandstone	0-120 m
	Marlstone Rock Formation	Ferruginous limestone	0-7 m
	Dyrham Siltstone Formation	Siltstone and mudstone	0-50 m

Coloured rows show north to south variation in the Great Oolite Group between the Forest Marble Formation and the Fullers Earth Formation

Figure 3. Dense fracturing in the Inferior Oolite in a quarry at Scottsquar Hill north of Stroud. BGS Photo P210369 by C.A.F. Friend (1966).

Figure 4. Dense fracturing in the White Limestone Formation of the Great Oolite Group at Breakspear's Pit, North Leigh, Oxfordshire. BGS photo P211849 by J.M. Pulsford (1st May 1975)

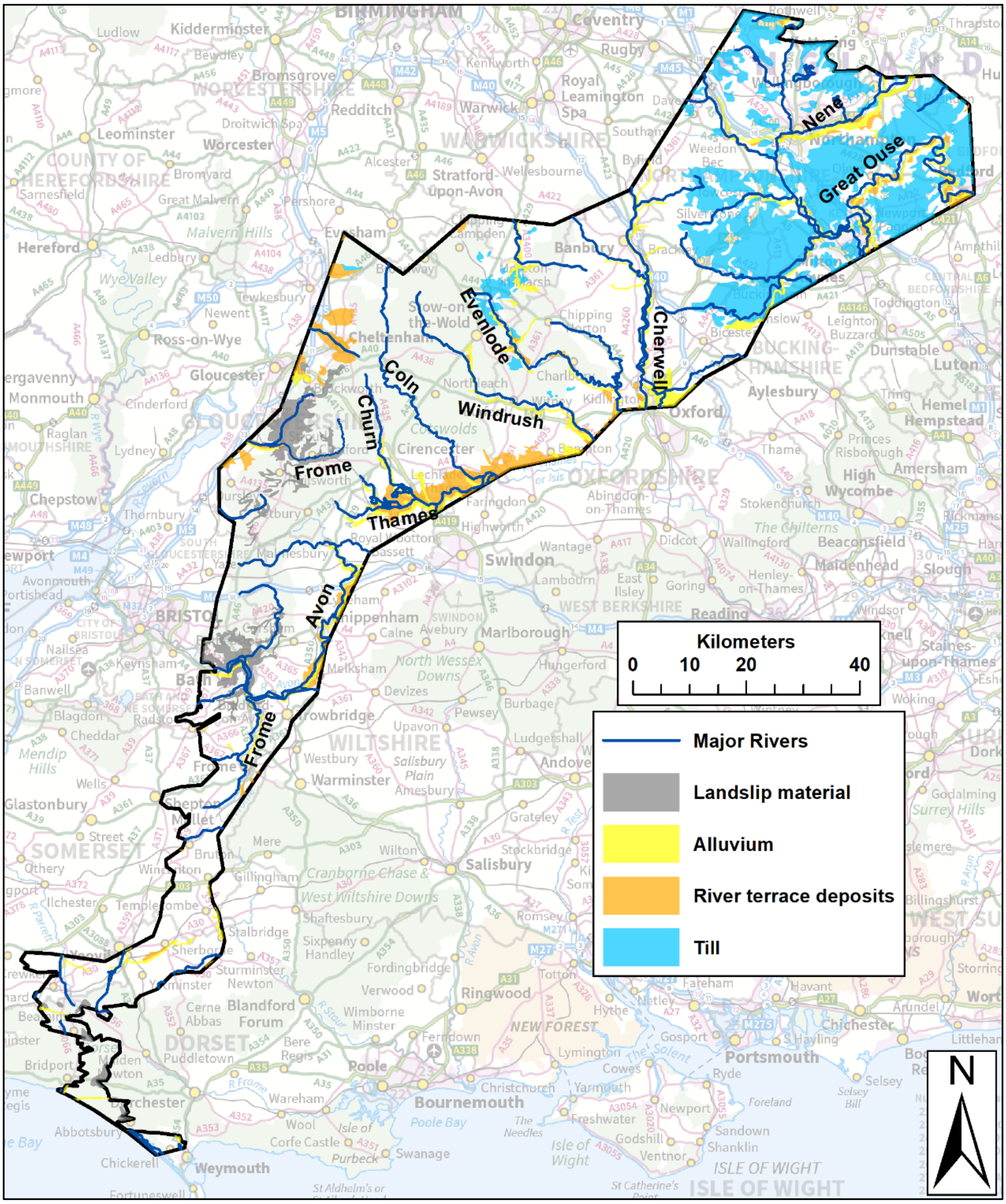

Figure 5. Superficial geology and major rivers.

1.2 WATER PROVIDERS AND REGULATORS

There are five water providers in the J3 Jurassic limestone area (Figure 6), and five Environment Agency areas (Figure 7).

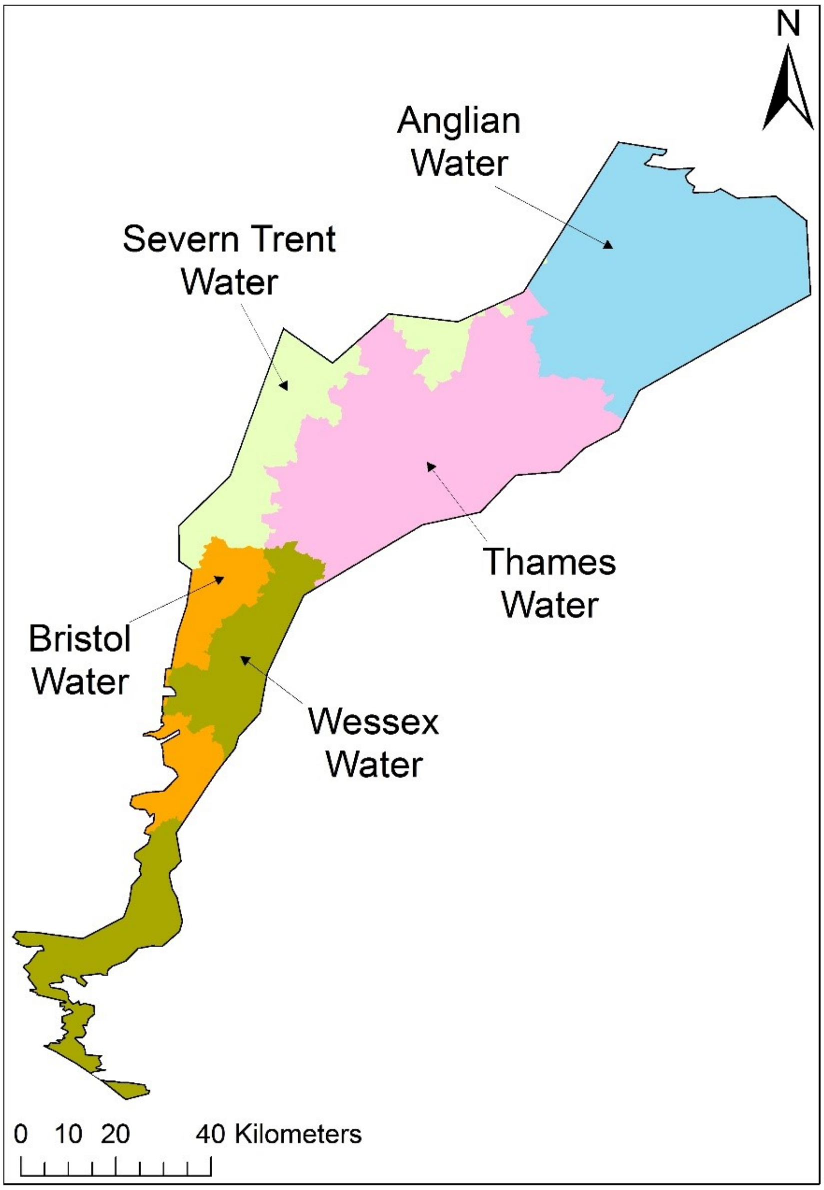

Figure 6. Water providers in the J3 Jurassic limestone area.

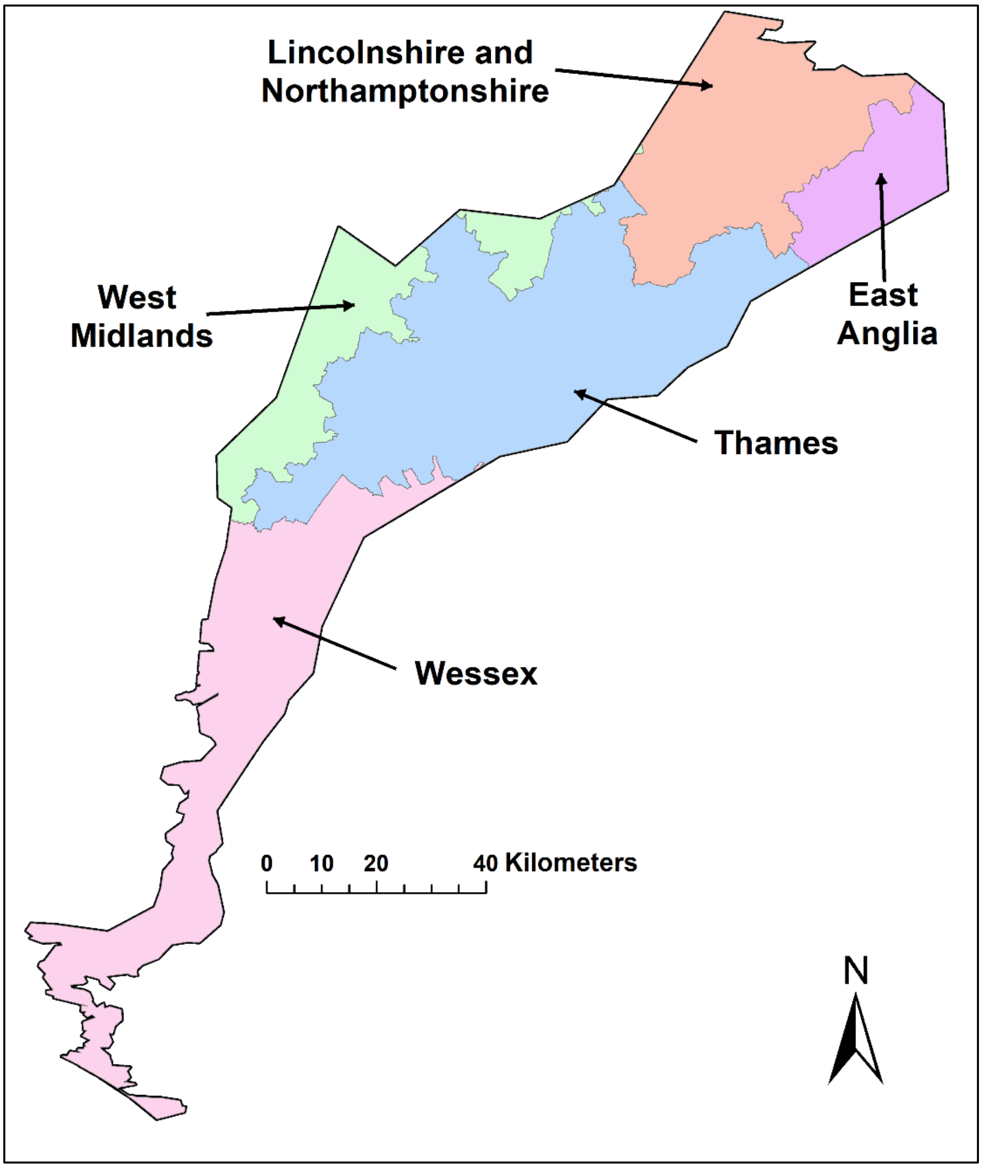

Figure 7. Environment Agency areas in the J3 Jurassic limestone area.

2 Karst geomorphology

2.1 CAVES AND CONDUITS

2.1.1 Introduction

There are very few significant karstic caves in the Great and Inferior Oolite group limestones in the J3 area. The distribution of cave and conduit records in the area is shown on Figure 8. These distributions are strongly influenced by the locations of the studies that have been conducted, and there are likely to be other sites with conduits, and perhaps some other short caves, as there has been no systematic survey.

The data include records from the Natural Cavities database. This is a legacy dataset held by the British Geological Survey and Peter Brett Associates (now Stantec). It comprises data from a range of sources originally commissioned by the Department of the Environment and by Applied Geology Limited (1993). Most of these records (222) are “Gull fissures”, which are voids formed by mass movement processes, and are not karstic in origin. There are also 18 records in this database which are classified as either “vadose cave” and/or “phreatic cave”. The implication is that these are karstic caves, and one is also listed as a swallow hole, and one as a spring. However, there is very little information on the caves in the database and the records have not been verified for this project.

Cave locations from the BGS karst database are also shown on Figure 8. These are divided into records that are listed as Gull caves (12 sites from Self and Boycott, 1999); and other caves which may be of karstic origin, and include 12 from Barrington and Stanton (1977) which are classified in the BGS karst database as “ICAVE” (1) or “OCAVE” (11), and one cave marked on a BGS fieldslip which is classified as “CAVITY”. The remaining records shown on Figure 8 are from a brief literature review on caves and conduits for this report (discussed below). There are likely to be some duplicate records among the three sources of cave locations (the Natural Cavities database, the BGS karst database, and those from literature review), and not all Gull cave locations recorded in the literature are included on Figure 8, as outlined below.

2.1.2 Gull caves

Non-karstic caves, known as Gull caves, are very common in the Great and Inferior Oolite group limestones of the Cotswolds (Self and Boycott, 1999, 2004, 2005, 2011; Self and Farrant, 2013; Farrant and Self, 2016). These caves are formed by landslip processes and mass-movement, although some of them have evidence of small scale dissolutional enlargement of joints, and in some cases the walls appear water worn (e.g. Figure 9). Dating of speleothems within Gull caves have indicated that these are between 49 500 and 346 000 years old, providing information on valley incision and scarp retreat rates (Farrant et al., 2015).

The largest Gull cave is Sally’s Rift in the Avon valley near Bath (Self and Boycott, 2004). Gull caves in the Cotswolds are described in detail by Self and Boycott (1999, 2004, 2005, 2011), Self and Farrant (2013), and Farrant and Self (2016). The locations of the Gull caves reported in these references have not been digitised for this report as they do not have a predominantly karstic origin. However, grid references are available in the papers, and those that are included in the Natural Cavities database and/or the BGS karst database are shown on Figure 8. In this literature on the Gull caves, the term “fissure” is used to describe a cave or opening formed by mass movement (as opposed to the use of the term “fissure” in the BGS karst reports, which is defined as fractures that are enlarged by dissolution, as outlined in the glossary).

Self and Boycott (2005) suggest that many landslip Gull caves in the northern Cotswolds area were previously incorrectly thought to be karstic, and suggest that most caves in this area are Gull caves. Self and Boycott (2004) do suggest that some of these caves (e.g. those on Blackquarries Hill east of Wotton-under-Edge; caves at Wotton Hill; and Coaley Wood cave north of Uley) contain flowstone and other speleothems suggesting some drips/small flows of saturated groundwater within them. Self and Boycott (2005) also report a group of caves on the dip slope that might have an alternative origin involving water. These are Boxer Pot, Coombe Farm Hole, Blockley Pot and an unnamed hole near Bourton-on-the-hill. These four caves are included on Figure 8 as "Gull/karst cave?". These caves have no significant horizontal development but Self and Boycott (2005) report that they are significantly different to many of the Gull caves. Nevertheless, Self and Boycott (2005) conclude that it is probable that these are caves that were formed by mass movement processes and which may have a more recent local water input. For example, Boxer Pot is described as a "deep fissure whose walls have been carved by drip dissolution" (Self and Boycott, 2005). Self and Boycott (2005) suggest that it is unclear whether Boxer Pot was created by a stream sink or whether it was originally formed by mass movement processes and then became a local focus for flow. It is only about 100 m from the escarpment crest and there is a line of depressions parallel to the scarp which take very local drainage (Self and Boycott, 2005).

In summary, Gull caves formed by mass movement are common in the J3 area. There are many known Gull caves that have not been included on Figure 8, as well as potential for others in areas outside the main Cotswolds area which has been intensively explored and documented. Whilst these caves are not karstic in origin, in some places they may have a hydrogeological role enabling recharge through the unsaturated zone. For example, MacDonald et al. (2001) suggest that recharge in the Combe Down area near Bath may be facilitated by Gull landslip features. Current evidence does not suggest that Gull caves generally take substantial stream flow. However, the role of Gull fissures and caves in recharge could be of interest for future study.

2.1.3 Karstic caves

There is little development of karstic caves in the Inferior and Great Oolite group limestones in the J3 area. Self and Boycott (2004) report that although there are many springs and some stream sinks in the "middle Cotswolds" (which they define as the area between Cheltenham in the north and Tormarton in the south), no accessible cave passages had been found associated with these karst features. In a brief review of caves in the Inferior and Great Oolite group limestones, Drew and Smith (1972) report that there are very few karst caves. They report previous studies of caves in the Cotswolds by Standing, I.J.S. (1964a), Standing, P.A. (1964b) and Davis (1971), noting that these studies concluded that the caves were not formed by water action, although they may have been slightly modified by dissolution. Most of the karstic caves are reported from the Frome area (Figure 8), where the most significant are Cloford Quarry cave and Vallis Quarry cave.

Cloford Quarry cave [ST 7168 4453] is 145 m long (Mendip Cave Registry). Drew and Smith (1972) highlight the importance of Cloford Quarry cave, primarily as a rare example of an unconformity cave (formed along the unconformity between the Carboniferous Clifton Down Limestone Formation and the Inferior Oolite Group), but also as a rare example of solutional cave development in the Inferior Oolite Group. Cloford Quarry Cave includes passages developed in the Carboniferous limestones, passages developed solely in the Jurassic Inferior Oolite Group, and some passages developed in both limestones (Drew and Smith, 1972). The cave is not hydrologically active, with only a few small drips and intermittent pools, and is described in detail by Drew and Smith (1972) who also provide a survey. The passages developed in the Inferior Oolite Group are strongly joint controlled, with some evidence of bedding control. Passages in the Inferior Oolite Group are predominantly phreatic in shape with typical karstic circular or oval cross sections (Drew and Smith, 1972). An example is shown in Figure 10. Drew and Smith (1972) present a hypothetical sequence of events that might have led to the cave development at Cloford associated with the unconformity between the Carboniferous limestones and the Jurassic Inferior Oolite Group.

There are three other very short caves (~ 2 m) reported by the Mendip Cave Registry that have been associated with palaeokarstic fissure infills at Cloford Quarry [ST 7186 4454], although these are now largely destroyed.

Drew and Smith (1972) suggest that there is one other cave which is similar to Cloford Quarry cave, which is the Vallis Quarry Cave (Barrington and Stanton, 1970). The Mendip Cave Registry report that Vallis Quarry Cave is 31 m long and located at [ST 7577 4867], and that the unconformity between the Carboniferous limestones and the Jurassic Inferior Oolite Group is exposed within chambers in the cave.

The Mendip Cave Registry also reports a karstic cave near Bridport known as Walditch Cave [SY 48543 92159] which is 46 m long and described as “a single straight phreatic rift”. This cave is in the south of the J3 area (Figure 8). The cave is in the Inferior Oolite Group limestones. The entrance to this cave is shown in Figure 11. The cave is described by Poole (1988) who also provides a survey. The passage shape is consistent with a karstic origin for the cave, and is quite large (Figure 11, Figure 12 and Figure 13). The cave ends in a collapse of boulders that cannot easily be passed.

Overall the available data suggest that cave sized conduits can develop in the ooidal limestones (Figure 10 to Figure 13). Currently all the caves of predominantly karstic origin are in the Inferior Oolite Group. It is possible that some additional small cave passages will be discovered in the J3 area, but it seems unlikely that long or large karstic caves will be found, given the high intensity of fracturing in these aquifers which appears to result in many flow paths, rather than concentration of flow and dissolution along a small number of pathways to form caves.

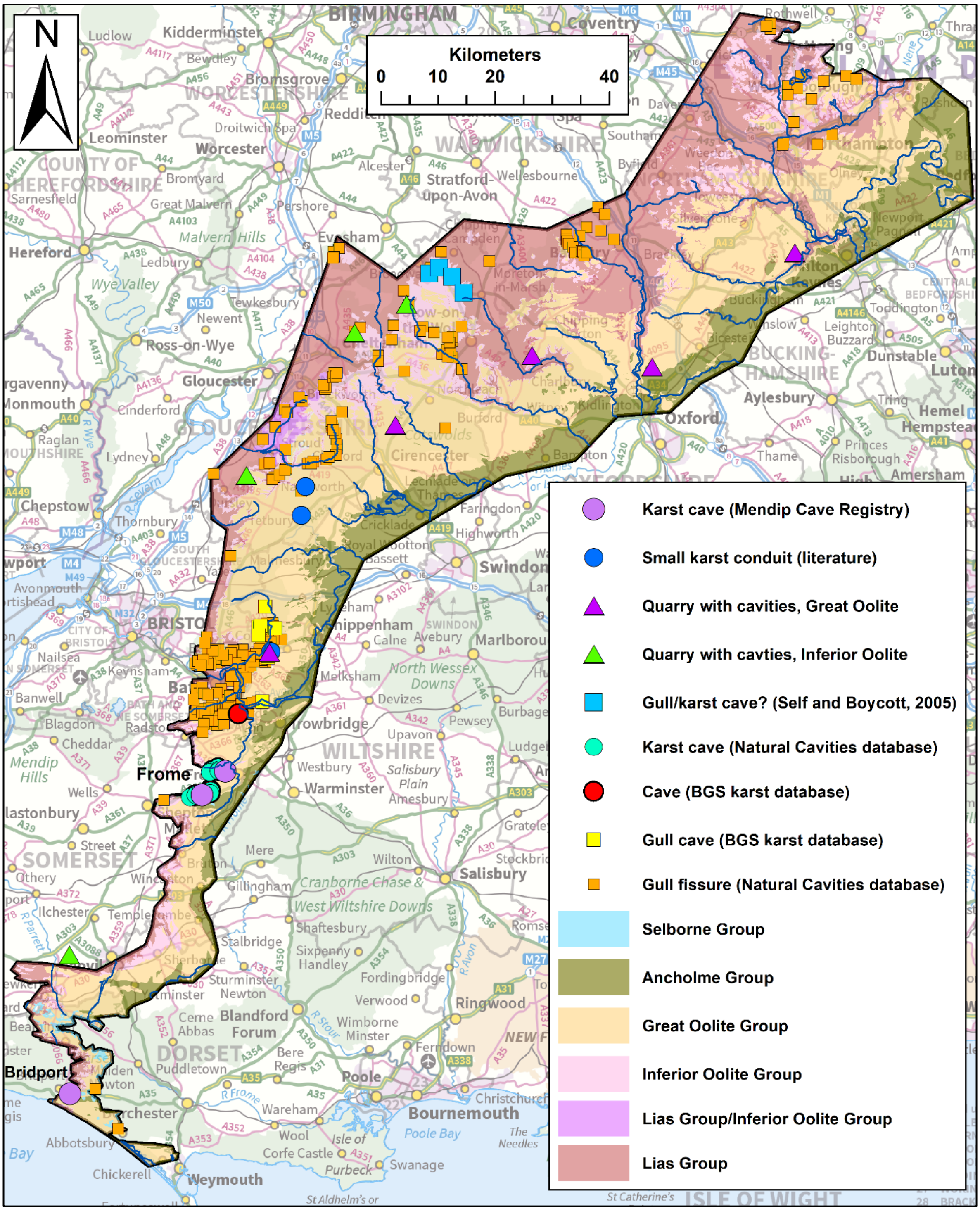

Figure 8. Caves and conduits in the J3 area

Figure 9. Water worn Gull passage in the Box underground stone quarries (from Farrant and Self, 2016).

Figure 10. Passage in Cloford Quarry cave developed entirely within the Jurassic Oolites (photo by D.I. Smith, from Drew and Smith, 1972).

Photo reproduced with permission from University of Bristol Spelaeological Society.

Figure 11. Entrance to Walditch Cave. Photo courtesy of Tim Rose. Reproduced with permission.

Figure 12. Looking out from Walditch Cave. Photo courtesy of Tim Rose. Reproduced with permission.

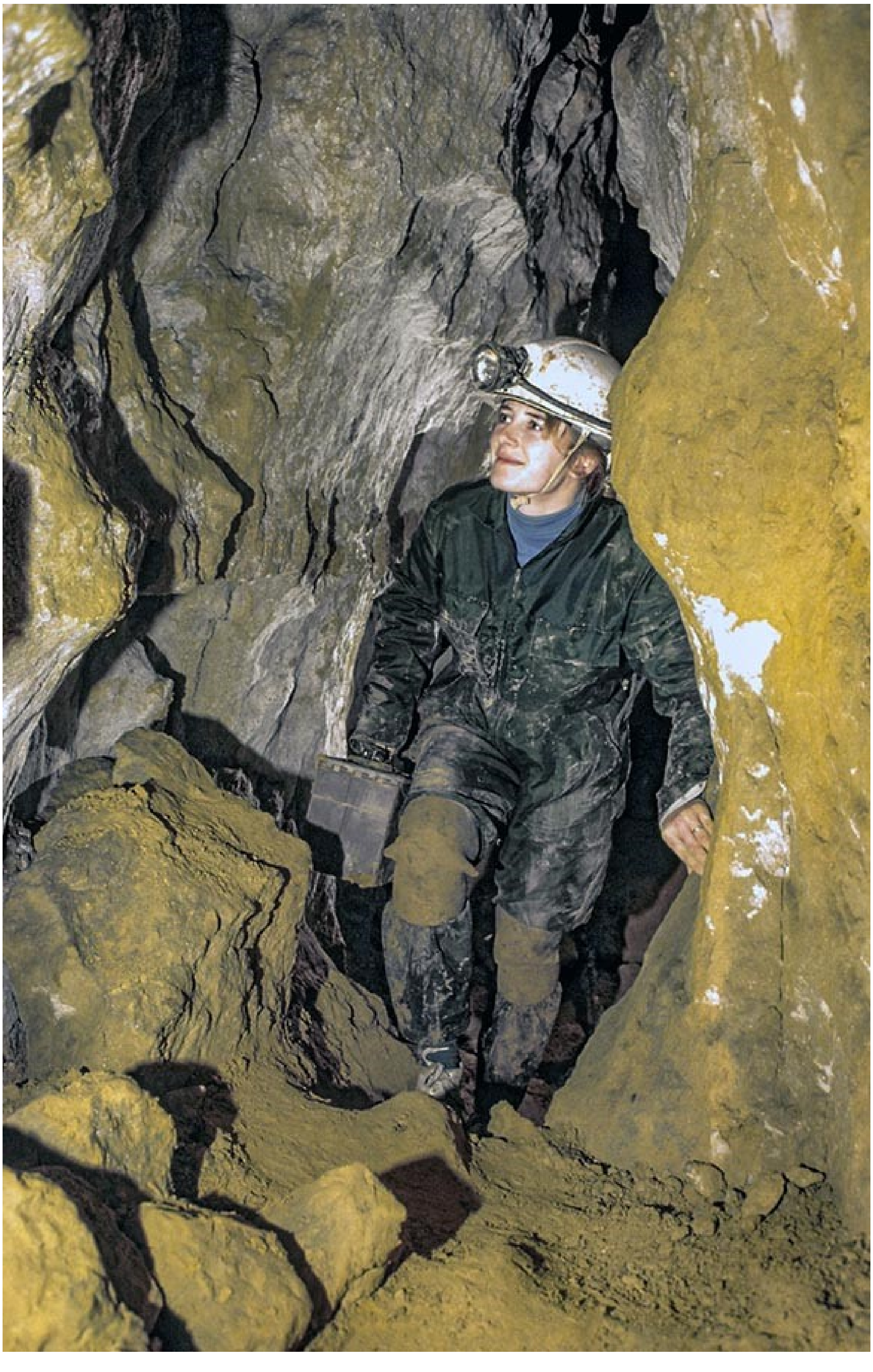

Figure 13. Inside Walditch cave. Photo courtesy of Peter Glanvill. Reproduced with permission.

2.1.4 Solutional conduits and fissures

Solutional fissures and conduits are likely to be common in the Great and Inferior Oolite group limestones, and groundwater flow is reported to be predominantly through a small number of solutional fissures (Morgan-Jones and Eggboro, 1981; and examples from borehole logging by Robinson, 1974). Solutional development of fractures to form fissures and conduits in the area is discussed in Neumann et al. (2003), Allen et al. (1997), Paul (2014), and Farrant and Self (2016). Extensive small-scale dissolutional conduits can be observed in the old underground stone quarries around Bath. These are typically developed on bedding planes within the Chalfield Oolite Formation (Figure 14). Self and Farrant (2013) suggest that there is often dissolution along the north-west to south-east joint sets in the southern Cotswold hills. In a study of spring discharges in the Frome valley, Paul (2014) noted that the larger springs (small for karst springs, with flow rates of 1 to 3.5 l/s in the largest springs) were those where there was direct flow from the limestone bedrock, from solutionally enhanced bedding parallel fissures. The karstic morphology of spring outlets is also implied by Richardson et al. (1946) who report two "tub holes from which water emerges and rushes into a ditch called Doctors Ditch" at Asthall Church, River Windrush. The precise location of these is unclear.

Three sites where there is reported karstic conduit development are included on Figure 8 (blue circles):

(1) The most northerly of these is at Cherington spring [SS 8979 9855], which feeds the Nailsworth stream, a southerly tributary of the River Frome (Maurice et al., 2008). At one of the spring outlets at Cherington, water was observed to flow out of a small karst conduit ~30 cm by ~ 50 cm (Maurice et al., 2008).

(2) Self and Boycott (2004) report that "phreatic solution channels" (small karst conduits) are occasionally observed in the "middle Cotswolds" area (between Cheltenham and Tormarton), and give the example of a cliff near Tetbury (the village of Tetbury is marked as a small karst conduit on Figure 8), which is just to the south of the Cherington spring site. They also note solutional widening of fractures in this area.

(3) Farrant and Self (2016) report that in parts of the Box underground stone quarries near Corsham, small scale solutional features can be observed, including bedding guided phreatic conduits (e.g. Figure 14), and vadose shafts.

It is highly likely that these three sites are not unusual features, and that karstic conduit development on this scale (voids of up to ~10 to 50 cm) is quite common in the Great and Inferior Oolite group limestones in the J3 area. For example, voids have been noted in boreholes in the Chipping Norton Limestone Formation near Chipping Norton (Gill Davies, Environment Agency, personal communication, 2016). Data on karstic conduits from borehole images and outcrops were not collated for this report as they are not reported in the literature.

No literature was found specifically on karstic development of permeability observed in quarry and outcrop exposures, but there are indications that karst fissures occur. Smart (1985) reported solutional modification of fractures in a quarry in the Cotswolds in the Great Oolite Group limestones. Beckinsdale and Beckinsdale (1976) reported solutional enlargement of a fracture creating "a sizeable underground water channel" near Stanway (Goudie and Parker, 1996). Owen et al. (2005) provide a list of sites of geological interest in the Cotswolds which includes many sites where the Great and Inferior Oolite group limestones are exposed and can be directly observed. These sites might be a useful resource for investigating the frequency and types of solutional fissures and conduits in the ooidal limestones. Karst is generally not discussed in the quarry site list in Owen et al. (2005) which is more focused on the other geological features of the exposures, although at a small number of the sites palaeokarst or karstic "surfaces" are mentioned.

The BGS photo archive includes many pictures of quarries and outcrops (https://mapapps2.bgs.ac.uk/geoindex/home.html?layer=BGSPhotos). Some examples of cavities in the Great Oolite Group from this archive are shown in Figure 15, and examples from the Inferior Oolite Group in Figure 16; with the locations included on Figure 8. The term “cavity” is used here as it is not certain whether the voids in these pictures are solutional or mass movement in origin. However, at some sites “fissures” are described in the notes as solutional (e.g. Figure 15 e), many of the voids have a karstic conduit like cross section (e.g. Figure 15 a, b and c), and in all these pictures many of the more extensive vertical and horizontal fissures do appear to have solutional forms/surfaces. These images illustrate the highly fractured nature of the Great and Inferior Oolite group limestones, and the extensive enlargement of fractures by karstic and mass movement processes. The high prevalence of vertical features suggests the potential for rapid flow through the unsaturated zone.

Figure 14. Half of a karstic phreatic tube preserved in the roof of an underground stone quarry, Box, near Bath, in the Chalfield Oolite Formation (from Farrant and Self, 2016)

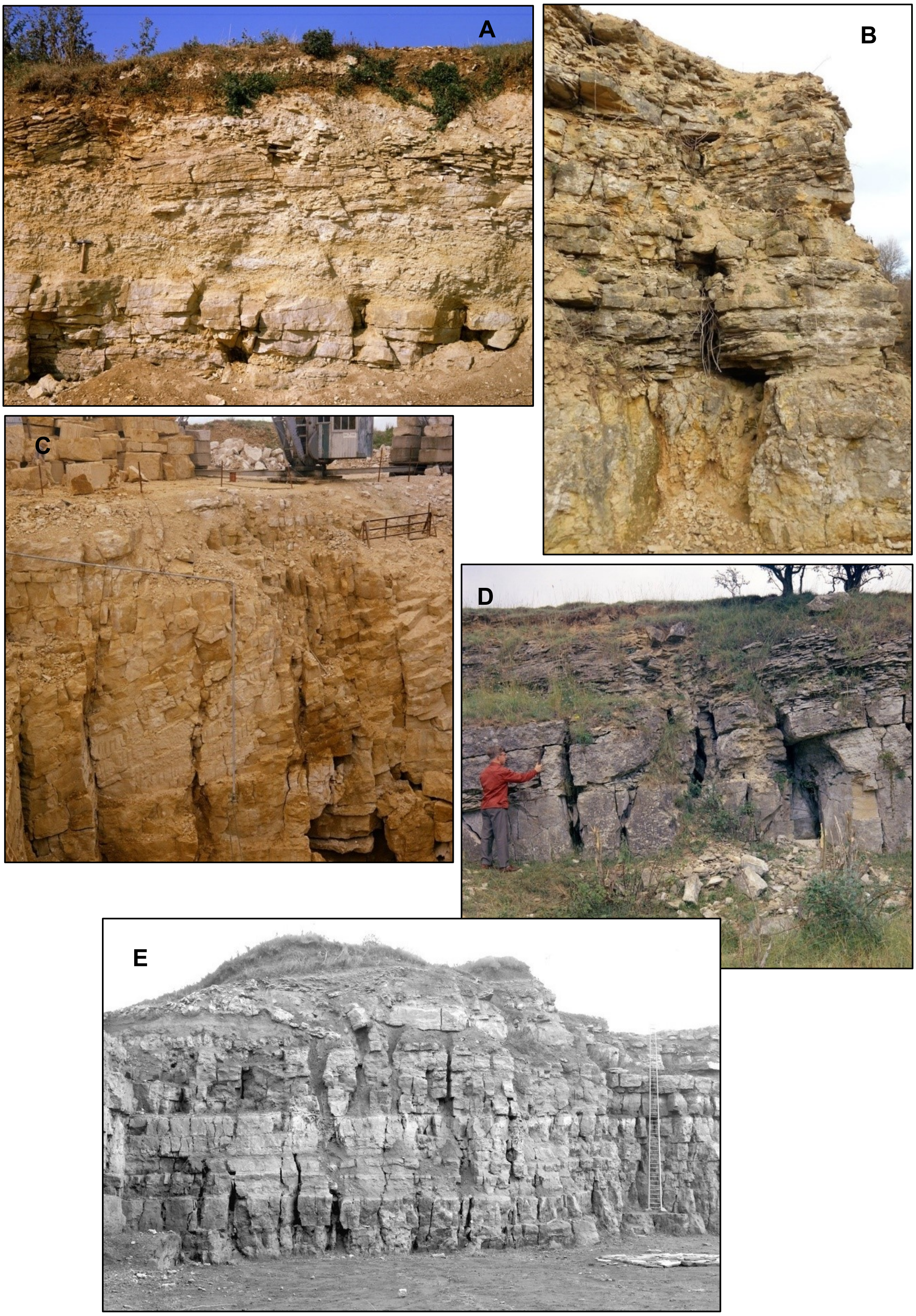

Figure 15. Cavities in the Great Oolite: (A) Roadside Quarry, Deanshanger (J.M. Pulsford, 1964). (B) Foss Quarry, Cirencester (M. Barron, 2011). (C) New Hazelbury Quarry, Box Hill (C.A.F. Friend, 1967). (D) Lyneham Barrow Quarry (J.M. Pulsford, 1960). (E) Kirklington cement pit (J Rhodes, 1925). Photos from BGS archives (P210075, P775230, P210747, P209763, P203122).

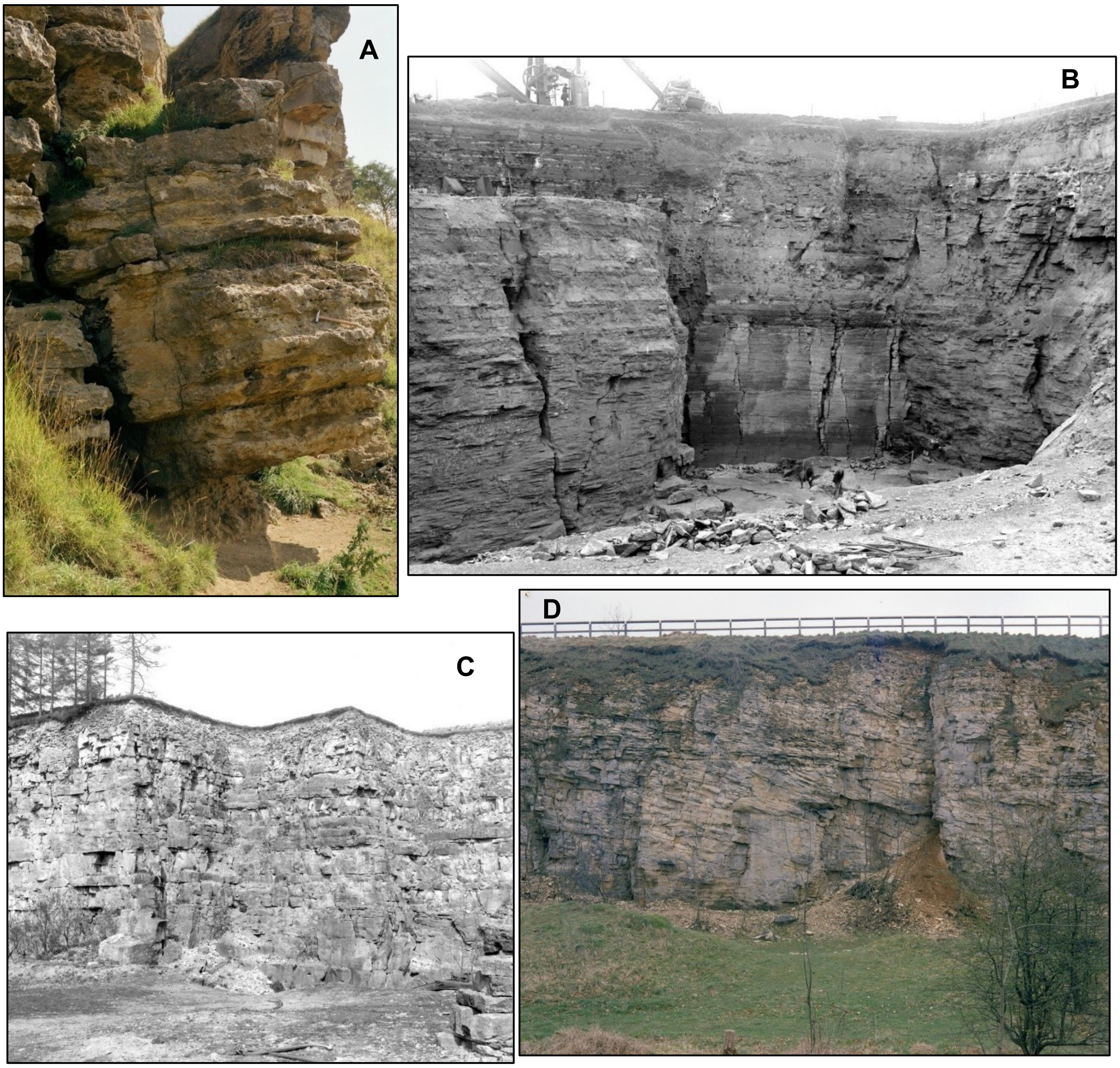

Figure 16. Cavities in the Inferior Oolite: (A) Cleeve Cloud (C.J. Jeffrey, 1982). (B). Ham hill quarries, Montacute (J. Rhodes, 1928). (C) Jackdaw quarry, Stanway (J. Rhodes, 1928). (D). Frocester quarry (C.A.F. Friend, 1966). Photos from BGS archive (P213086, P202108, P204182, P210365).

2.2 STREAM SINKS AND RAPID RECHARGE

2.2.1 Introduction

Records of stream sinks are shown on Figure 17. Many of these are from the BGS karst database which holds records of 44 stream sinks. These are records from Ordnance Survey maps and BGS field slips. These stream sinks have not been systematically checked, and need to be verified in the field. The BGS karst database does not cover the whole area, and there has been no systematic survey of stream sinks associated with the Inferior and Great Oolite group aquifers, therefore there are likely to be other unrecorded stream sinks. For example, in the south of the area, some stream sinks can be identified on LiDAR on the Cornbrash Formation and on the Forest Marble Formation (shown as yellow circles on Figure 17). Figure 17 also shows 15 stream sinks recorded by Smart (1977a), which were the injection points for tracer tests (Section 3). Sinks into karstic features are recorded within the Sapperton Canal Tunnel (Rushton et al., 1992; Maurice et al., 2008), and stream sinks have been reported at Combe Down (MacDonald et al., 2001); and these locations are shown. Figure 17 also shows the (generally approximate) locations of streams sinks from other literature (Richardson, 1930a; Richardson et al., 1946; Sumbler, 1995, Goudie and Parker, 1996; Self and Boycott, 2004; and Owen et al., 2005). Some of these may be duplicates of records in the BGS karst database. Further information on these stream sinks, on river losses to the aquifers, and on soakaways, is provided in the Sections 2.2.2 to 2.2.4, from a brief review of the literature.

The geographical distribution of stream sinks in Figure 17 reflects the locations of records rather than the actual distribution of karst features. There are no stream sinks recorded in large parts of the north-east of the J3 area where low permeability till deposits may provide an additional source of surface runoff that might sink into the limestones at the till margins. There are also no stream sink records in the far south of the area.

Discerning natural patterns in stream sink distributions is difficult given the limitations of the dataset. The geology is complex and heterogeneous with lower permeability mudstones present as well as the limestones (Table 1), and considerable spatial variations in facies composition and thickness (Section 1.1), which impacts where stream sinks occur. However, there is evidence for stream sinks and/or river losses on the Inferior Oolite Group limestones and the Great Oolite Group limestones (including some streams sinking into the Forest Marble Formation and the Cornbrash Formation). Stream sinks generally occur where surface runoff generated on the lower permeability mudstone layers reaches limestone. At the top of the sequence, stream sinks in the Cornbrash Formation are near the boundary with the Kellaways Formation mudstone. The underlying Forest Marble Formation comprises both limestone and mudstone facies, and sinks within the Forest Marble Formation occur at the contact between these facies (for example around Westonbirt and Badminton). Allen et al. (1997) note that within the Great Oolite Group, surface streams forming on the low permeability mudstone in the Forest Marble Formation sink into the underlying limestone formations, and groundwater emerges again at the surface at the boundary between the limestone beds and the underlying mudstones of the Fuller's Earth Formation. Surface runoff on the Fuller's Earth Formation can also sink when it reaches the underlying limestones of the Inferior Oolite Group, and there may also be stream sinks on the Inferior Oolite Group where runoff on the lower permeability Lias Group strata flows onto the Inferior Oolite Group aquifer.

Evidence for rapid groundwater recharge is reported more generally in the literature. Rushton et al. (1992) report (in the Cotswolds area) that there is a rapid increase in river flows soon after the start of the recharge season, which they attribute to rapid lateral flow via the fissure system. MacDonald et al. (2001) note that Hawkins (1994) reports increased infiltration through the roof of underground workings within 3 hours of rainfall in the Combe Down area. There are some indications of point recharge in this area where MacDonald et al. (2001) note that there are no surface water courses on the Combe Down plateau due to the high permeability of the limestones, and suggest that infiltration may also be facilitated by the Gull landslip cavities. Very rapid recharge through unconfined ooidal limestones after heavy rain has also been observed during BGS visits to the Box underground stone quarries.

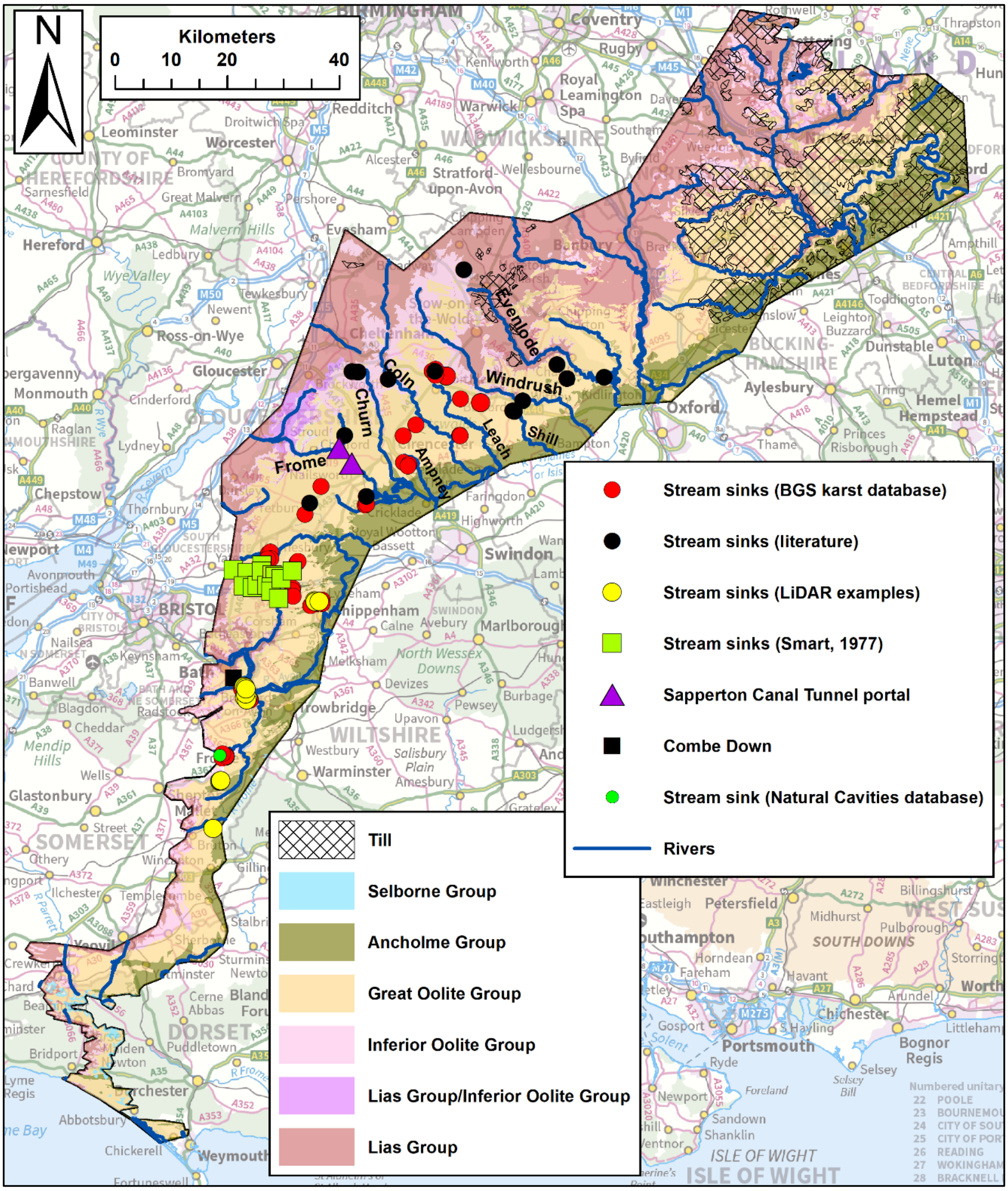

Figure 17. Stream sink records.

2.2.2 Stream sinks

There are a number of reports of classic karst stream sinks in the J3 area, with various terms used to describe them. They are often referred to as "swallow holes" or "swilly holes", and Self and Boycott (2004) note that there are subsidence depressions in some valley bottoms known locally as "whorley pitts" (Guise,1877) or "whirley holes". There are also some reports of "sinks" and "sink holes" for which it is unclear whether the author is referring to active stream sinks or dolines. There is some uncertainty about the precise location of some of the stream sinks, but it is clear that stream sinks are developed across the whole stratigraphic sequence; with records on the Cornbrash Formation, the Forest Marble Formation, the underlying main limestones of the Great Oolite Group, and on the Inferior Oolite Group. In most cases there is no information on the amount of flow going into the stream sinks. Apart from the work by Smart (1977a; 1985) in the Bybrook catchment north-east of Bristol, there has been no tracer testing, and the outlets for the stream sinks are unknown. There are many springs, some known to be large (Section 2.4; Figure 23 and Figure 25), and groundwater from the stream sinks is likely to emerge down gradient via the larger springs in the major river valleys, although the highly heterogeneous nature of karst could result in unexpected flow directions. Information on stream sinks in the central Cotswolds area, and the Chippenham-Bath-Frome area to the south is summarised below, with maps showing more detail of the underlying geology.

Central Cotswolds area

Some stream sinks in the central Cotswolds area are described by Richardson (1930a) and Richardson et al., (1946). Some other reports of stream sinks are in publications that are difficult to access, but summaries are provided by Goudie and Parker (1996) and Self and Boycott (2004). Figure 18 shows the records of stream sinks in the Central Cotswolds area, including the main sites described in the literature. These are described below, moving down through the geological sequence:

At Oaksey, near Cirencester (site 1 on Figure 18), water sinks into the Cornbrash Formation at Oakwell Swallet (Richardson, 1930a; Standing, 1964c, Self and Boycott, 2004). Richardson (1930a) suggests that the flow path may be shallow, with twigs observed in springs at cottages at Oak Well in wet weather. Goudie and Parker (1996) report that "Swilly holes" are reported at the base of the Oxford Clay at Ramsden Heath (site 2 on Figure 18) and Combe (site 3 on Figure 18) by Arkell (1947) and Richardson et al. (1946). These are presumably also sinking into the Cornbrash Formation.

Arkell (1947) and Richardson et al. (1946) also report a "swilly hole" at the base of the Forest Marble Formation at Watermans Lodge, Wychwood (Goudie and Parker, 1946), site 4 on Figure 18. Self and Boycott (2004) suggest that there are karst swallets near Tetbury (reported by Ward, 1986a,b), site 5 on Figure 18. Although the precise locations of these is uncertain, they may be associated with the Forest Marble Formation, which outcrops in this area. "Swilly holes" are reported at three places on the Shill Brook near Sturt Farm and also downstream of Signet (Richardson et al., 1946 and Beckinsdale, 1982; reported in Goudie and Parker, 1996). These are site 6 on Figure 18 and are likely to be water sinking into the upper parts of the Great Oolite Group limestones below the Forest Marble Formation.

"Swallow holes" that may be feeding into the Great Oolite Group have also been observed inside the Sapperton Tunnel on the disused Thames and Severn Canal (Rushton et al., 1992). The tunnel is between Stroud and Cirencester, and is 3.5 km long from the Daneway portal to the Coates Portal (these portals are site 7 on Figure 17 and are shown as purple triangles). The tunnel passes through the Fuller's Earth Formation, the Inferior Oolite Group, a faulted section of the Fuller's Earth Formation, and the Great Oolite Group (Taunton, 1872; https://www.cotswoldcanals.net/sapperton-canal-tunnel.php). The literature on the Sapperton Tunnel swallow holes is discussed by Maurice et al. (2008) who note that Hadfield (1969) reported losses of 5056 m^3/day (equivalent to ~ 60 l/s) from the tunnel. Maurice et al. (2008) also report that other literature (University of Birmingham, 1987; http://www.stroudwater.co.uk/t&scanal/tunnel/tunnel.html) suggests that the swallow holes in the tunnel may be estavelles which only lose water in summer. When the canal tunnel was operational, there were many problems as powerful springs breached the canal lining during winter (with enough pressure to break a thick concrete layer), and then water drained away through these holes in summer leaving insufficient water in the canal. (http://www.stroudwater.co.uk/t&scanal/tunnel/tunnel.html). These are clearly significant features which highlight the karstic nature of the ooidal limestones in this area. Rushton et al. (1992) suggest that water from the Great Oolite Group aquifer lost from the Sapperton Tunnel swallow holes may be discharged from the Inferior Oolite Group aquifer in the Frome catchment to the west. No tracer tests have been conducted to verify this.

Several stream sinks occur in the Inferior Oolite Group, many taking runoff from the overlying Fullers Earth Formation and/or sinking through the beds of rivers as they pass over the Inferior Oolite limestones (Section 2.2.3). Goudie and Parker (1996) note “swallow holes” in the Inferior Oolite Group in the Francombe Wood valley (site 8 on Figure 18) reported by Ackerman and Cave (1967) and Murray and Hawkins (1973). Goudie and Parker (1996) also report water disappearing down a “swallow hole” into the Inferior Oolite Group on the right bank of the River Coln about 750 m above Withington (site 9 on Figure 18), reported by Dury (1955). Richardson et al. (1946) report that there was a swallow hole on the River Windrush “200 yards above Widford Cornmill” which had been blocked up (site 10 on Figure 18). Water is also reported to sink into the Sherborne Brook (Sumbler 1995; site 11 on Figure 18; see Section 2.2.3), which is incised into the Inferior Oolite Group.

Needlehole “swallow hole” is a stream sink into the Inferior Oolite Group at Upper Coberley near Cheltenham (Richardson, 1930a; Richardson, 1941; Goudie and Parker, 1996; Self and Boycott, 2004; site 12 on Figure 18). This is a fairly large triangular shaped karst depression which takes runoff from the Fuller’s Earth Formation (Richardson, 1930a). There is an obvious triangular depression very near Needlehole on LiDAR at [SO 9768 1681] and circular shaped depressions can also be seen on LiDAR in the area, for example at [SO 9774 1652] and [SO 9802 1684]. (https://maps.nls.uk/geo/explore/side-by-side/#zoom=16.1&lat=51.84763&lon=-2.03334&layers=1&right=LIDAR_DTM_2m). Richardson (1930a) suggests that the water sinking here flows through the Inferior Oolite Group aquifer to an outlet in the River Churn. The location of this outlet is not reported, and this proposed connection does not appear to have been verified by tracer tests. Owen et al. (2005) suggest that there is a “sink hole” in the Fuller’s Earth Formation at Seven Springs (site 13 on Figure 18 is the location of Seven Springs village). It is possible that they are referring to the Needlehole site. Owen et al. (2005) also suggest that there are two “sink holes” in the Inferior Oolite Group at Blockley (Site 14 on Figure 18).

Maurice et al. (2008) also note that in the Frome catchment (near Stroud) there are springs marked on Ordnance Survey maps which end at “sinks” or “spreads” suggesting that the water may sink back into the Inferior Oolite Group, although these could be anthropogenic drains. These are not included on Figure 17 or Figure 18, but there are some stream sinks recorded in the karst database in this area. Maurice et al. (2008) also discuss “swallow holes” in the bed of the River Frome (see Section 2.2.3 on river losses).

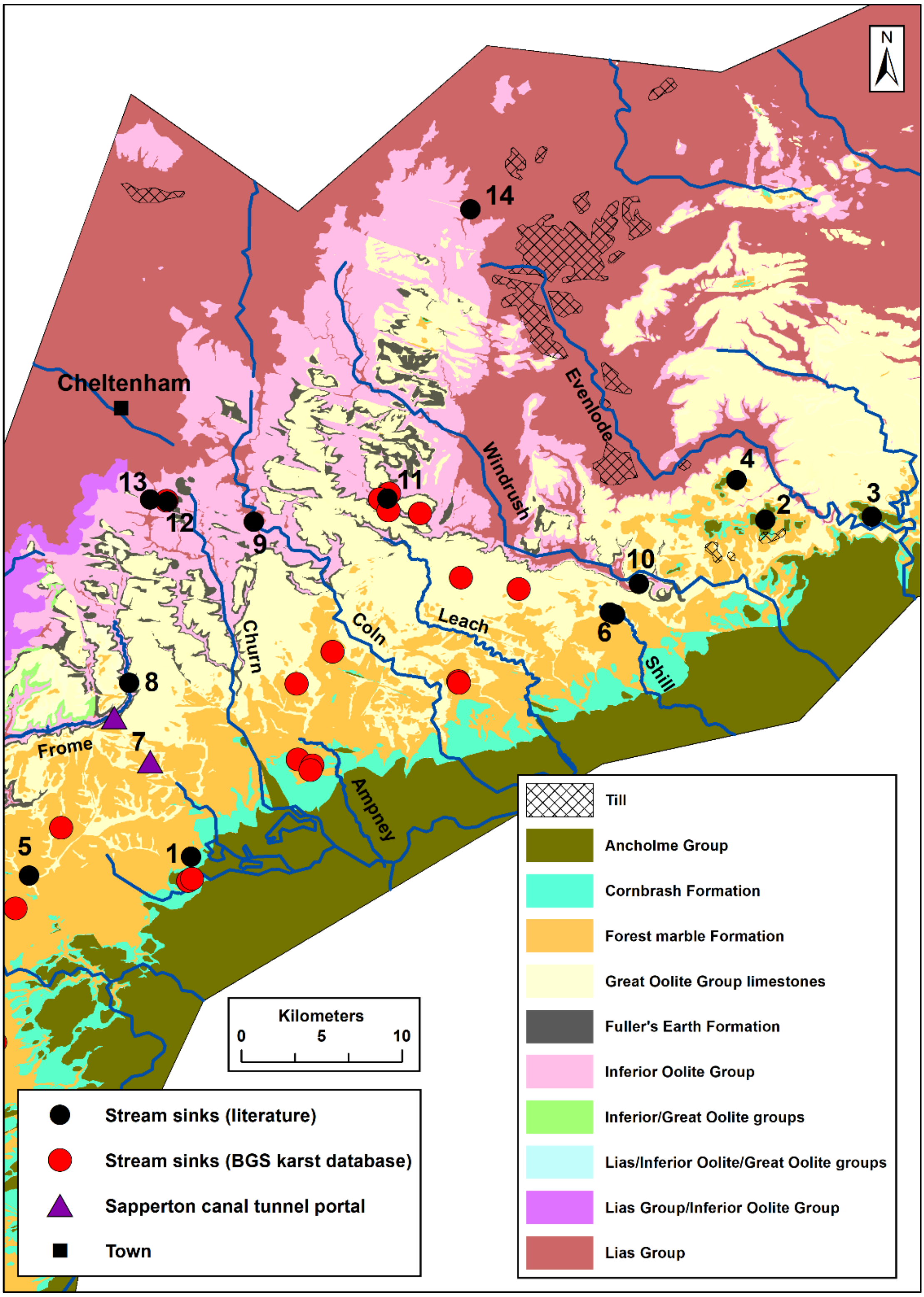

Figure 18. Stream sinks in the Central Cotswolds area.

Chippenham-Bath-Frome area

To the south of the central Cotswolds area there are some reports of stream sinks in the Great and Inferior Oolite group limestones (Figure 19). There are several areas where LiDAR data suggest that there are streams sinking into the Cornbrash Formation, for example: an area near Chippenham (locality A on (Figure 19); near Cloford to the south-west of Frome (locality B on Figure 19; and Chargrove Farm to the north of Wincanton (locality C on Figure 19). There are also sites on the Forest Marble Formation where LiDAR data suggest stream sinks may be present, for example to the south-east of Bath (locality D on Figure 19). Many of the stream sinks recorded in the Great Oolite Group to the north-east of Bristol by Smart (1977a) are also located on the Forest Marble Formation, with some sites in the limestones further down the Great Oolite Group sequence. There are also some stream sinks in the Inferior Oolite Group. In the Combe Down area south of Bath (locality E on Figure 19), MacDonald et al. (2001) report that there are streamflow losses to the Inferior Oolite group aquifer, and also suggest that “sink holes” have been mapped on the northern edge of the Combe Down plateau (no grid references or references are provided).

In this part of the J3 area, the geology is particularly complex, with some small patches of older strata interspersed with the Jurassic geologies. Stream sinks recorded in the BGS karst database and the natural cavities database at locality F on Figure 19 are at the boundary of the J3 area and in fact sink into Carboniferous aged limestones which unconformably underlie the Jurassic aged limestones in this locality (Barrington and Stanton, 1977; Stanton, 1982).

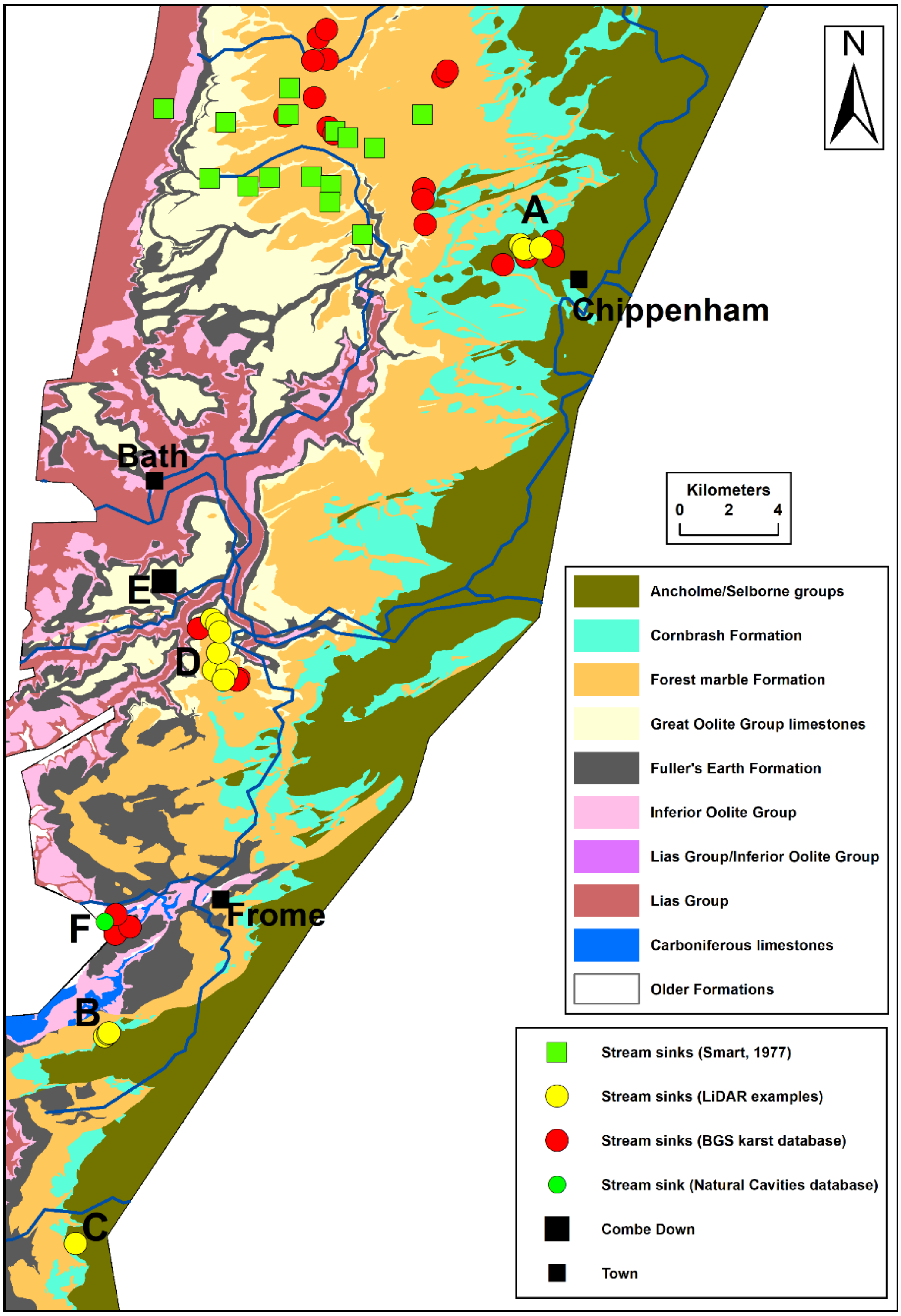

Figure 19. Stream sinks in the Chippenham-Bath-Frome area.

2.2.3 River losses

Many streams and rivers in the J3 area have substantial losses to the limestone aquifers, and these are well documented in a section on rivers in Richardson (1930a) pages 30-44, and also discussed by Richardson et al. (1946), Rushton et al. (1992), Allen et al. (1997), Owen et al. (2005), Maurice et al. (2008), Bricker et al. (2014), and Paul et al. (2018). Some rivers that are reported to have losses are labelled on Figure 17. It is quite possible that other rivers in the J3 area have losses where they cross the Inferior and Great Oolite group limestones, with the possible exception of those in the north of the area where the aquifers are overlain by glacial till deposits (Figure 17). In some cases, the river losses may be through visible sinks in the bed or sides of the river, but in many cases the sinks cannot take all the flow and therefore the sink points are not visible, being concealed beneath the water.

River losses are geologically influenced, and occur to both the Inferior and Great Oolite group aquifers. Allen et al. (1997) note that in the central and southern Cotswolds, where drainage is towards the Thames, streams that rise on the Upper Lias Group clays lose water when they cross the Inferior Oolite Group. They also suggest that although the streams in the North Cotswolds are generally gaining, there are locally losing sections, especially during low flow. Allen et al. (1997) also report recharge to the Great Oolite Group aquifer through rivers and streams as they cross the outcrop. One example is the River Leach which “disappears when it reaches the Great Oolite aquifer” at times of low water levels, and emerges downstream from springs at East Leach (Allen et al., 1997). Losses and gains on the River Leach are outlined in Goudie and Parker (1996).

The main area where river losses are reported is this central Cotswolds area where (from north to south) the River Evenlode, River Windrush, Shill Brook, River Leach, River Coln, Ampney Brook, River Churn, and River Frome are all reported to lose water to the aquifers (see Figure 17 for locations of these rivers). Paul et al. (2018) suggest that karstic features in the Cotswolds are concentrated around the valleys of the dip slope rivers; the Churn, Coln, Leach, Windrush and Evenlode, and suggest that these rivers all have sections where flow is underground in drier periods. In some cases, there are estavelles within the streambeds, for example along the River Churn and Shill Brook (Richardson et al., 1946).

In a geological report on the Farmington area, Sumbler (1995) reports that during a survey in 1993-1994 “the Sherborne Brook was intermittent, passing beneath the surface near Holy Hill Coppice [SP 114 170] and reappearing near Picket Down Plantation [SP 144 155]”. The Sherborne Brook is a tributary of the Windrush. Richardson (1930a) also reports river losses from the Windrush basin, with dry river courses where the rivers cross the Inferior Oolite Group, except in wet weather. He notes that the River Dikler disappears at Hinchwick (the BGS 1:50 000 geological map suggests that Hinchwick is on the Inferior Oolite Group).

Figure 20 shows the area around the River Churn and the River Frome, with black squares indicating the places mentioned below in the text. River losses from the River Churn have long been documented. Richardson (1930a) reported that in 1859 equivalent to approximately 130 l/s was lost to the Inferior Oolite Group aquifer, and that when the water levels are low, water can be seen “disappearing down swilly holes in the bed of the river” but when water levels rise, water can be seen “rising up through the swilly holes”. Richardson (1930a) also notes that it was previously suggested that “water that disappeared down the swilly hole near North Cerney bridge emerged at Boxwell springs at South Cerney” but that he was of the view that this was not correct and that Boxwell springs are fed by water from the Cornbrash/Forest Marble formations. He also reports that to maintain the water supply for the flour mills they used to have to go upstream as far as Rendcombe “to repair leaks in the side and bed of the river”. Further downstream, there were losses to the Great Oolite Group between Baunton and a point near Stratton. Another old account is documented by Goudie and Parker (1996) who note that Phillips (1871) reported a decrease of ~ 150 l/s to ~ 5 l/s between 5.5 miles and 14.5 miles from the source of the river.

In more recent times, substantial losses from the River Churn have been documented. Bricker et al. (2014) present flow accretion profiles under maximum and minimum flow conditions (Figure 21). These show that a substantial part of the initial flow in the headwaters is lost into the Inferior Oolite Group (with losses in high flow conditions of ~800 l/s plus the flows from two upstream tributaries). There then appears to be a big increase as the river crosses the Fuller's Earth Formation (~1900 l/s in high flow conditions), with subsequent further losses into the Great Oolite Group (~ 700 l/s in high flow conditions). These river losses are, at least in part, due to abstraction (Rushton et al., 1992). Details of the losing sections of the River Churn are also described in Maurice et al. (2008) from information in University of Birmingham (1987); Rushton et al. (1992); and Environment Agency (1997): Losing sections that are highlighted include losses to the Inferior Oolite Group aquifer between Marsden and North Cerney, and losses to the Great Oolite Group aquifer for about 1 km from where the river first reaches it around Perrotts Brook. They report that as the river crosses the Great Oolite Group from Perrotts Brook to Cirencester there are losses and gains, but in dry summers the net losses are up to 10 000 m^3/d (Rushton et al., 1992). Beyond Cirencester the river flows over the Forest Marble Formation where it loses or gains depending on the time of year, and the Dunt tributary of the Churn loses water below Daglingworth.

Maurice et al. (2008) also describe river flows and accretion profiles in the Frome catchment (Figure 20). Whilst much of the River Frome and its tributaries gain flow, Maurice et al. (2008) also discuss some losing sections from reports by Bailey (1991), Bloxham et al. (1995), and Jeremy Benn Associates (1999). In particular, swallow holes are reported in the riverbed in the upper reaches of the River Frome, with losses to the Inferior Oolite Group. Fissures in the riverbed are reported to have been previously infilled to maintain flows, but Bailey (1991) reported that swallow holes had become more frequent, suggesting that they have re-opened (or new ones developed). The precise locations of these swallow holes is not known and they could be upstream of the stream sink site at Francombe Wood Valley (Section 2.2.2) which is shown in the River Frome valley on Figure 20. Losses were also reported in the Nailsworth stream tributary of the River Frome between Hattersley and Dudbridge, and possible losses in the Holy Brook tributary.

Overall there is considerable evidence for substantial river losses to the Inferior and Great Oolite group aquifers. Descriptions of "swallow holes" in riverbeds, the large volumes involved, and the soluble nature of the ooidal limestones suggest that this recharge is feeding into networks of karstic solutional fissures and conduits. Further work is needed to establish the groundwater outlets for these point recharge inputs, and to investigate the nature of, and the controls on, the subsurface karstic networks.

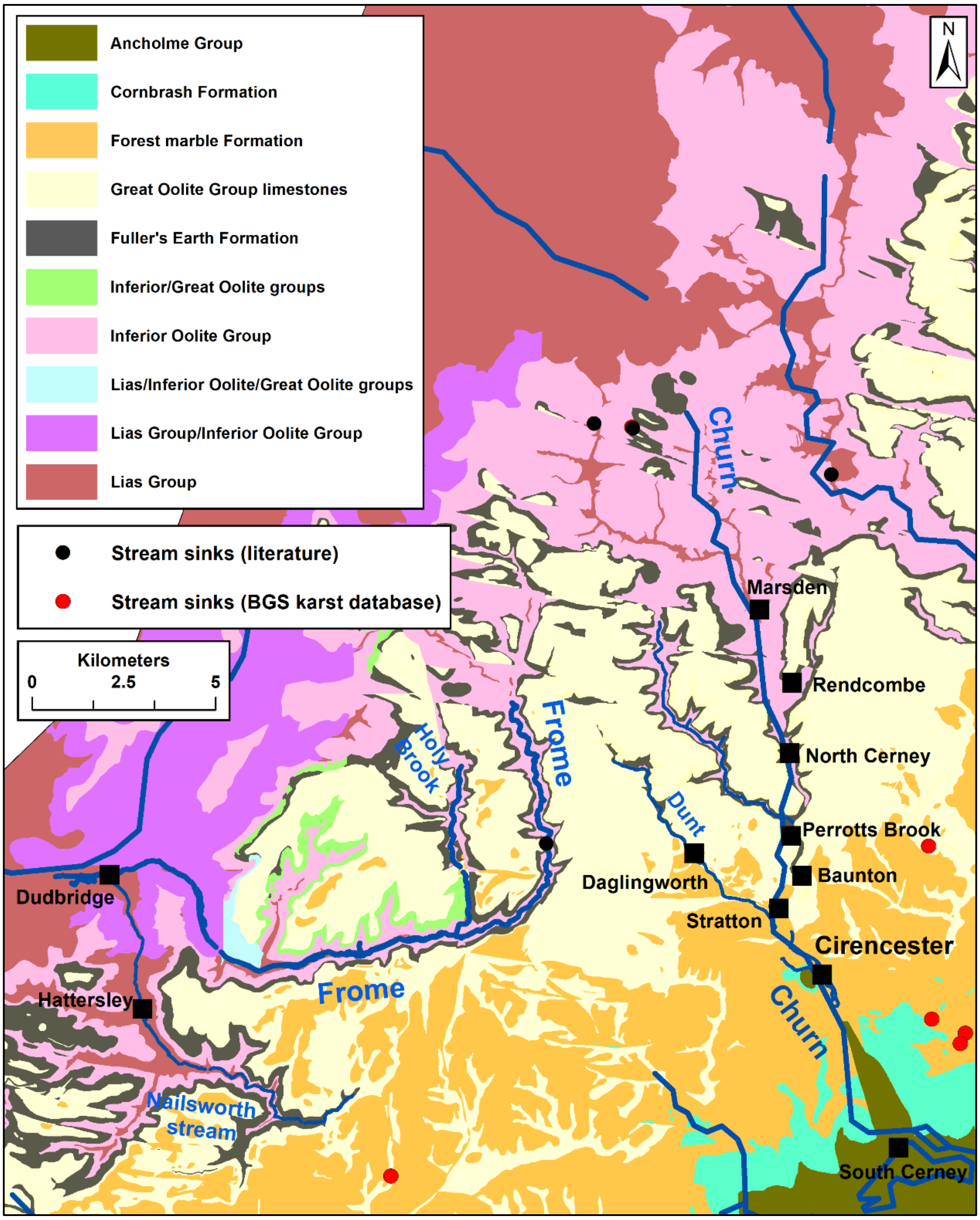

Figure 20. The area around the River Churn and the River Frome.

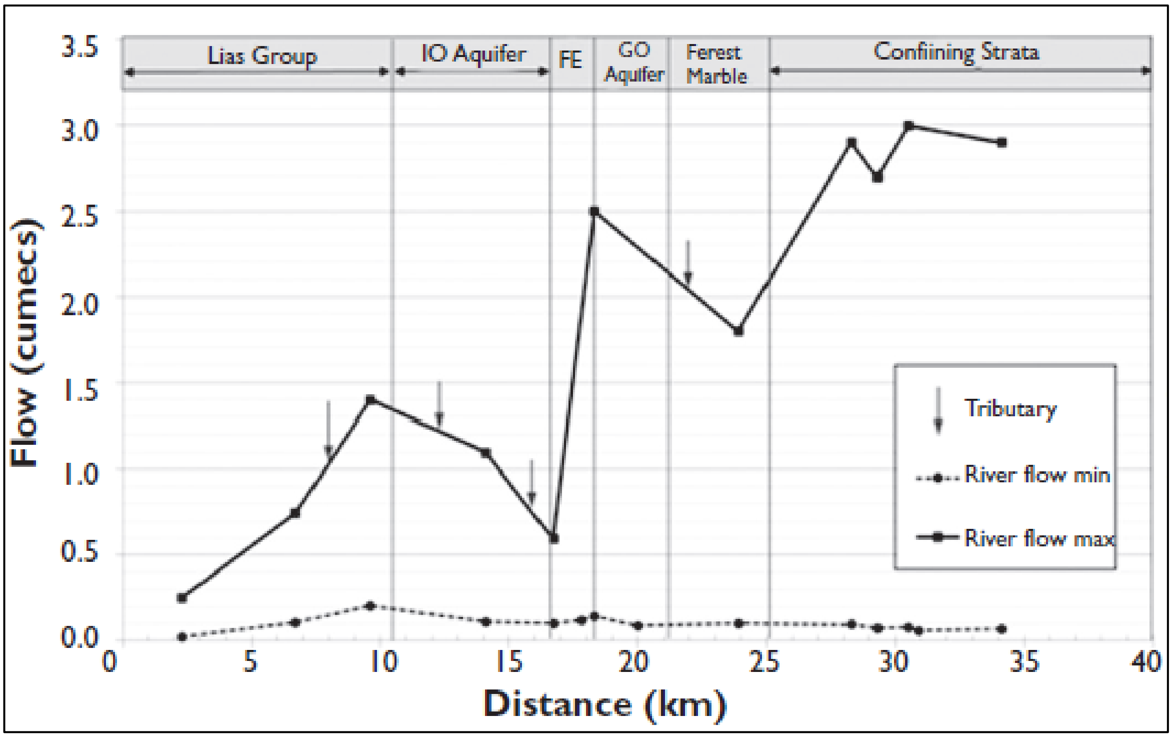

Figure 21. Accretion profile for the River Churn (from Bricker et al., 2014). River flow data © Environment Agency copyright and/or database rights 2012. All rights reserved.

2.2.4 Soakaways

One area of uncertainty concerns the amount of point recharge via anthropogenic features, which has not been assessed for this report. Drainage of unwanted runoff from roads, urban areas, and fields is disposed of via soakaways and SuDs (Sustainable Drainage systems). The volumes and flow rates entering the aquifer from such features are uncertain. Whilst these are not natural karst features, at places where there is a high infiltration rate directly into the Inferior or Great Oolite Group limestones, water may be recharging solutional fissure networks, with implications for both the potential for contaminant transport, and rapid water level responses.

MacDonald et al. (2001) report the locations of 5 soakaways in the Combe Down area, with some information on flow rates. The maximum reported flow rate is 50 m^3/day (equivalent to ~0.6 l/s of continuous discharge), and most of them are small with maximum flows of ~ 1 m^3/day (equivalent to ~0.01 l/s of continuous discharge), and therefore not indicative of well-developed solutional networks in the limestone. It is unclear whether more substantial soakaways are present in the J3 area.

2.3 DOLINES AND DISSOLUTION PIPES

There are 92 dolines recorded in the BGS karst database, predominantly from BGS field slips, or from a BSc thesis that recorded dolines in the Westonbirt area (Davidson, 1988). Recorded dolines are mostly distributed on the Great Oolite Group, in the middle of the J3 area (Figure 22). There are 30 records of “sinkholes” and “solution pipes” in the Natural Cavities database (Applied Geology Limited, 1993), of which one is only classified as a “sinkhole”, two are only classified as “solution pipes”, and the rest are classified as both. It is not clear from the information in this database whether these are dolines or dissolution pipes, but many of these features are also recorded as dolines in the BGS karst database. Goudie and Parker (1996) give locations of three surface depressions that may be karstic in origin, and Richardson et al. (1946) suggest that a “circular subsidence” to the north of Signet is related to spring outlets. The location of Barnsley is also included on Figure 22 because Allen et al. (1997) report that there are small solution features which have been broken into by tractors in the area around Barnsley and towards Winterwell. There has been no systematic survey of dolines, and the BGS karst database is not complete in the J3 area, so there are probably other dolines present. The distribution of dolines shown on Figure 22 is likely to reflect the distribution of records rather than the distribution of karst features.

There is little evidence for dissolution pipes associated with the Great and Inferior Oolite group limestones. No studies of dissolution pipes were found for this report, and dissolution pipes are not generally apparent on pictures of quarries (see examples in Section 2.1). In other areas and aquifers, dissolution pipes are often associated with unconsolidated material overlying the carbonate aquifer, and the general lack of superficial deposits in this area may mean that there are fewer of these types of features present. It is possible that there are some dissolution pipes associated with the glacial till deposits in the north-east of the area.

Overall there do not appear to have been many studies of dolines and dissolution pipes in this area and further work (including verification of existing records in the field) is needed to improve understanding of the development of dolines and dissolution pipes associated with the Great and Inferior Oolite group limestones in the J3 area. However, there do appear to be some geological situations where dolines are more likely to occur. These are associated with permeable-impermeable geological boundaries, for example those between the Cornbrash Formation and the Kellaways Formation; between the Forest Marble Formation mudstones and limestones (e.g. dolines around Hinton Charterhouse and Limpley Stoke, near point A on Figure 22); and those associated with the Fullers Earth Formation mudstone/limestone boundary (e.g. many dolines around Westonbirt Arboretum near point B on Figure 22).

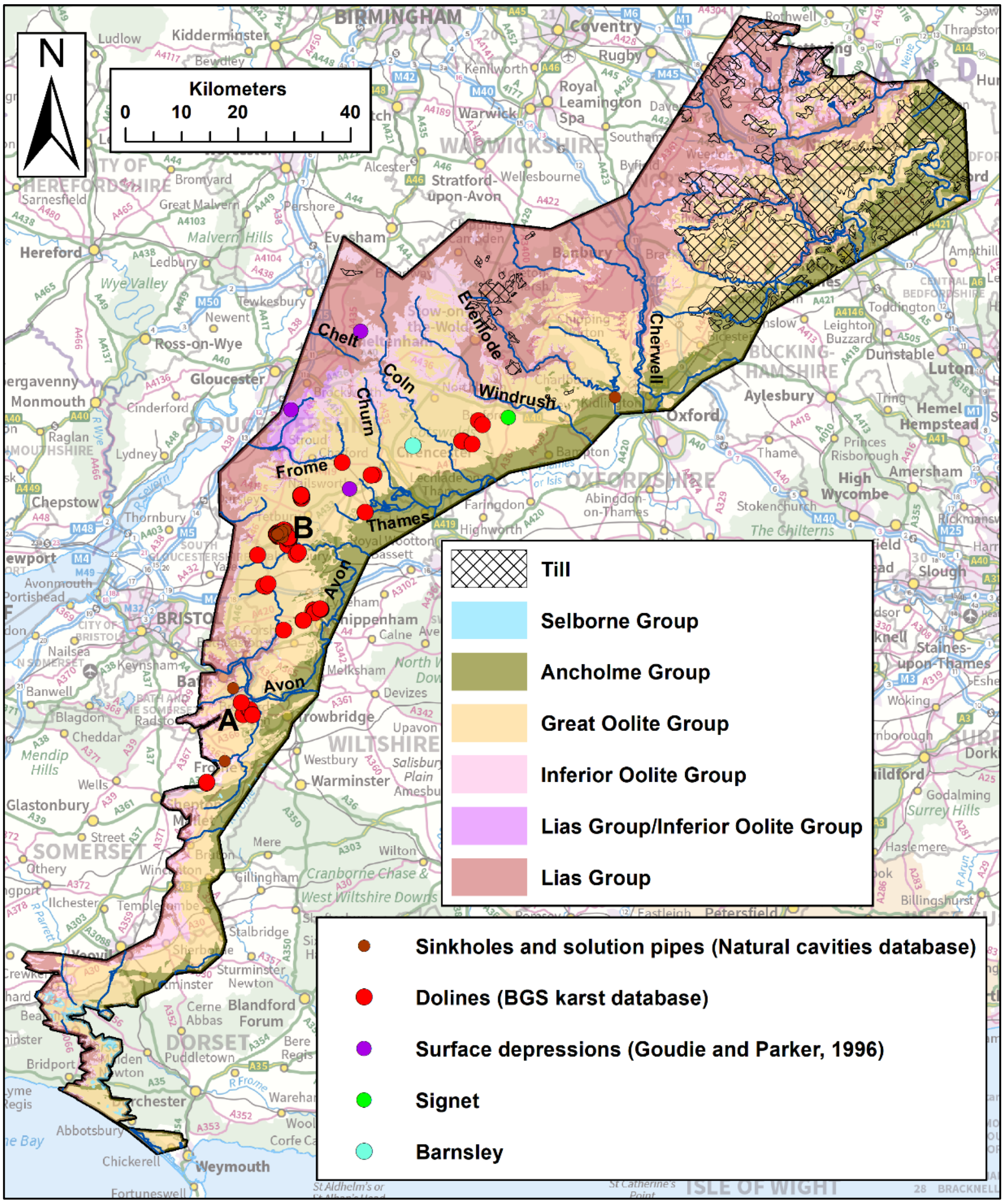

Figure 22. Dolines and dissolution pipes.

2.4 SPRINGS

2.4.1 Introduction and controls on spring distributions

There are more than 5000 springs recorded on the Inferior and Great Oolite groups in the J3 area (Figure 23). The records shown on Figure 23 mostly comprise BGS records of springs. In addition, location data from Richardson & Whitaker (1928), Smart (1977a), Morgan-Jones & Eggboro (1981), Maurice et al. (2008), Paul (2014), and from the Environment Agency were collated for this project, and are also included on Figure 23, some of which may not be in the BGS springs database. Figure 23 also includes springs on other geologies within the J3 area from the BGS springs database. Some of these may be discharging groundwater from the Inferior/Great Oolite group limestones where there is hydraulic connectivity with the overlying or underlying strata in which the springs are located. Springs in the area have been studied by Paul (2014, 2017); Paul et al. (2018); and Paul and Moore (2023), and the locations of 208 springs provided by J. Paul (personal communication, 2022) are also shown in Figure 23, where they are additional to the previously collated records. There are extremely high densities of springs throughout much of the J3 area, with particular concentrations along geological boundaries. It is likely that there are some additional springs.

The rivers in the area are predominantly spring fed and there are many detailed qualitative (and some quantitative) accounts of the river accretion profiles in the area which provide good information on gaining and losing reaches; and the locations of, and controls on, groundwater discharges (e.g. Richardson, 1930a, Rushton et al., 1992; Allen et al., 1997; Maurice et al., 2008; Bricker et al., 2014). There are geological influences on springs (Allen et al., 1997; Maurice et al., 2008; Bricker et al., 2014; Paul, 2014). Those in the Inferior Oolite Group aquifer are mostly at the base of the Inferior Oolite Group limestones, and/or within the underlying Bridport Sand Formation above the lower permeability Upper Lias Group. Springs occur in the Great Oolite Group at both the top and bottom of the formation at the junction with the overlying and underlying aquitards (Allen et al., 1997). Many are near the bottom of the Great Oolite Group at the junction between the limestones and the underlying Fuller's Earth Formation, and some of these have significant yields (Allen et al., 1997). Allen et al. (1997) also report that artesian springs from the Great Oolite Group also occur on the dip slope where water from the confined aquifer reaches the surface via faults and fissures.

Bricker et al. (2014) show the stratigraphical influence on spring locations in the Cotswold Hills area, with many more associated with the boundary between the Great Oolite Group limestones and the Fuller's Earth Formation (approximately 650), and the base of the Inferior Oolite Group aquifer (approximately 920), than in other units (generally less than 100 per unit). Bricker et al. (2014) also classify different types of springs in the Cotswolds: some that are perched (located at elevations above the groundwater levels in both the Inferior and Great Oolite group aquifers); some that are at the same elevation as the groundwater level in one of the aquifers indicating that they are discharging that aquifer; and some where the elevation is consistent with groundwater levels in both aquifers, suggesting they may be in hydraulic continuity. Bricker et al. (2014) present a map showing the distributions of these different types of springs.

Faults also appear to be an important influence on spring location, although there are very large numbers of both faults (Figure 2), and springs (Figure 23), in the area. It should also be noted that not all geological map sheets have been updated, and this also impacts on the apparent mapped distribution of faults. MacDonald et al. (2001) suggest that in the Combe Down area, WSW-ENE trending faults influence the occurrence of springs, for example the Horsecomb Vale Farm springs which are approximately located on faults. Bricker et al. (2014) show that in the northern part of the Cotswolds area there are large numbers of springs in the Inferior Oolite Group aquifer (and also many in the Great Oolite Group aquifer) that are located within 50 or 100 m of a fault (Figure 24). Bricker et al. (2014) suggest that the water discharged through these springs does not rise up along faults under artesian pressure, but that the springs are perched and discharge water that is above the main water table in the Inferior Oolite Group.

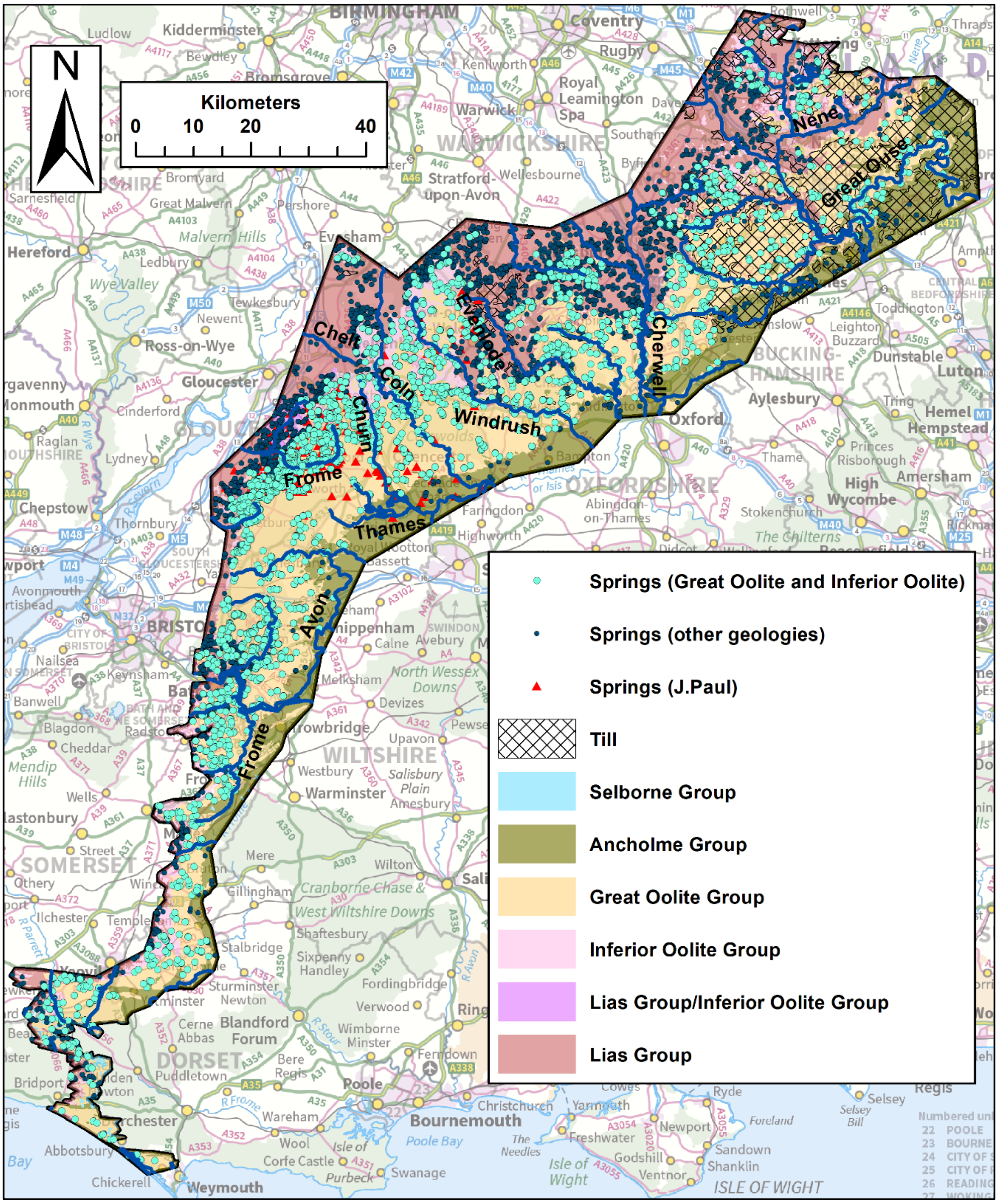

Figure 23. High densities of springs in the J3 area

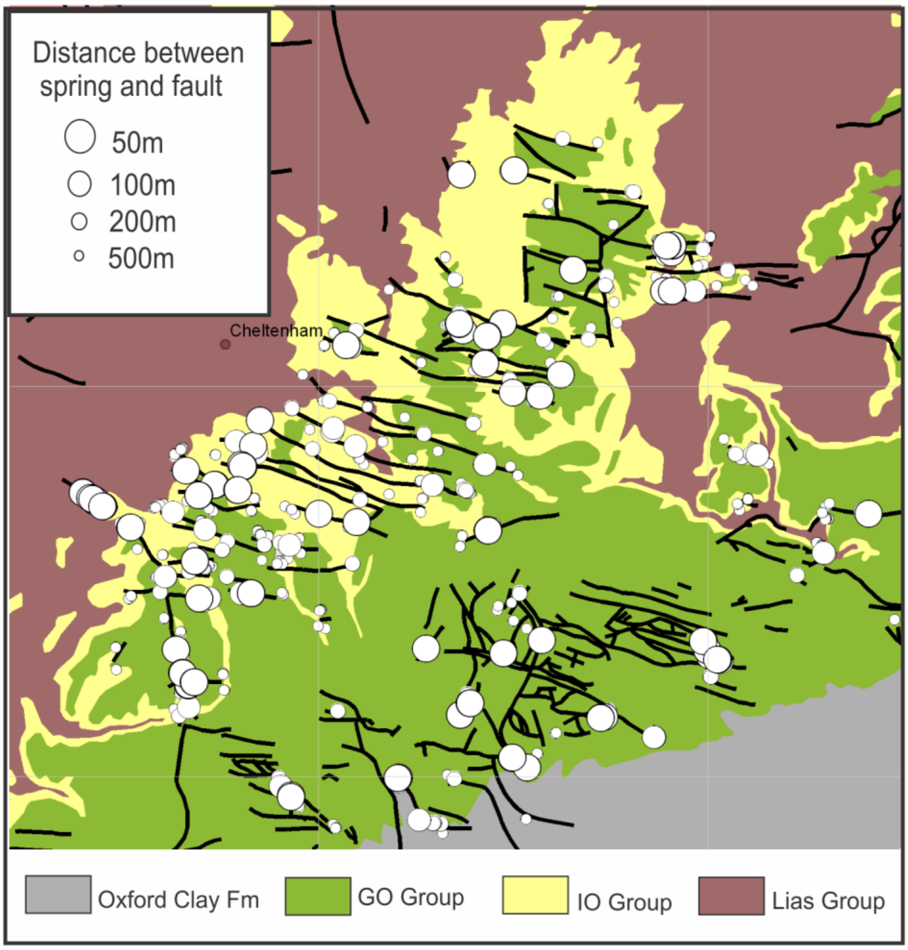

Figure 24. Springs associated with faults in the northern Cotswolds (from Bricker et al., 2014).

2.4.2 Spring discharges

In karst aquifers, where there is extensive development of solutional networks of conduits and fissures, large springs form the discharge point for these networks. Large springs in carbonate aquifers are therefore usually indicative of these karst networks. For the majority of springs recorded in this area (Figure 23) there is no easily available information on their discharge (and for most their discharge has probably not been measured). However, there is some information on spring discharges, and 31 springs have measured flows of > 10 l/s, some of which have flows of > 100 l/s (Table 2, Figure 25). Table 2 and Figure 25 also include one spring with no discharge data that is described as large by Allen et al. (1997), and Lyd Well spring at the head of the Thames which is a large ephemeral spring (Richardson, 1930a). Figure 25 also shows springs monitored in tracer tests by Smart (1977a) which are likely to be significant. The dataset on large springs is very incomplete, due to the limited data on spring discharge, and it is likely that there are many more springs with maximum flows of > 10 l/s and some with > 100 l/s. There may also be unrecorded large springs concealed within flowing river channels. For example, Paul et al. (2018) report that Goudie (1967) and Paterson (1970) discuss “continual effusive bubbling and disturbance to flow” in the River Chelt from the Inferior Oolite Group. An overview of the data on spring discharges is provided below:

Springs in the Inferior and Great Oolite group aquifers in the J3 area are described in the old geological memoirs relating to water supply/springs and wells for: Gloucestershire

(Richardson, 1930a), Warwickshire (Richardson, 1928), Worcestershire (Richardson, 1930b), Bedfordshire and North Hampshire (Woodward et al., 1909), Buckinghamshire and Hertfordshire (Whitaker, 1921), Oxfordshire (Tiddeman and Mill, 1910), and Somerset (Richardson and Whitaker, 1928); and also in some geological memoirs, for example the memoir for Moreton-in-Marsh (Richardson, 1929). The spring locations from these records were not digitised for this project as there are very large numbers of them and many are likely to be in existing springs datasets. Some spring discharges in gallons per day are recorded, especially in Richardson (1930a). Large springs with flows equivalent to more than 10 l/s were included in Table 2 where they were identified. There are also quite a few references to "large" or "powerful" or "strong" springs in these memoirs, which were not collated for this study, but are likely to be large springs with flows of more than 10 l/s. The discharge data in Richardson (1930a) included many springs with recorded flows of 1000s or 10000s gallons per day (equivalent to ~0.05 to ~0.5 l/s), suggesting that there are many of these smaller springs. This is also consistent with modern day reports of small spring discharges.

Morgan-Jones and Eggboro (1981) provide a table with details of 48 springs in the Jurassic limestones of Gloucestershire including their grid reference, flow rate, and whether they are in the Inferior or Great Oolite group aquifer. The reported flow rates range from < 0.1 l/s to 37.9 l/s.

Flows measured by Halcrow and Wessex Water between April 1994 and April 1995 at 48 springs in the Great Oolite Group aquifer and two springs in the Inferior Oolite Group aquifer in the Combe Down area of Bath are reported by MacDonald et al. (2011). Most of these springs have small flows with a maximum of a few l/s. However, four in the Great Oolite Group aquifer had larger flows of ~ 10 to 20 l/s and one in the Inferior Oolite Group aquifer had a maximum flow of ~ 25 l/s (Table 2).

Paul (2014) measured the flows of 67 small springs in the Frome valley in the central Cotswolds in December 2009 and also in summer 2010 when 22 of the sites were dry. Flows were higher in the Inferior Oolite Group aquifer (winter flow maximum 3.5 l/s and mean 0.8 l/s, n =23) than in the Great Oolite Group aquifer (winter flow maximum 1.5 l/s and mean 0.2 l/s, n =44). In a subsequent study of 25 small springs (winter flows of 0.05 to 0.71 l/s) in the Inferior Oolite Group aquifer in the same area, Paul (2017) found that the higher discharges (generally on the western side of the valley) correlated well with higher measured bedrock porosity and higher dissolved calcium carbonate, perhaps suggesting the importance of a bedrock matrix contribution to these small springs. Flow measurements were carried out at an additional 52 small springs in 2020 by Paul and Moore (2023) which had maximum flows ranging from 0.02 to 1.67 l/s.

Smart (1977a) reports three major groups of springs in the Great Oolite Group in the By Brook area to the north east of Bristol (Figure 25). These are shown in more detail in Figure 26 and comprise: the Hancocks Well to Alderton spring system to the north, the Gaulters Mill Farm springs at the head of the By Brook, and the West Kingston Springs on the Broadmead Brook; with higher springs east of Acton Turville under high discharge conditions. Measured discharges are not reported for most of these springs, but they may have maximum flows of > 10 l/s, and Smart (1977a) demonstrated that these springs are connected to karst stream sinks (Section 3). Most of these springs appear to discharge from the Chalfield Oolite Formation (Figure 26). In the context of other tracer tests at a landfill site at an unspecified location in the Cotswolds (see Section 3), Smart (1985) discusses 3 springs, including "spring 2" which was reported to have flows varying from <1 to > 50 l/s.

Maurice et al. (2008) reported spring flow observations during a field visit to the River Frome catchment (Stroud) in August 2008, although no measurements of flow were made. There had been substantial rainfall in the preceding days and several flowing springs were visited. At Cherington one spring was observed to be flowing out of a small karst conduit ~30 cm to ~50 cm wide. A very approximate visual estimate suggested the flow was ~5 l/s, with other dry spring channels indicating higher flows at other times. Springs visited in the Toadsmoor valley were visually estimated to have flows of < 5 l/s, and some had tufa deposits. Water was observed bubbling up in the field at Oakridge, even though no spring was apparent on the Ordnance Survey map at this location.

Richardson and Whitaker (1928) provide a description of the approximate position of 27 groups of springs in the Batheaston area. These either discharge from the boundary between the Great Oolite Group limestones and the underlying Fullers Earth Formation, or the boundary between the Inferior Oolite Group/Bridport Sand Formation and the underlying Lias Group. Richardson and Whitaker (1928) report some average daily discharges for some of these spring groups, including three that had average discharges of > 10 l/s which are included in Table 2. The precise locations of the larger springs are not apparent from Richardson and Whitaker (1928), and therefore the grid references in the table are approximate.

2.4.3 Spring characteristics

Classically karstic springs often have a rapid response to rainfall. There is almost no discharge time series data with which to consider the responsiveness of the Inferior and Great Oolite group aquifer springs to rainfall. Allen et al. (1997) note that "the Bath high level springs, at the base of the Great Oolite Group, increase in discharge by a factor of 15 after rain", whilst the Inferior Oolite Group "Bath Lower level springs", at the base of the Inferior Oolite Group aquifer, are much less responsive to rainfall ("varying by a factor of two"). A difference between the Inferior and Great Oolite group aquifers was also observed by MacDonald et al. (2001) in the Combe Down area near Bath: Time series flow data for the Whittaker springs in the Great Oolite Group and the Tucking Mill Springs in the Inferior Oolite Group obtained by Halcrow (1996) are presented by MacDonald et al. (2001), who report that Halcrow (1996) suggest that the Great Oolite Group spring responds to rainfall within 3 days. The data presented in MacDonald et al. (2001) are from 1994 to 1998 and vary from daily to monthly measurements. Whilst the measurement frequency is insufficient to understand the detailed response of the springs, the data suggest that the Great Oolite Group spring has a flashier response to rainfall and a lower baseflow than the Inferior Oolite Group spring. MacDonald et al. (2001) also note that there does not appear to be a significant lag between the peak in the Great Oolite Group spring and that in the Inferior Oolite Group spring, suggesting that the deeper aquifer is also responsive to rainfall. This is supported by the presence of coliforms at both springs indicating a rapid flow component (Section 4). Possible mechanisms suggested by MacDonald et al. (2001) for the rapid flow in the Inferior Oolite Group include sinks into the Inferior Oolite Group that have been mapped on the northern side of the plateau (Section 2.2), and structural features providing rapid recharge pathways.

Spring responses to pumping over long distances is also indicative of connected networks of fissures and conduits. For example, Swan springs north-east of Cirencester, which rise from the Inferior Oolite Group, responded rapidly to pumping at a borehole approximately 8 km away. During pumping, discharge in the spring was reduced by 20%, with depletion by between 20 and 22 l/s (Allen et al., 1997).

Boxwell springs near South Cerney [SU 0628 9762] are discussed by Richardson (1930a) who reports flows of 58 l/s in August 1864 during drought conditions, 59 l/s in October 1864, and 54 l/s in July 1886 when there was "some leakage from the gauge board". Richardson (1930a) reports that these springs are located near a fault. Richardson (1930a) also discusses two theories for the source of water in the springs: either water lost to the River Churn above Cirencester into the Bridport Sand Formation and Inferior Oolite Group that rises up the fault, or water from the "Cornbrash tract to the north". Richardson (1930a) thought that the second was most likely. These reported discharges might suggest that Boxwell springs have a relatively consistent flow although more data would be needed to verify this, and it is likely that many spring flows in the Inferior and Great Oolite group aquifers do have seasonal variations.

Paul (2014) suggests that there is high seasonal variation in the discharges of many of the small springs in his study.

The seasonal variation in spring flows is apparent from the large number of bournes in the area. Bourne behaviour (the migration of the riverhead) is common in streams/rivers on the Great and Inferior Oolite group aquifers (see Richardson, 1930a; Richardson et al., 1946; Allen et al., 1997; Maurice et al., 2008; Bricker et al., 2014). This is a known characteristic of karst aquifers where the capacity of a conduit/fissure network is exceeded leading to the activation of previously unsaturated conduit/fissure networks that discharge at upstream ephemeral springs, which can be some considerable distance upstream from the lower discharge point. The Ampney Brook is an example that exhibits Bourne behaviour: Bricker et al. (2014) identify four specific locations that the riverhead migrates to over a distance of very approximately 5 to 10 km (the straight-line distance in the figure in Bricker et al. (2014) is about 5 km, but the river takes a meandering route). The River Leach also migrates upstream in a similar manner (Allen et al., 1997), as does the Shill Brook (Richardson et al., 1946). The large channel of the River Frome, floored by large boulders indicating high flows, can be dry at Trellis Bridge, 15 km from its source (Paul, 2014). Another example is the By Brook where Smart (1977a) reports seasonal springs near Acton Turville.

There are also indications of the complexity of spring catchments. MacDonald et al. (2001) note that the delineation of spring catchments in the Combe Down area (for example Prior Park, Whittaker and Tucking Mill springs) is difficult due to the structural controls on flow, and also note that there are uncertainties about recharge and flow mechanisms in this area. The complexity of the aquifers is also illustrated by the Bibury springs example. Here there are significant springs which were initially thought to be from the Great Oolite Group, due to their water chemistry (Morgan-Jones and Eggboro, 1981) but which were impacted by pumping in the Inferior Oolite Group indicating that they are derived from this aquifer (Rushton et al., 1992; Allen et al., 1997). The difficulties in spring catchment delineation in the J3 area are likely to reflect the karstic nature of the aquifers, with flows determined by karstic solutional processes that result in highly heterogeneous and anisotropic flow paths, with the added complexity of faulting and the variable connectivity between the Great and Inferior Oolite group aquifers.

2.4.4 Conclusions (springs)

Overall, there is certainly evidence for karst from the characteristics of springs in both the Inferior and Great Oolite group aquifers with: some springs discharging via karstic conduits (Section 2.1.4), connectivity with stream sinks, bourne behaviour, some rapid responses to precipitation, some interactions between springs and pumping over long distances, difficulties in catchment delineation, and some springs with high discharge rates. There are few easily available spring discharge measurements, and almost no times series data. However, spring discharge data collated for this report indicate that there are springs with large discharges of 10s or 100s of l/s (Table 2). There is also evidence for large numbers of small springs, often clustered together. Whilst it is highly likely that many springs have reduced discharges due to the development of groundwater resources for supply, there do appear to be very large numbers of small springs which may never have been large. This supports the hypothesis that the aquifer includes many flow paths that discharge via springs, perhaps reflecting the highly fractured nature of the aquifer resulting in high permeability of the primary fracture network enhanced by both karstic solutional processes, and in some areas mass movement processes.

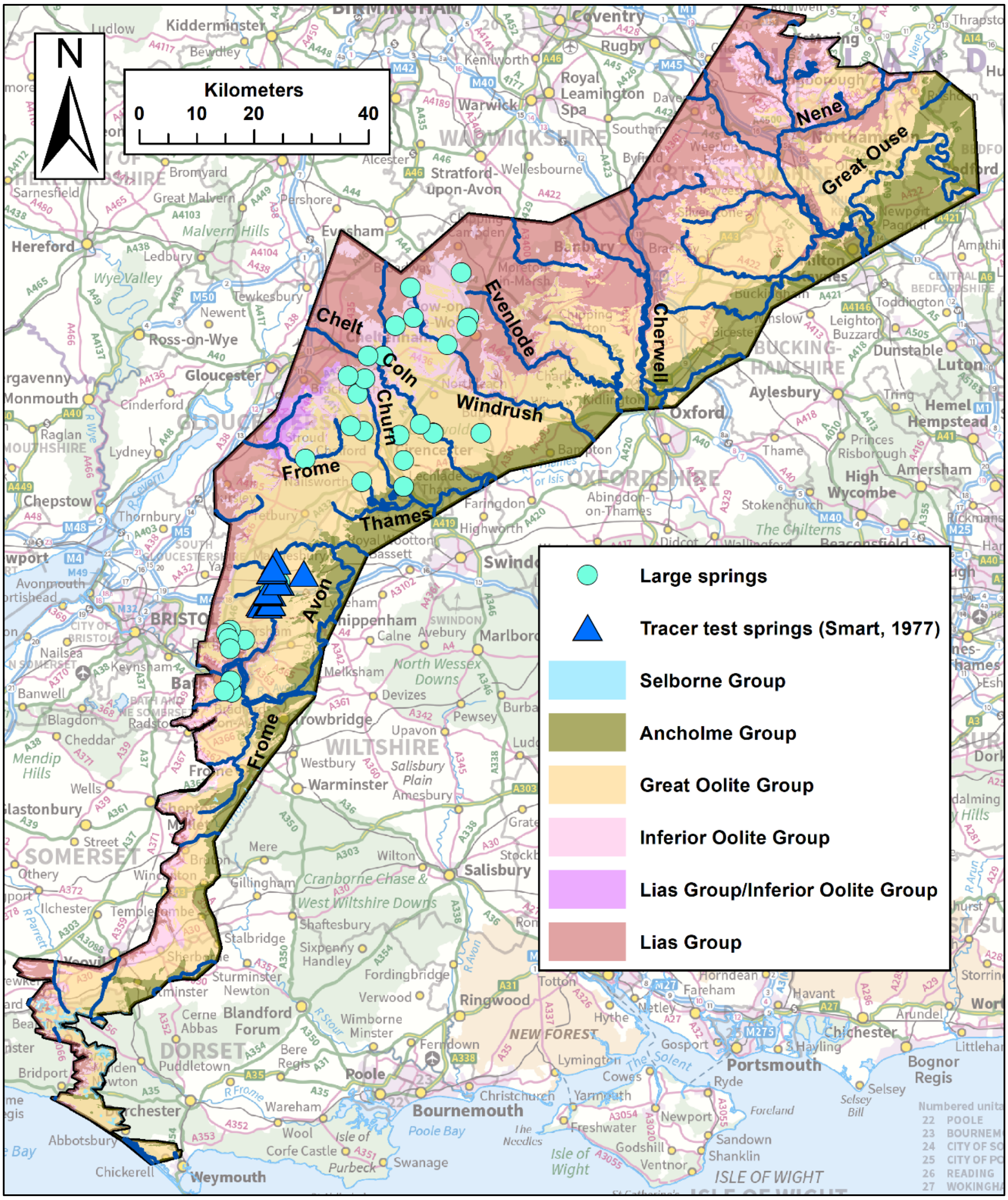

Figure 25. Large springs in the J3 area.

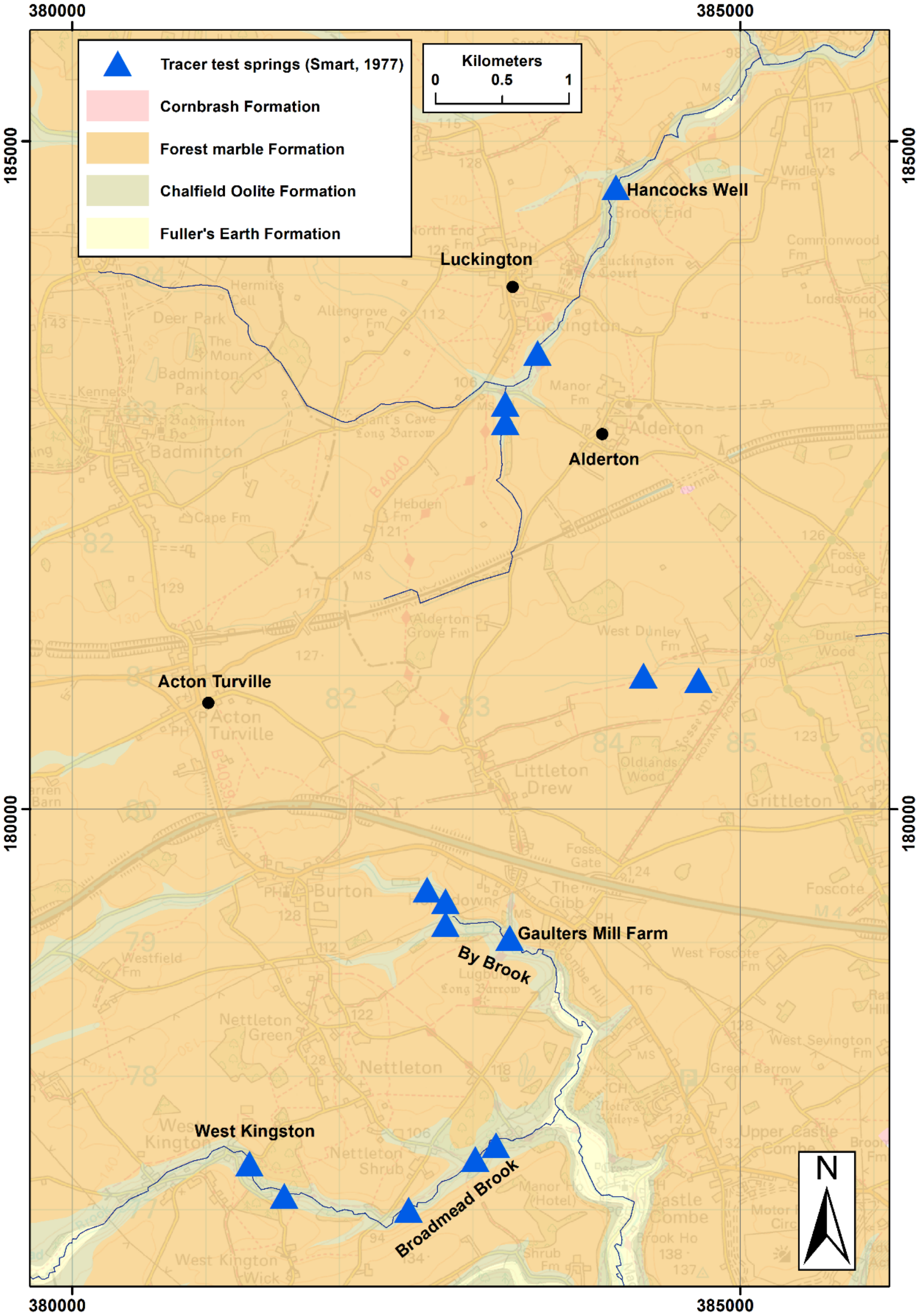

Figure 26. Springs in the By Brook area monitored during tracer tests by Smart (1977a)

Table 2. Large springs discharging water from the Inferior and Great Oolite group aquifers

Spring	East	North	Discharge (l/s)	Geology	Reference
Westbury Farm	398260	213820	10	Birdlip Limestone Formation	Morgan-Jones & Eggboro (1981)
Pinchley Cottage	399520	216450	10	Birdlip Limestone Formation	Morgan-Jones & Eggboro (1981)
Seven Springs 2	413900	222400	38	Birdlip Limestone Formation	Morgan-Jones & Eggboro (1981)
Pinnock springs	407990	227150	16	Birdlip Limestone Formation	Hydro-Logic Limited (1996)
St Kenelm's Well spring	404880	225720	19	Birdlip Limestone Formation	Hydro-Logic Limited (1996)
Stanway springs	407450	232370	10	Birdlip Limestone Formation	Hydro-Logic Limited (1996)
Syreford springs	402690	220420	158-263	Birdlip Limestone Formation	BGS Records
The Seven Springs Coberley	396610	216930	199	Birdlip Limestone Formation	BGS Records
Swan springs	411420	206990	100 -110	Taynton Limestone Formation	Allen et al. (1997)
Eastleach springs	419743	206941	N/A	Taynton Limestone Formation	Allen et al. (1997)
Chalford Springs	389150	202430	208	Birdlip Limestone Formation	Neumann et al. (2003); Maurice et al. (2008)
Bliss Mill springs, Chalford	Not reported		~ 80	Birdlip Limestone Formation?	Richardson (1930a)
Clerk's Flour Mill springs, Chalford	Not reported		~ 90	Birdlip Limestone Formation?	Richardson (1930a)
Dartley Farm	399280	207320	20	Taynton Limestone Formation	Morgan-Jones & Eggboro (1981)
Duntisbourne	397000	208210	10	Taynton Limestone Formation	Morgan-Jones & Eggboro (1981)
Gaulters Mill Springs	382805	179170	8-15	Chalfield Oolite Formation	Smart (1977a)
St Catherine's and Oakford valleys	378590	170840	33	Lias Group/Inferior Oolite Group boundary	Richardson & Whitaker (1928)
Bulls Hill, Whiteway, and Monkswood springs	375744	171109	30	Lias Group/Inferior Oolite Group boundary	Richardson & Whitaker (1928)
Batheaston springs	376000	169300	23	Fullers Earth Formation/Chalfield Oolite Formation	Richardson & Whitaker (1928)
Boxwell springs	406284	197629	~ 50-60	Cornbrash Formation	Richardson (1930a)
Chelt headwaters	400061	220407	Average ~ 44	Birdlip Limestone Formation	Richardson (1930a)

Ampney springs	406292	202196	~500-1500	Forest Marble Formation	Richardson (1930a)
Winterwell	405482	206584	~150	Great Oolite Group	Richardson (1930a)
Whittaker spring	376199	162098	<5 to > 30	Great Oolite Group	MacDonald et al. (2001)
Tucking Mill spring	376300	161700	<10 to >25	Inferior Oolite Group	MacDonald et al. (2001)
Prior Park V	376110	163760	22.9 (max)	Great Oolite Group	MacDonald et al. (2001)
Valley spring III	374934	161975	10	Great Oolite Group	MacDonald et al. (2001)
Upper Swell	417600	227050	> 50	Birdlip Limestone Formation?	BGS records
Lower Swell	417300	225580	~ 20	Birdlip Limestone Formation?	BGS records
Blockley	416290	234980	minimum 17	Birdlip Limestone Formation?	BGS records
Bibury	411467	206942	~ 50 but also reported to be larger than Ampney springs	Inferior and Great Oolite?	Richardson (1930a)
Winson	409167	208519	Equal to Bibury springs	Fuller's Earth Formation	Richardson (1930a)
Lyd Well	398974	198487	Large spring	Great Oolite Group	Richardson (1930a)
Spring 2	n/a	n/a	<1 to > 50	Great Oolite Group	Smart (1985)

3 Tracer tests

There has generally been very little tracer testing conducted in much of the J3 area. However, extensive tracer testing was undertaken by Peter Smart in the southern Cotswolds from stream sinks (Smart, 1977a); and at an undisclosed location in the Cotswolds at a landfill site (Smart, 1985).

The tracer tests by Smart (1977a) were in the By Brook catchment in the southern Cotswolds 12 km east of Bristol (Figure 25). The By Brook is a tributary of the Bristol Avon. The tracer tests proved 29 separate connections, with 27 "stream sink to spring" pathways and two "borehole to spring" pathways (Figure 27; Table 3). The pathways are within the Chalfield Oolite and Forest Marble formations of the Great Oolite Group (Figure 27). Smart (1977a) notes that there are many streams on the Forest Marble Formation which sink into the Great Oolite Group limestones, and that springs are located at the boundary with the underlying Fuller's Earth Formation where the dip surface is dissected by deep river valleys. The specific breakthrough curve and velocity data are only presented for the connection between Nettleton Sink 1 and Gaulter's Mill Springs (Table 3) and demonstrated a groundwater flow velocity of 4000 m/day over a distance of 1 km, based on the time to peak tracer concentration. The tracer recovery for this test was 30%. More generally, velocities based on time to peak concentration for 22 of the pathways ranged from 0.24 to 5.18 km/day, with a mean of 2.03 km/day, and velocities based on first arrival of tracer were up to 10 km/day (Peter Smart, personal communication, 2018). There was some extensive tracer breakthrough curve tailing. For example, Smart (1977a) reports that along a 1 km flow path, time to tracer arrival and peak were very rapid, but tracer continued to be discharged for 51 days, indicating dispersion/diffusion within the aquifer. Velocities based on last detection times for 17 connections ranging from 0.02 to 0.4 km/day, with a mean of 0.15 km/day (Peter Smart, personal communication, 2018). Tracer recoveries for many of the tests are shown in Table 3, and are high. They range from 5 to 95 %, with a mean recovery of 43 %. The tracer losses are likely to be due to dilution to below detection in the dye tail (Smart, 1977a). Distances from injection sites to tracer outputs range from approximately 0.8 to approximately 5.2 km. Smart (1977a) notes that with the large (15 m) groundwater level fluctuations in the area, the groundwater divides vary under high and low flow conditions, impacting tracer results from tests carried out under different flow conditions. Overall, the tracer tests indicate very rapid groundwater flow over long distances, with tracer recovered at multiple outlets over a very wide area indicating an extensive and complex karstic network, whilst tailing in the breakthrough curves and some tracer losses suggest dispersion/diffusion between the main conduits and the smaller fractures and fissures. These characteristics are similar to the karstic development observed in the Chalk (Farrant et al., 2021, Maurice et al., 2021).

The tracer tests reported by Smart (1985) were conducted at an unspecified landfill location in a quarry in the Great Oolite Group somewhere to the north of the tests reported in Smart (1977a). Seven tracer tests were conducted with the aim of confirming leachate contamination of a spring, determining the on-site hydrology of the landfill, and assessing the regional groundwater flow. The first two tests aimed to confirm leachate contamination of a spring ("Spring 2") a little under 1 km from the landfill site, located near the boundary between the Great Oolite Group limestones and the underlying Fuller's Earth Formation. Dye tracer injected into the quarry sump where a small flow was entering the limestone aquifer was detected 12 hours later at the spring, with a peak concentration 45 hours after injection; the test proving a direct rapid connection in the Great Oolite Group between the landfill site and Spring 2. In the second test, a hole was dug in the landfill material with water that was pumped into it soaking away rapidly. Dye injected here took 30 hours to arrive at Spring 2, proving the landfill leachate as the source of contamination at the spring. This and two further dye tracer tests at the landfill site were also used to determine the on-site hydrology and connections between the different parts of the site/waste. The final three tests were undertaken to investigate the regional groundwater flow: water discharged at Spring 2 sinks into the Inferior

Oolite Group, and the fifth test was an injection into this natural sink point, with monitoring at 19 springs in the valley within the Inferior Oolite Group/Bridport Sand Formation. No tracer was detected and the second test was a repeat injection with an increased quantity or tracer, which resulted in low levels of dye at some of the spring sites several weeks after injection. The final (seventh) tracer test was from a “field sink” in the Inferior Oolite Group which also resulted in low levels of dye (near to the detection limit) at several springs with travel times of between 2 and 5 weeks.

The only other reference to a tracer test in the J3 area that has been found for this study is reported in Allen et al. (1997). They suggest that a tracer put into the River Churn was detected at a borehole at Baunton within minutes, but no further details are available.

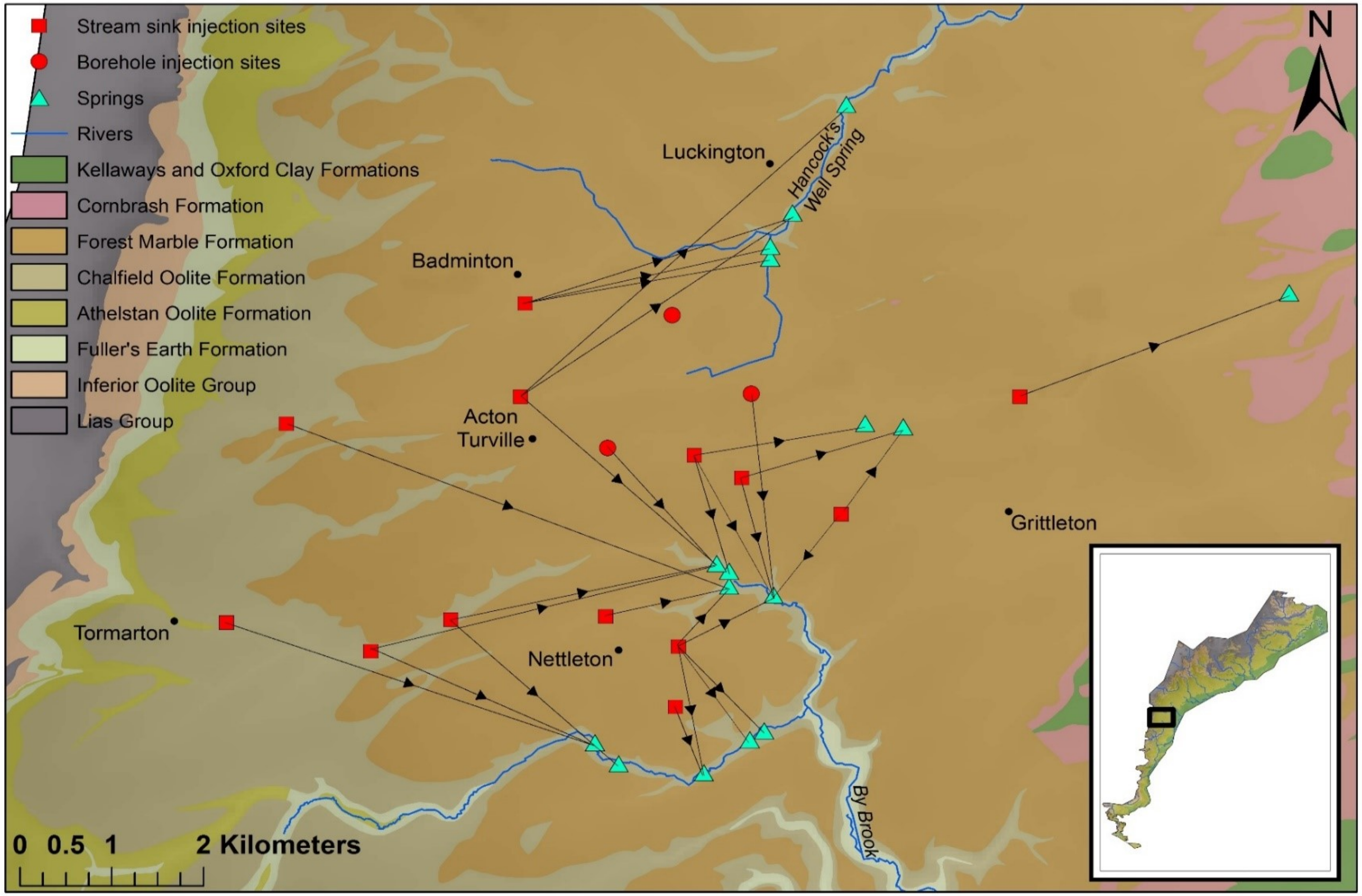

Figure 27. Tracer test locations and pathways identified by Smart (1977a).

Table 3. Tracer tests by Smart (1977a) in By Brook catchment, south Cotswolds. Velocity is based on time to peak tracer concentration.

Author	Input	Output	Input type	Distance	Velocity	Recovery
Smart (1977a)	Nettleton Sink 1	Gaulters Mill Springs	Stream sink	1000 m	4000 m/day	30 %
		Horsedown Spring 1	Stream sink	880 m	N/A	N/A
		Nettleton Spring 1	Stream sink	1470 m	N/A	N/A
		Nettleton Spring 2	Stream sink	1320 m	N/A	N/A
		Nettleton Spring 3	Stream sink	1340 m	N/A	5 %
	Nettleton Sink 2	Nettleton Spring 1	Stream sink	820 m	N/A	N/A
	Tormarton 1	Horsedown Spring 1	Stream sink	5170 m	N/A	55 %
	Tormarton 2	West Kington Spring 1	Stream sink	4250 m	N/A	67 %
	Badminton	Luckington Spring 1	Stream sink	2720 m	N/A	95 %
		Luckington Spring 2	Stream sink	2750 m	N/A	N/A
		Luckington Spring 3	Stream sink	3090 m	N/A	5 %
	Acton Turville Sink	Luckington Spring 3	Stream sink	3640 m	N/A	N/A
		Hancock's Well	Stream sink	4880 m	N/A	30 %
		Horsedown Spring 3	Stream sink	2870 m	N/A	70 %
	Kington Down 1	Horsedown Spring 3	Stream sink	3900 m	N/A	11 %
		West Kington Spring 1	Stream sink	2660 m	N/A	60 %
	Kington Down 2	Horsedown Spring 3	Stream sink	2970 m	N/A	60 %
		West Kington Spring 2	Stream sink	2470 m	N/A	20 %
	Burton	Horsedown Spring 1	Stream sink	1390 m	N/A	70 %
	Littleton Drew 1	Horsedown Spring 2	Stream sink	1380 m	N/A	50 %
		Gaulters Mill Springs	Stream sink	1820 m	N/A	N/A
		West Dunley Farm Spring	Stream sink	1900 m	N/A	30 %
	Littleton Drew 2	Gaulters Mill Springs	Stream sink	1390 m	N/A	30 %
		Brimsol Springs	Stream sink	1850 m	N/A	40 %
	Oaklands Wood	Gaulters Mill Springs	Stream sink	1190 m	N/A	75 %
		Brimsol Springs	Stream sink	1210 m	N/A	10 %
	West Dunley Farm	Hullavington Springs	Stream sink	3170 m	N/A	N/A
	Alderton Grove Farm	Gaulters Mill Springs	Borehole	2320 m	N/A	65 %
	Acton Turville Well	Horsedown Spring 3	Borehole	1780 m	N/A	23 %

4 Other hydrogeological evidence of karst

Transmissivity can provide an indication of karstification because more extensive networks of solutional fissures and conduits have higher transmissivity than unmodified fracture networks. Higher transmissivity in karst aquifers may also occur due to connectivity with permeable unconsolidated aquifers, but this is generally not likely in the J3 area except where the Bridport Sand Formation contributes to the Inferior Oolite Group aquifer. The Inferior and Great Oolite group limestones are very highly fractured and therefore may have a higher transmissivity within the primary fracture network than many karst aquifers. The transmissivity of this primary fracture network is uncertain, but it is probable that at least for higher transmissivities of more than 1000 m^2/day (and possibly for transmissivities of 100s m^2/day) solutional networks are required to produce the transmissivity; and in general, it is likely that the higher the transmissivity the more extensive the solutional networks are.

The distribution of transmissivities is shown in Figure 28. These data are the best "locality" estimates of transmissivity from the BGS national aquifer properties database (Allen et al., 1997). At many sites there are multiple estimates of transmissivity, either because pumping tests were carried out on different boreholes, or because multiple tests were carried out on the same borehole. For each test, the most appropriate value of transmissivity was determined (based on factors such as the length of the test), and then a site value (incorporating all tests within 100 m) was determined by selecting the most reliable test result (Allen et al., 1997). The maximum and minimum transmissivity values are also available, and there are several sites in this area where the maximum value was > 1000 m^2/day whilst the "locality" estimate was not. Whilst the "locality" values may generally be the most useful, in considering karst, the maximum values may also be of some interest at localities with multiple boreholes, because some of the between borehole variation may be due to karstic heterogeneity, and the maximum value may indicate where karst is important.

It is apparent that although there are some sites with high transmissivities of > 1000 m^2/day, many sites have lower transmissivity (Figure 28). In some areas low transmissivity is thought to be due to the small saturated thickness of the aquifer (Allen et al., 1997). The data on Figure 28 are not separated into the Inferior and Great Oolite group aquifers, and many boreholes on the Great Oolite Group abstract from the underlying Inferior Oolite aquifer. Transmissivities in the Cotswolds area are reported to range from 4 to 5900 m^2/day (geometric mean 212 m^2/day) for the Great Oolite aquifer, and from 3 to 11000 m^2/day (geometric mean of 139 m^2/day) in the Inferior Oolite aquifer (Allen et al., 1997), suggesting fairly similar transmissivities for the two aquifers. In the area to the north, transmissivity of the Great Oolite Group ranged from 0.5 to 2800 m^2/day; whilst in the Wessex area to the south, transmissivity ranged from 57 to 1400 m^2/day (Allen et al., 1997).

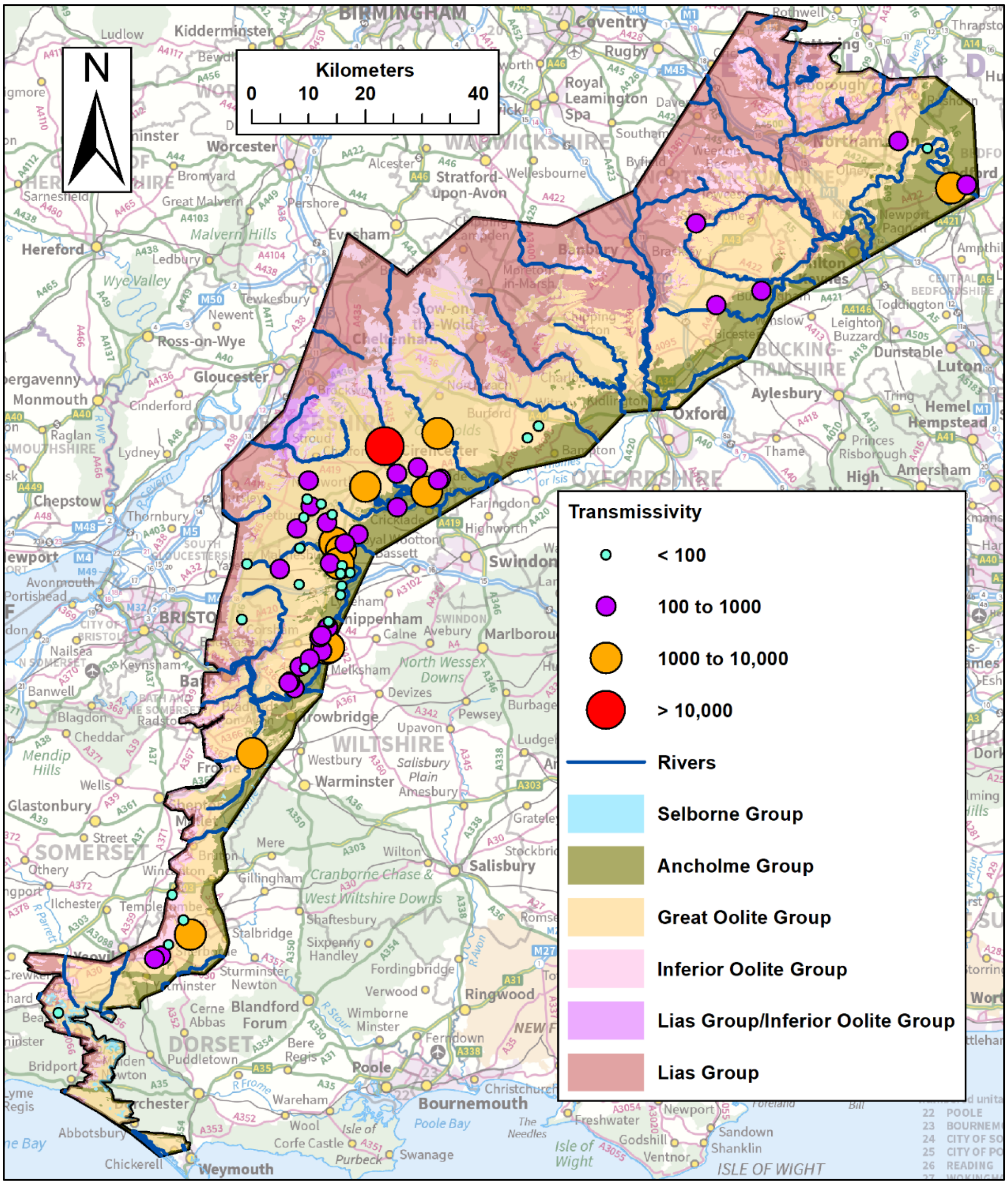

Figure 28. Best locality values of transmissivity (m^2/day) in the Inferior and Great Oolite aquifers from the BGS aquifer properties database.

The hydrogeology of the Great and Inferior Oolite group aquifers in southern England is described in detail by Allen et al. (1997) with particular emphasis on the Cotswolds, and some information on the area to the north, and the Wessex area of Inferior Oolite Group limestones in Somerset to the south. In this report, there are many indications of karstic behaviour of the aquifer and the extensive nature of the networks supplying abstractions including: (1) strong connectivity between abstractions from the Inferior Oolite Group and rivers (e.g. at Baunton, Meysey Hampton and Bibury); (2) impacts from pumping over an extensive area. For example, pumping 10,000 m^3/day (~115 l/s) from the Inferior Oolite Group at Meysey Hampton impacted springs at Bibury more than 8 km away, causing a 20% (1700 to 1900 m^3/day or ~ 20 l/s) reduction in flow. Another example is given in the Inferior Oolite Group in the Wessex area where abstraction at Lake near Sherborne affected another borehole over a kilometre away; (3) high heterogeneity in the Great and Inferior Oolite group aquifers with drawdowns due to pumping unrelated to yield or distance (e.g. abstractions near Sherborne that had no impact on sites 20 m away); (4) rapid responses of groundwater levels to rainfall (e.g. at the Royal Agricultural College borehole at Cirencester, and in the Inferior Oolite Group at Baunton); (5) evidence for conduit/fissure network control of water levels. For example sites where the water level never exceeds a particular level (e.g. at Ampney Crucis, Hampton Field Barn, and Westonbirt School), or sites where the water level never falls below a particular level (e.g. Coln St Aldwyn); (6) flow in the aquifers from a small number of solutional horizons (e.g. at Meseyhampton in the Great Oolite Group 65% of the 57 l/s that was pumped came from fractures at 74-76 m, and in the Inferior Oolite Group 80-95% of the 29 l/s that was pumped came from fractures at 130-132 m; (7) high yields (e.g. > 89 l/s from the Inferior Oolite Group at Lake near Sherborne in the Wessex area).

Information in other reviews and studies of the hydrogeology of the area also provide similar evidence for the karstic nature of the aquifer (e.g. Morgan-Jones and Eggboro, 1981; Rushton et al., 1992; Maurice et al., 2008; Bricker et al., 2014). Many note the rapid response of the Inferior and Great Oolite group aquifers to rainfall (Smart, 1977a; 1985; Rushton et al., 1992; Bricker et al., 2014). Richardson (1930a) describes Lyd Well in the Great Oolite Group at the head of the River Thames near Kemble, which flows for much of the year. He notes that "as the water table rises the water boils up out of Lyd Well in increasing velocity and volume, and springs break successively higher up the valley".

There are several reports of high yielding abstractions including 300 l/s (Rushton et al., 1992) and 324 l/s (Morgan-Jones and Eggboro,1981) in the Great Oolite Group at Latton; 115 l/s in the Great Oolite Group at Meyseyhampton (Rushton et al., 1992); ~140 l/s (Rushton et al., 1992) and 101 l/s (Morgan-Jones and Eggboro, 1981) in the Great Oolite Group at Ashton Keynes; and ~70-80 l/s from the Inferior Oolite Group at Baunton and Bibury (Morgan-Jones and Eggboro, 1981). Cave et al. (1977) report abstraction licenses of 110 l/s at Long Newnton from the Inferior Oolite Group aquifer, and 132 l/s at Shipton Moyne (from both the Inferior and Great Oolite group aquifers). These abstractions are approximately 6 km north-west of Malmesbury. Such high yields are likely to be indicative of extensive networks of solutional fissures and conduits.

Groundwater catchments do not appear to coincide with surface water catchments; for example, flow in the Great Oolite Group aquifer in the Upper Thames catchment is thought to supply the Inferior Oolite Group aquifer in the Frome catchment to the west and north-west where there are large increases in flow where the river crosses the Inferior Oolite Group outcrop which cannot be accounted for by the small recharge area of the Inferior Oolite Group (Rushton et al., 1992; Maurice et al., 2008).

Dry valleys and misfit streams are very common in the Cotswolds (Owen et al., 2005), and are likely to occur because of the reduction of surface drainage following the development of permeable solutional networks in the Great and Inferior Oolite group limestones (Paul, 2014). Owen et al. (2005) include karstic landforms in their overview of Geodiversity in the Cotswolds, noting that dry valleys are one of the most common karst features.

The vulnerability of the Inferior and Great Oolite group aquifers in the Cotswolds area which is illustrated by tracer tests (Section 3) is also highlighted by Neumann et al. (2003). They present the Environment Agency vulnerability map, and note that the area has high vulnerability due to the limited potential for attenuation in the soil zone, as well as fissures in the Interior and Great Oolite group limestones enabling rapid flow to the saturated zone.

Water quality data indicating rapid groundwater flow have not been systematically reviewed for this report. However, some water supply springs in the area have some bacterial contamination indicating a rapid groundwater flow component. For example, at two groundwater sources in the Jurassic ooidal limestones in the J3 area (with confidential locations) coliforms were present in ~40 and ~66 % of samples (~ 330 samples per site in 2010 to 2016), whilst at two other springs they were present in ~ 7 % of samples (231 samples per site in 2010 to 2016). In the Combe Down area, MacDonald et al. (2001) report bacteriological contamination of Whittaker springs in the Great Oolite Group and Tucking Mill springs in the Inferior Oolite Group. They report higher levels of contamination in the Great Oolite Group springs (mean coliform counts of 78.5/100 ml) than the Inferior Oolite Group springs (mean coliform counts of 2.7/100 ml). The maximum count in the Great Oolite Group springs was > 300/100 ml, whilst in the Inferior Oolite Group springs it was 110/100 ml, although there were more samples in the Great Oolite Group springs (96) than in the Inferior Oolite Group springs (19). In a study of the use of fluorescence spectroscopy for identifying bacteriological contamination of groundwater, Sorensen et al. (2018) investigated a spring source in the Jurassic ooidal limestones near Bath. The Inferior Oolite Group outcrops in the sides of the valley suggesting that the springs are from these units. This spring source is impacted by bacteriological contamination with episodic occurrence of E. Coli contamination in 12% of samples, indicating at least some component of rapid flow at this spring. Cave et al. (1977) suggest that the Inferior Oolite Group supplies in the Malmesbury geological sheet area are also impacted by bacteriological contamination, although no specific locations are discussed.

Overall, hydrogeological work in this area suggests that limestones in both the Great and Inferior Oolite groups are karstic in nature with solutional development of the high-density primary fracture network. In some places, as well as enlargement of fractures by dissolution, the enlargement of fractures by cambering may contribute to permeability (e.g. in the Frome area, Paul et al., 2018). The high permeability of the aquifers may result in thinner saturated zones, as there are highly permeable pathways allowing drainage down through the unsaturated zone (with extensive vertical fissures observed in quarries, see Figure 3 and Figure 4). The aquifers appear to comprise extensive networks of solutional fissures and conduits which result in high transmissivity, some high yielding abstractions and springs with high flows, stream sinks and river losses, and rapid aquifer responses to rainfall. Faults and stratigraphical inception horizons both seem to exert controls on these solutional networks. The very high densities of small springs and the high degree of fracturing suggest that there are many flow paths enlarged to a small degree rather than a small number enlarged to form cave networks. Given the impact of karst on these aquifers, consideration of karst in groundwater management and modelling is likely to be beneficial, together with the development of karst specific methods for groundwater protection.

5 Summary

- There is strong evidence for karst in the Inferior and Great Oolite group aquifers of southern England.
- Few caves are recorded, but smaller conduits have been observed and solutional fissures are common. Further work is needed to determine the extent of conduit development.
- There is little evidence for dissolution pipes associated with the Inferior and Great Oolite group limestones, which may be due to the lack of unconsolidated cover in much of the area.
- There are records of dolines, although the dataset is incomplete, and there has been little work on dolines in this area.
- Small karstic stream sinks are common in some areas, and may be present in others as there has been no systematic survey.
- Rivers exhibit highly karstic characteristics, with substantial losses where they cross the Inferior and Great Oolite group limestone outcrops, sometimes with very high losses of 100s l/s and sometimes with losses via distinct karstic "swallow holes".
- Rivers are spring-fed, often by large springs, and many rivers show classic karstic bourne behaviour.
- Over 5000 springs are recorded in the Great and Inferior Oolite group limestones. There is a strong geological control with springs commonly at the base of the Inferior Oolite Group aquifer, associated with the Fuller's Earth Formation in between the two aquifers, or at the top of the Great Oolite aquifer; and many springs that appear to be associated with faults.
- There are limited spring discharge data, but 32 springs have reported flows of > 10 or > 100 l/s, and it is very likely that there are many more large springs, as well as springs that have greatly reduced flows since the exploitation of groundwater resources for supply. There are also large numbers of small springs that have maximum flows of ~ 1 l/s or less.
- Tracer tests by Smart (1977a) in the By Brook catchment proved 29 connections between stream sinks and springs or boreholes and springs, over distances ranging from ~0.8 to ~5.2 km, demonstrating very rapid groundwater flow. Velocities based on first arrival of tracer were up to 10 km/day. Velocities based on time to peak were 0.2 to 5.2 km/day (mean = 2.03 km/day). Recoveries were high (ranging from 5 to 95 % (mean = 43 %).
- Tracer tests by Smart (1985) demonstrated rapid flow from a quarry sump at a landfill site to a spring a little under 1 km away.
- Other hydrogeological evidence of karst includes: some high transmissivities, some high borehole yields, rapid aquifer response to rainfall, and responses to pumping over long distances.
- The Great and Inferior Oolite group aquifers appear to comprise extensive networks of solutional fissures and conduits, with many flow paths enlarged to a small degree, rather than a small number enlarged to form cave networks.
- Given the extensive evidence for karst in the Inferior and Great Oolite group aquifers, a karst specific approach to Source Protection Zone delineation is likely to be useful.
- Further investigation of karst (e.g. investigations of dolines, stream sinks, spring discharges, tracer tests, water quality indicators of rapid flow) would enable improved conceptualisation of the karstic nature of the Inferior and Great Oolite group aquifers and would be useful to assist with protection and sustainable management of groundwater resources.

Glossary

Cave: A subsurface solutional conduit large enough for humans to enter.

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.

Doline: A surface depression formed by karst processes.

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

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 > 2 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. The term fissure is also widely used for larger aperture fractures that are not formed by dissolution. In this report the distinction is made between solutional fissures and fissures formed by mass movement processes.

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.

Phreatic: Sub-water table. Cave passages that are described as phreatic are those thought to have been formed beneath the water table, and are generally circular or oval in shape.

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.

Sump: Cave passage in which the water reaches the roof (i.e. the passage is entirely water filled).

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. Therefore the term stream sink is generally used in these reports, as the presence of an active stream recharging the aquifer is directly inferred. However, many older reports of stream sinks use the term swalllow hole to describe stream sinks.

Vadose: Vadose cave passages are those that have formed above the water table and are often taller than they are wide.

References

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