BGS Karst Report Series: J1 Karst in the Jurassic Limestone Corallian Group of Northern England

Environmental Change, Adaptation & Resilience Programme

Open Report OR/22/009

BRITISH GEOLOGICAL SURVEY

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Keywords

Karst, Caves, Corallian limestone, Springs, Groundwater, Tracer tests, Transmissivity, Boreholes.

Front cover

Calcite formation in the Main streamway in Excalibur Pot. Photo courtesy of Gary Douthwaite, York Caving Club.

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Executive Summary

This report documents the evidence for karst and rapid groundwater flow in the Jurassic Corallian limestones of Northern 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. This area represents something of an anomaly in the Jurassic limestones as there is evidence of extensive cave development. The series is the main output of the NERC funded Knowledge Exchange fellowship "Karst knowledge exchange to improve protection of groundwater resources". 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 the Jurassic Corallian limestones of Northern England are highly karstic. Although cave development is not as extensive as in the Carboniferous limestones of the Yorkshire Dales, the discovery of the Excalibur Pot cave system in the North York Moors in 2007 demonstrated that large and extensive caves can form in the Corallian limestones. This cave system is now more than 3.8 km long, and there are several other karstic caves recorded in the J1 Jurassic limestone area. There are many large river sinks, with eight major rivers that lose water as they cross the Corallian outcrop. The Forge Valley swallow holes on the River Derwent are particularly substantial, providing point recharge of more than 375 $l.s^{-1}$. There are several hundred springs recorded in the area, but there is little information on their discharge. At least 15 have very substantial flows, many of them more than 100 $l.s^{-1}$. There are no records of dolines or dissolution pipes in the area, although some surface depressions above known caves are thought to be karst dolines. Records of karst features are not well developed in this area, and it is recommended that further work be done to develop improved karst datasets.

Most tracer testing studies in the area have focused on the Forge Valley swallow holes, and consequently this karst system is very well characterised, with tests demonstrating rapid groundwater flows to multiple outlets spread over a wide area to the south and west of the swallow holes (Foley et al., 2012). Groundwater velocities based on time to peak concentration ranged from 18 to 13000 m/day over distances of between 18 and 7250 m. These tests demonstrate that borehole abstractions in the area have a high degree of connectivity with the main karst systems fed by swallow holes. The groundwater supply Source Protection Zones (SPZs) in this area have been modified, with the development of a bespoke approach to SPZ delineation reflecting the highly karstic nature of the aquifer, and the results of the tracer tests from the Forge Valley swallow holes.

In areas away from the River Derwent there has not been much tracer testing. Tests have been conducted to investigate the Excalibur Pot cave system fed by stream sinks on the Hutton Beck, proving velocities of thousands of metres per day; and tracer tests from boreholes have demonstrated rapid flows of hundreds of metres per day to springs at Brompton and Keld Head.

Hydrogeological studies in the area provide further evidence of karst and demonstrate that the karst impacts on boreholes. Transmissivity is variable, but there are some sites with very high transmissivities and/or yields indicating connectivity with extensive karstic networks. Borehole logging studies have demonstrated that flows to boreholes are via a small number of high yielding karstic fissures.

Overall, there is clear evidence of karstic systems in the Jurassic limestones in this area, which are comparable to those in highly karstic aquifers, with a high proportion of rapid recharge at some groundwater outlets. Consideration of karst is important for all aspects of hydrogeology and aquifer management in this area. Further work is recommended to develop better karst datasets and investigate local karstic networks.

Introduction to the BGS Karst Report Series

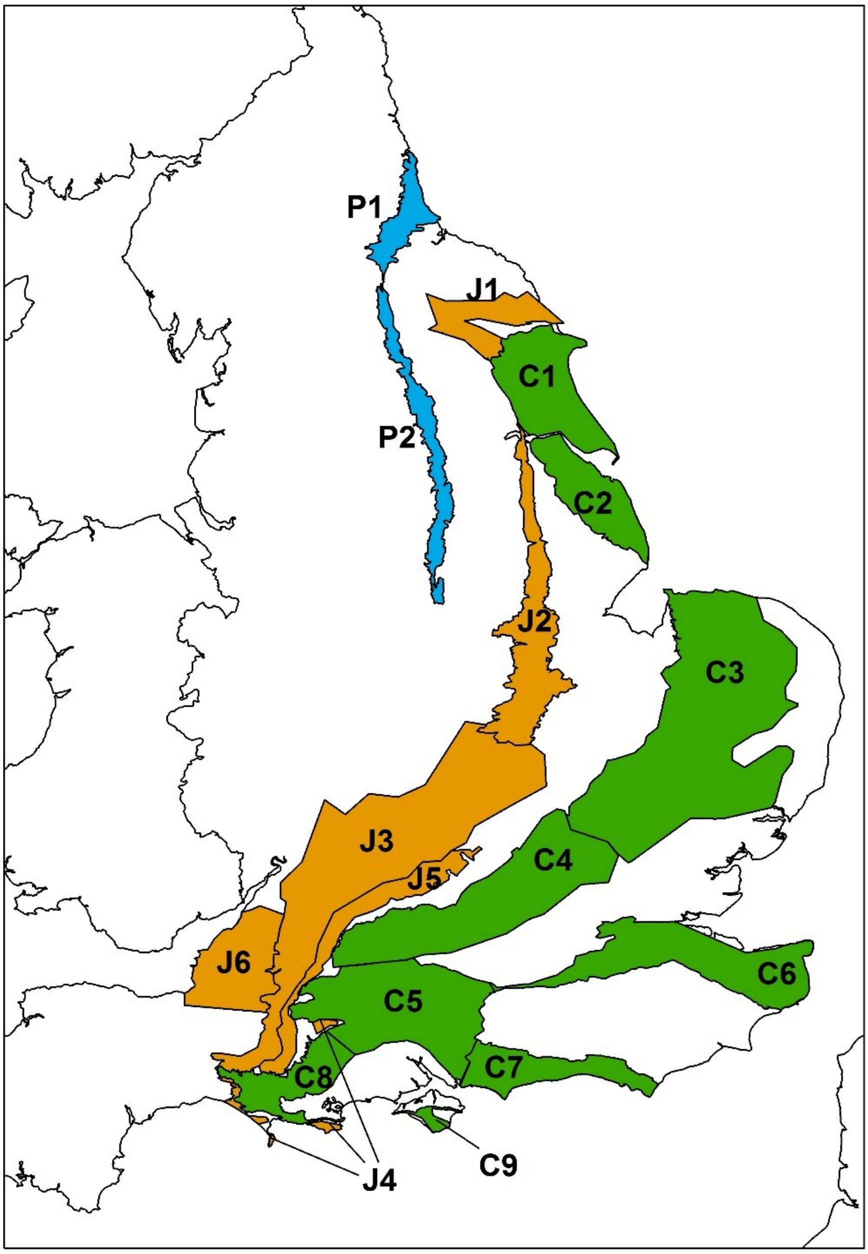
The BGS karst report series is focused on karst aquifers in England in which cave development is limited – The Chalk and the Jurassic and Permian limestones. The series is the main output of the NERC funded Knowledge Exchange fellowship "Karst knowledge exchange to improve protection of groundwater resources" undertaken between 2015 and 2022.

The term "karst" applies to rocks that are soluble. In classic karst there are extensive caves; and there are large scale surface karst landforms such as dolines, shafts, river sinks, and springs. In the past the Chalk and the Jurassic and Permian Limestones of England were not considered karstic because they have limited cave development, and because karst features are 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 (generally short) caves in all three aquifers; they all have dolines, stream sinks and large springs; and rapid flow can occur over long distances. Karst is therefore an important feature of these aquifers.

The series comprises 17 reports which provide an overview of the evidence for karst in different areas of England. The Chalk 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 Jurassic limestones of central England (predominantly the Lincolnshire Limestone Formation). J3 covers the Great and Inferior Group oolites 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 Southwest England and comprises several small outcrops within a large area.

Karst data are compiled from the British Geological Survey databases on karst, springs, and transmissivity; peer reviewed papers and reports; and through knowledge exchange between 2015 and 2022 with the Environment Agency, universities, water companies, consultants, and cavers. The data are not complete and further research and knowledge exchange is needed to obtain a fuller picture of karst development in these aquifers, and to investigate the detail of local catchments. The reports provide an initial overview of the evidence for karst and demonstrate that surface karst features are much more widespread in these aquifers than previously thought, and that rapid groundwater flow is common. Consideration of karst and rapid groundwater flow in these aquifers will improve understanding of how these aquifers function, and these reports provide a basis for further investigations of karst to enable improved management and protection of groundwater resources.

The reports are structured to provide an introduction to the area and geology, evidence of karst geomorphological features in the area (caves, conduits, stream sinks, dolines 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 Southwest England
P1) Karst in the northern outcrop of the Permian limestones
P2) Karst in the southern outcrop of the Permian limestones

Introduction to Karst Data

This section provides background on each type of evidence for karst, the data sources used, and any limitations in the data. 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 $l.s^{-1}$, have been identified. There are also some springs with no discharge data but which have been observed during field visits to be large (likely to be > 10 $l.s^{-1}$), or 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 flowpaths in which groundwater flow is rapid. The development of cave-sized conduits is not a pre-requisite for rapid groundwater flow, and in these aquifers where cave development is limited, the karstic flowpaths may comprise connected networks of smaller conduits and solutional fissures.

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

Other evidence of karst and rapid groundwater flow

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

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

Acknowledgements

We thank Aidan Foley (Mott MacDonald) for providing data and information from his PhD work in the area with Tim Atkinson at University College London, and for providing helpful comments on the report. We also acknowledge cavers from the York Caving Club and the North York Moors Caving Club for their work in the area and thank them for their assistance. We particularly thank Matt Ewles and Gary Douthwaite for providing information, surveys and photographs of the caves, and useful feedback on the report. We thank Carl Thomas and John Dale for enabling us to use their pictures and information on caves in the area; and Richard Wilsdon, Tony Waltham, Andy Brennan and Paul Horner for enabling us to use their photographs of caves.

We thank Mark Morton and Paul Speight at Yorkshire Water; and Ed Wrathmell, Ruth Buckley, Sharon Thomas, Andrea Lancaster, Rolf Farrell, Harris Tarnanas, and Hannah Threadgould at the Environment Agency for their input and advice on hydrogeology and karst in this area; and we thank Ruth Buckley and Sharon Thomas for enabling us to reproduce figures in this report. We also thank Pauline Smedley from BGS for reviewing the report. This work was carried out under the Natural Environmental Research Council (NERC) Knowledge Exchange Fellowship Scheme, grant ref NE/N005635/1.

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1 Introduction

1.1 AREA/GEOLOGY

The J1 Jurassic (Corallian Group) limestone area of Northern England extends from just east of Thirsk to Scarborough (Figure 1). The higher ground in the area forms the southern part of the North York Moors. The area is drained by the River Derwent, which flows towards the southwest, and is joined by a number of major southwards draining tributaries (Figure 2). There are many dry valleys in the area (Foley, 2006). The Corallian Group crops out within the Cleveland Basin, with the Oxford Clay Formation and other older formations present to the north and south (Figure 2, Table 1). The Corallian Group comprises the Lower Calcareous Grit Formation, the Coralline Oolite Formation and the Upper Calcareous Grit Formation (Allen et al., 1997). Karst is developed within the limestones of the Coralline Oolite Formation. Most karst and cave development is in the Hambleton Oolite Member and the Malton Oolite Member (Dale & Thomas, 2015). The Corallian Group is overlain by the Ampthill Clay and Kimmeridge Clay Formations which outcrop in the centre of the Cleveland Basin (Powell, 1998). The Helmsley-Filey faults (also known as the Ebberston-Filey faults) extend west to east across the area and truncate the Corallian limestones against the downthrown Kimmeridge Clay Formation (Allen et al., 1997; Foley, 2006). There are a number of other faults, especially in the south of the area (Figure 2).

Figure 3 shows the superficial deposits in the area, which are mainly found in topographical lows. The Vale of Pickering contains extensive proglacial lake deposits. Alluvium is present in some major river valleys and till is present in some interfluve areas.

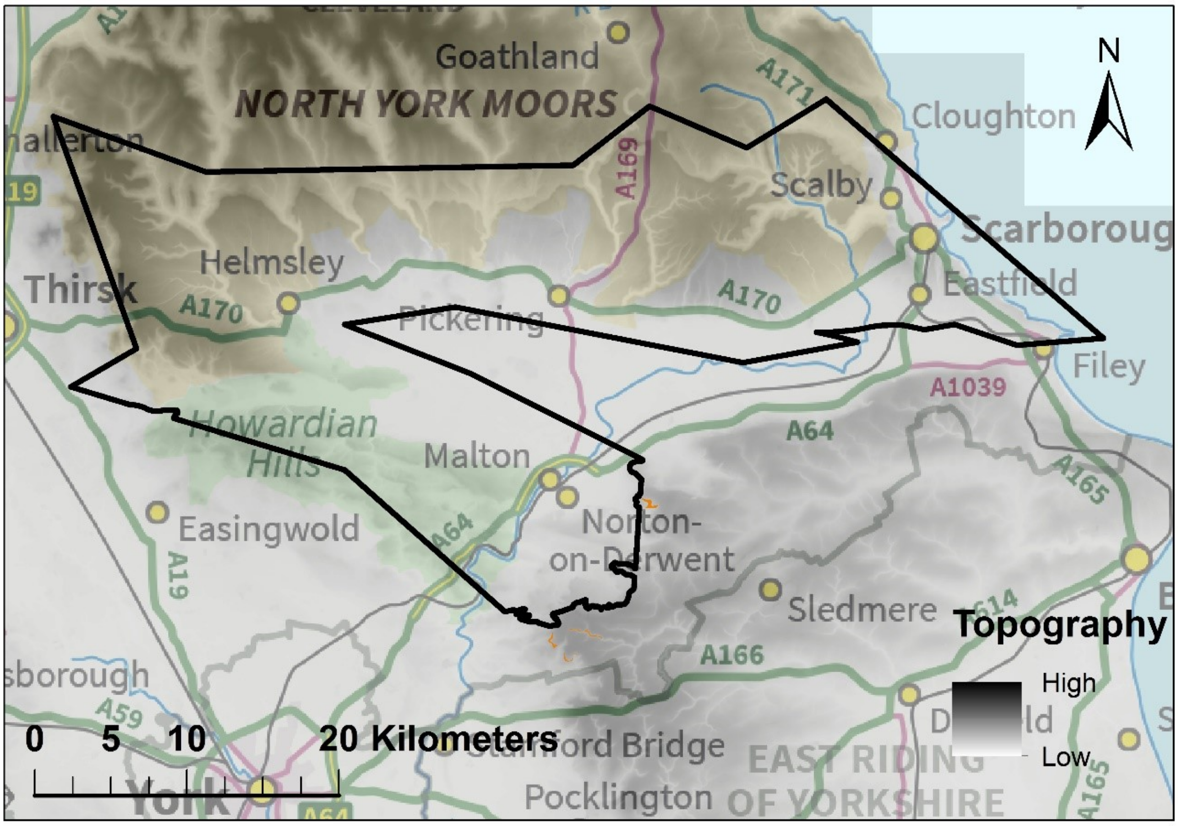

Figure 1. The J1 Jurassic Limestone area.

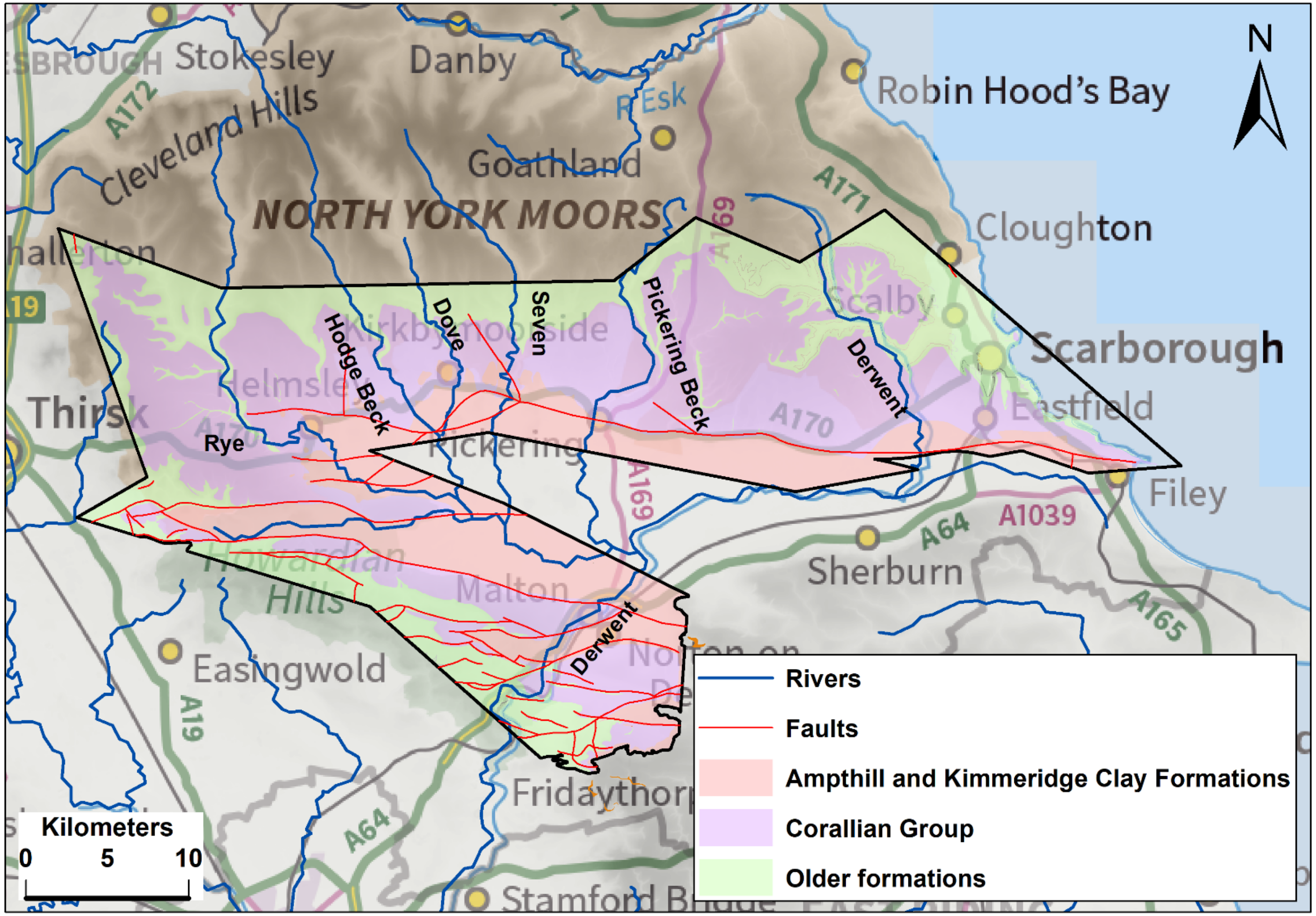

Figure 2. Bedrock geology and major rivers.

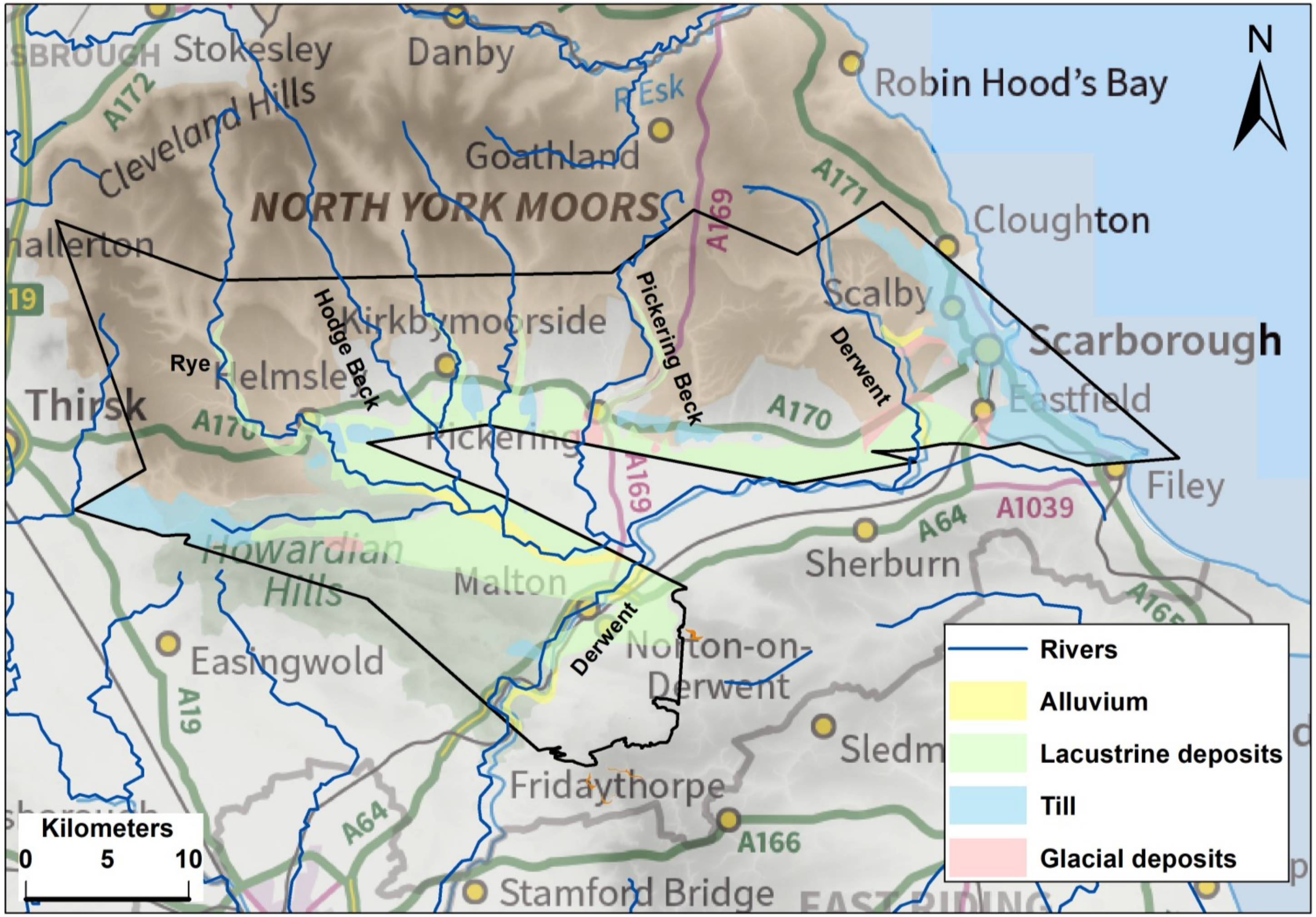

Figure 3. Superficial geology

Table 1. Stratigraphy in the J1 Jurassic Limestone area (Powell, 1998; Allen et al., 1997)

Group	Formation	Member	Lithology	Thickness
Ancholme Group	Kimmeridge Clay Formation		Mudstone	0-385 m
	Ampthill Clay Formation		Mudstone	45-50 m
Corallian Group	Upper Calcareous Grit Formation		Calcareous sandstone	9-33 m
	Coralline Oolite Formation	Coral Rag Member	Ooidal limestone	0-12 m
		Malton Oolite Member	Ooidal limestone	0-40 m
		Middle Calcareous Grit Member	Calcareous sandstone	12-15 m
		Hambleton Oolite Member	Ooidal limestone	0-35 m
		Birdsall Calcareous Grit Member	Calcareous sandstone	0-27 m
		Yedmandale Member	Sandstone and limestone	16 m
	Lower Calcareous Grit Formation		Calcareous sandstone	16-60 m
Ancholme Group	Oxford Clay Formation		Mudstone and sandstone	0-35 m
No group	Osgodby Formation		Sandstone	0-28.5 m
No group	Cornbrash Formation		Limestone and subordinate sandstone	0-6.5 m
Ravenscar Group			Sandstone, siltstone, mudstone, ironstone and limestone	44.5-263 m
Lias Group			Mudstone, sandstone and ironstone	0-458 m

1.2 WATER PROVIDERS AND REGULATORS

Yorkshire Water are the only water provider for the J1 Corallian limestone area, which is entirely within the Yorkshire Environment Agency area.

2 Karst geomorphology

2.1 CAVES AND CONDUITS

The North York Moors have the most well developed karstic cave systems in the Jurassic limestones of England, including the 3.8 km long Excalibur Pot system. Detailed descriptions, photographs and surveys of the caves in this area can be found in Gibbs & Stewart (2003), York Caving Club (2010, 2014, and 2022), and Dale & Thomas (2015). Further information can also be found on caving club websites: York Caving Club (https://yorkcavingclub.org.uk/), and the North York Moors Caving Club (http://nymcc.org.uk/) The North York Moors Caving Club website includes a cave library with grid references and descriptions of caves (http://nymcc.org.uk/cave-library/). These records of caves also include features known as "the windypits" (Cooper et al., 1976a). These are cavities formed by mass-movement processes, also known as 'gull caves'. They are locally common and can be more than 100 m long. These are not karstic in origin, although Dale & Thomas (2015) do note that there are flowstone deposits on some of the walls indicating local solutional processes. Cavers have occasionally noted some dissolutional features in landslip caves.

The locations of caves and cavities in the area are shown in Figure 4, with details of the karstic caves provided in Table 2. More information on the more significant karst caves in given in Sections 2.1.1 to 2.1.8. The grid reference location data are predominantly from the North York Moors Caving Club and York Caving Club websites and journals. The features have been classified with the assistance of the local knowledge of cavers (Matt Ewles, personal communication (2022). There are only a small number of known karstic caves that are hydrologically active, and these are entirely focused in the area of the Hutton Beck and the River Dove (Figure 4), and are associated with the Excalibur Pot cave system (Section 2.1.1). There are a few more inactive karstic solutional caves that are distributed more widely and provide evidence of past karstic development. These are mostly short (a few 10s of metres at most) with the exception of Kirkdale Cave, Kirkbymoorside (near the Hodge Beck) which is more than 400 m long (Table 2). The karstic caves are generally formed within the Coralline Oolite Formation, often at the boundary between the Coral Rag Member and the Malton Oolite Member (Fox-Strangeways, 1892; Dale & Thomas, 2015). There are also some locations where karstic fissures/smaller conduits have been observed, mostly in quarry exposures. These are also unsaturated, but again provide evidence that karstic solutional development of the Corallian limestones occurs in this area. Figure 4 also shows the locations of landslip caves. These can be divided into two groups; the more extensive and substantial "windypits/landslip caves" that can be spacious caves several hundred metres long and tens of metres deep, and usually involve descending holes that have opened up in fields; and "landslip cavity in cliff" caves which are short landslip caves usually accessed from cliff faces (Matt Ewles, personal communication, 2022).

There are a number of records of "natural cavities" in this area in the Natural Cavities database which is a legacy dataset held by The British Geological Survey and Peter Brett Associates (now Stantec). This dataset comprises data from a range of sources originally commissioned by the Department of the Environment and by Applied Geology Limited (1993). Almost all the records of natural cavities from this dataset in this area appear to be windypits/landslip features. These records are included in Figure 4, but have not been recently assessed or verified.

A presentation on the caves of the North York Moors by York Caving Club (2021) is available at https://www.youtube.com/user/YorkCavingClub. This presentation provides information, pictures and surveys of solutional caves and windypits; with considerable detail about the Excalibur Pot-Bogg Hall system, including recently discovered extensions which provide insights into the hydrology of the area.

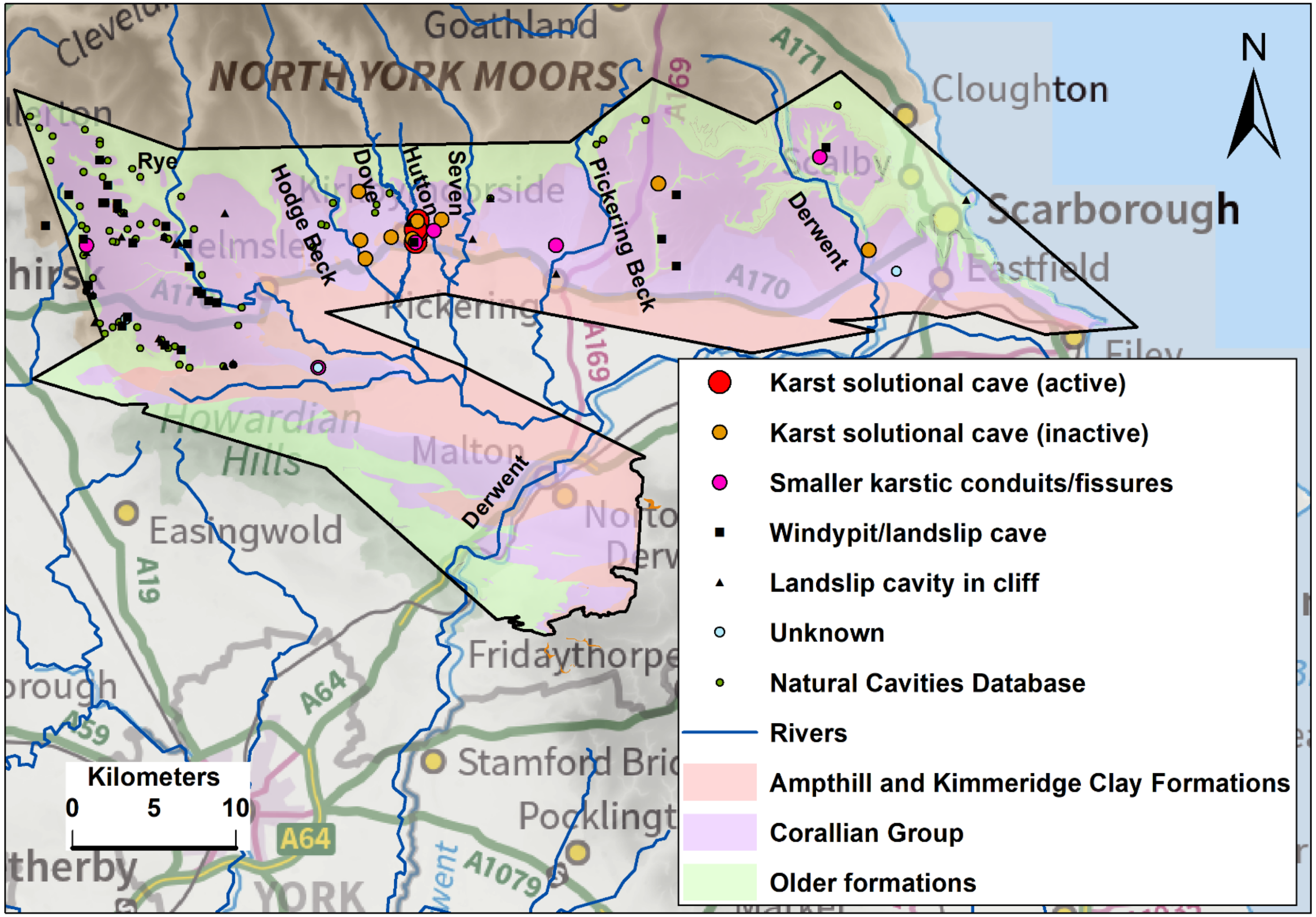

Figure 4. Cave and conduit locations.

Table 2. Karstic caves in the J1 area

Name	Length (m)	Notes	Source
Excalibur Pot	3800	Extensive active karst system with several entrances and streamways.	Dale & Thomas (2015), NYMCC, YCC
Kirkdale Cave	436	Extensive dry karst cave perched several metres above current water level of Hodge Beck, discovered by quarrying.	YCC/NYMCC
Bogg Hall Rising cave	200	Karst river cave, resurgence for Excalibur Pot system.	Dale & Thomas (2015), NYMCC, YCC
Boltby Quarry Caves	< 100 m total	Four dry caves, Cooper and Halliwell (1976) report karst characteristics.	Cooper and Halliwell (1976)
Guinevere's Slit	40	Small solutional cave, dropping into flowing water beneath River Dove, sumped (water filled) upstream and downstream.	YCC/NYMCC
The Well	~50	Artificially dug entrance (a well) into the underground route of The Dove. Dived downstream for ~50m and continues in good size sumped passage.	YCC/NYMCC
Fadmoor Caves	33,14,11	Three dry caves, including one classic karst shaped passage with scallops.	YCC/NYMCC
Eastfield Quarry Caves	30	May be landslip caves but some evidence of past dissolution, no water now.	YCC/NYMCC
Manor Vale Caves	30, 4.5, 3.5	Dry caves in the east and west cliffs of Manor Vale. Excellent examples of karst caves.	YCC/NYMCC
Spaunton Cave	~ 21	Cave reported from 1940s, probably karstic, location unknown.	YCC/NYMCC
Lingmoor Cave	12	Dry karstic cave just up the hillside from Excalibur Pot in the Malton Oolite. Possible former stream sink for Excalibur Pot system.	YCC/NYMCC
Kirkdale Howl	10	One of several short dry caves in Kirkdale Howl region showing evidence of karst.	YCC/NYMCC
Silpho Quarry Cave	10	Small, short dry karst cave.	YCC/NYMCC
T'une Mouth	9	Dry karst cave perched above the River Dove ~500m upstream of Bogg Hall; Sizable passage, mud choked.	YCC/NYMCC
Dowson Pot	4	Dry cave several metres above Hutton Beck, former stream sink associated with Excalibur Pot system.	YCC/NYMCC
Oooh Oooh Cave	4	Small, short dry karst cave above the River Derwent.	YCC/NYMCC

Lockton Phreatic Tubes	a few metres	Small, short dry karst cave explored for a few metres, east of the River Derwent.	YCC/NYMCC
Nunnington (Railway Cutting) cave		Cave with a pitch and sound of running water reported during railway cutting construction, cave lost/unknown location.	YCC/NYMCC
Guinevaks's Hole		In the streambed of River Dove, drops into sumped river passage.	YCC/NYMCC
Mutton Butty		Short dry cave with signs of past water flow (scalloping)	YCC/NYMCC
Back of the Parks		about 1 mile east of Kirby Moorside, quarries on both side of valley contain several small caverns and vertical fissures, sediment filled; location unknown.	Buckland-Reliquiae Diluvianae (1823), see NYMCC website
Appleton Common fissure		late 1930s quarryman reported fissure containing large stalactites 3 feet long, site location unknown.	YCC/NYMCC
Riccal dale cavern		"caverns" reported in Riccal dale in 1880 by C Fox-Strangeways, location unknown	YCC/NYMCC

Information predominantly from websites and journal publications of the North York Moors Caving Club and York Caving Club. Cave location grid references are available on the caving club websites.

2.1.1 Excalibur Pot cave system

Excalibur Pot, discovered in 2007, is the longest cave system in the area. Including most of the recent extensions discovered in 2020, it has a length of 3.8 km and a depth of about 30 m (although it is substantially deeper below the surface beneath the interfluve areas, Matt Ewles, personal communication, 2022). The cave is described in detail in Dale & Thomas (2015), and by York Caving Club (2010, 2014, 2021, 2022). The geology of the cave system is also discussed in Appendix C of Buckley & Howlett (2014). The cave system and surface geology in the area is shown in Figure 5 which is from Dale & Thomas (2015), with more recent surveys including the 2020 extensions shown in Figure 6 (York Caving Club, 2022) and Figure 7 (the recently updated survey by York Caving Club). Pictures of the cave are shown in Plates 1 to 13 to give examples of different karstic passage shapes and different areas of the cave system.

The cave is developed within the Hambleton Oolite Member in the middle of the Coralline Oolite Formation (Dale & Thomas, 2015). There are several entrances, all of which are associated with, or very close to, active or flood sink points within the Hutton Beck where it crosses the Corallian outcrop (see section 2.2); with Jenga Pot being the entrance furthest downstream in the Hutton Beck. In normal/drier weather, the water sinks to the north of the cave, but in wet weather the stream overflows and sinks at various points downstream in a flood overflow channel. The cave system comprises an active vadose streamway, and a higher-level network of relict phreatic and vadose passages, some of which become active in wetter weather. The stream inside the cave originates from the Hutton Beck stream sink to the north of the present entrance. It enters the cave and flows along a vadose canyon up to five metres high in places (Dale & Thomas, 2015), disappearing into a low flooded passage to the south-west of the Excalibur Pot entrance. It reappears into the River Dove at the major spring known as Bogg Hall Rising (Figure 5). In wetter weather, water sinking in the flood overflow channel enters the eastern side of the cave, taking an alternative route to the Bogg Hall Rising independent to that of the main streamway.

In 2020 further exploration extended the cave to the south and west of the Jenga Pot entrance (Figure 6 and Figure 7). Detailed surveys and descriptions of these extensions are presented by York Caving Club (2021). The new discoveries of 2020 also included a passage called "the Second Wave" which intersected a new section of the main underground stream between Excalibur Pot and Bogg Hall Rising. These passages had not been surveyed when Figure 6 was produced, and the estimated positions of these passages are shown as dotted lines. These passages have recently been surveyed and the new survey (Figure 7) shows that "the Second Wave" extends more or less directly northwards, and is almost twice the length originally estimated, before it encounters the short new section of the main Excalibur Pot streamway (Matt Ewles, personal communication, 2022). This new section of streamway emerges from Sump 6 and disappears into Sump 7. The 2020 discoveries included a stream in which water flows from the south (Sump 4, see Figure 7). In 2022, this stream has been followed southwards for at least 50 m, with exploration ongoing (Ewles, personal communication, 2022). This stream flowing in from the south is in direct contrast to the main conduit flow-paths in the cave system which all flow towards the south from the Hutton Beck stream sinks.

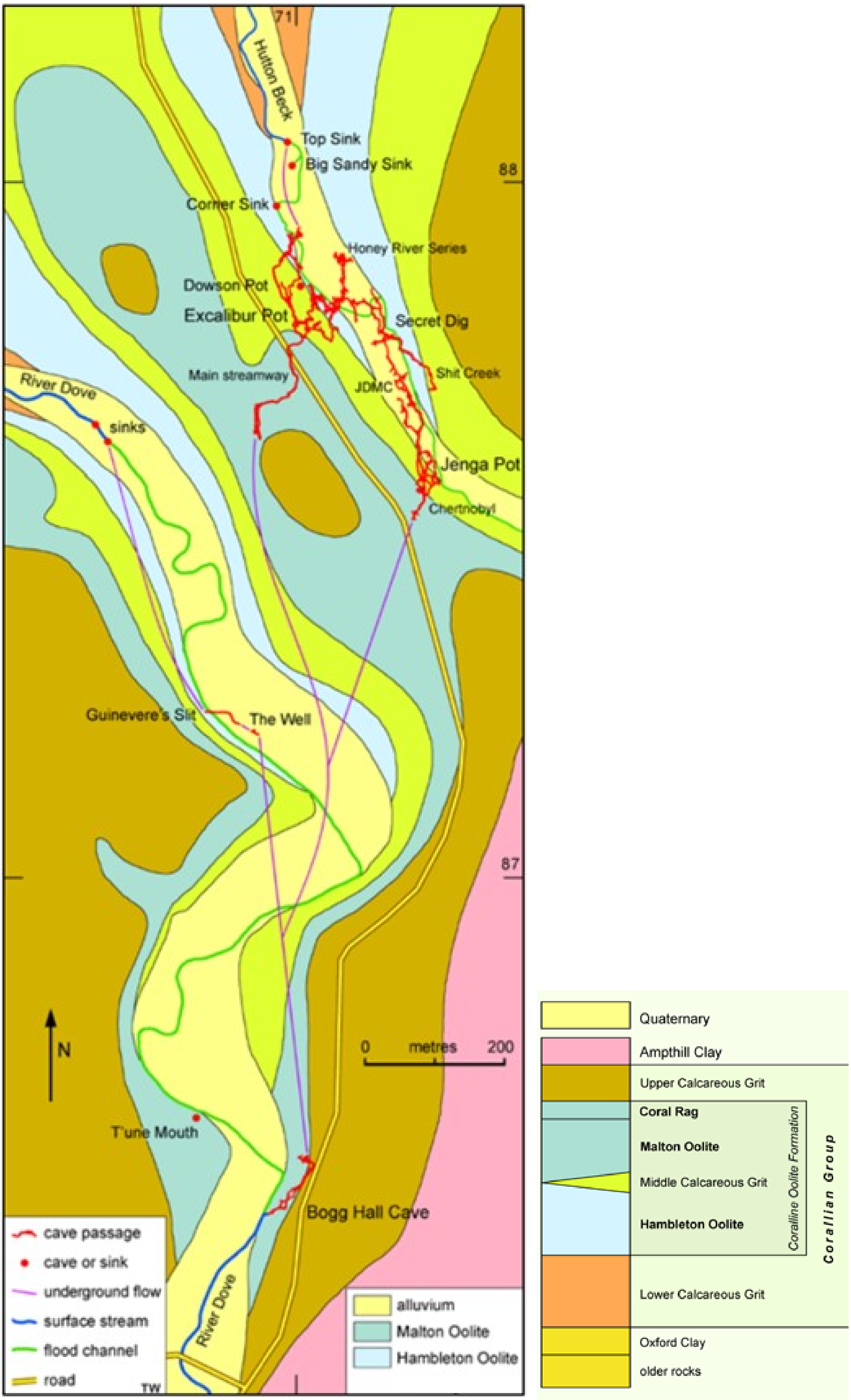

Figure 5. Cave passages relating to the Hutton Beck and the River Dove reproduced with permission from Dale & Thomas (2015). Underground flow lines refer to pathways which have been demonstrated in tracer tests.

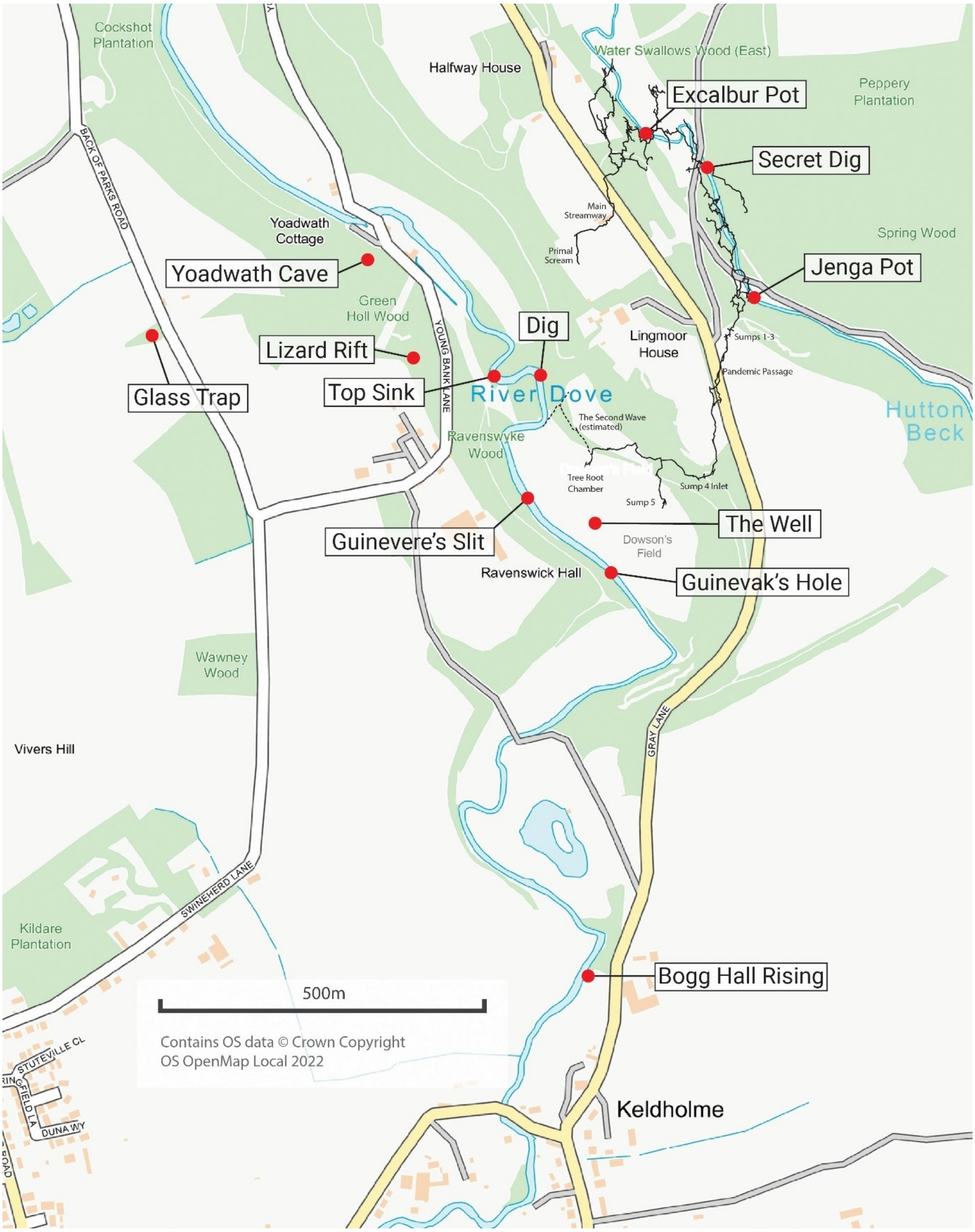

Figure 6. Excalibur pot and caves in the vicinity, including the 2020 extensions to Jenga Pot. Reproduced with permission from York Caving Club (2022), Douthwaite and Ewles

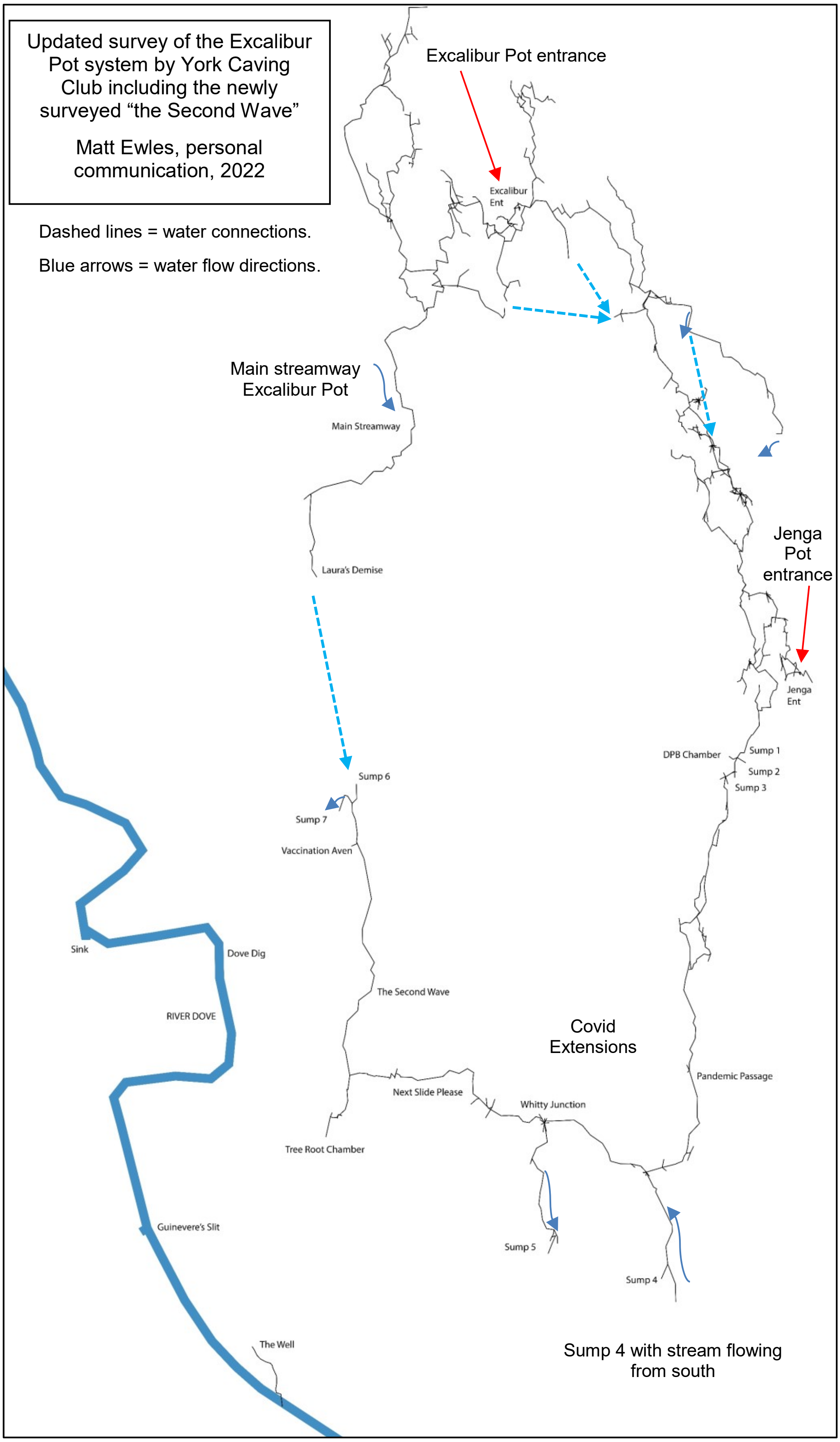

Figure 7. York Caving Club survey of the Excalibur Pot system (Courtesy of Matt Ewles, personal communication, 2022).

Plate 1.   Flowstone in Excalibur Pot. Photo courtesy of John Dale.

Plate 2. One of the shafts through which it is possible to enter Excalibur Pot cave. Photo courtesy of John Dale.

Plate 3. Excalibur Pot main streamway. Photo courtesy of Gary Douthwaite.

Plate 4. Inlet passage, in the east of the Excalibur Pot system. Photo courtesy of John Dale.

Plate 5. High level chamber in Jenga pot, the roof is only 5 m below the Hutton Beck. Photo courtesy of John Dale.

Plate 6. Passage in Jenga Pot. Photo courtesy of Gary Douthwaite.

Plate 7. The slops, Jenga Pot. Photo courtesy of Gary Douthwaite.

Plate 8. Chert Alley, Jenga Pot. Photo courtesy of Gary Douthwaite.

Plate 9. Pandemic passage, Jenga Pot. Photo courtesy of John Dale.

Plate 10. Well-developed passages in the 2020 Jenga Pot extensions (Pandemic passage). Photo courtesy of Gary Douthwaite.

Plate 11. Pandemic passage, Jenga Pot. Photo courtesy of Gary Douthwaite.

Plate 12. The second wave, Jenga Pot. Photo courtesy of John Dale.

Plate 13. Towards the end of the covid extensions, Jenga Pot. Photo courtesy of John Dale

2.1.2 Bogg Hall Cave

Bogg Hall Cave is a 200 m long resurgence cave (Wilsdon & Hanan, 1983; North York Moors Caving Club, 2022). It is the largest spring in the North York Moors (see Section 2.3), and is the main resurgence for water sinking in the Hutton Beck (including Excalibur Pot) and the River Dove (Figure 5). The cave is developed within the Malton Oolite Member (Figure 4). At the end of the cave there is a sump pool which is approximately 18 m deep with a large waterflow emerging at the bottom from a deep fissure which probably extends down into the Hambleton Oolite Member (Dale & Thomas, 2015).

Plate 14. Large passage in Bogg Hall Rising with deep water. Photo courtesy of John Dale.

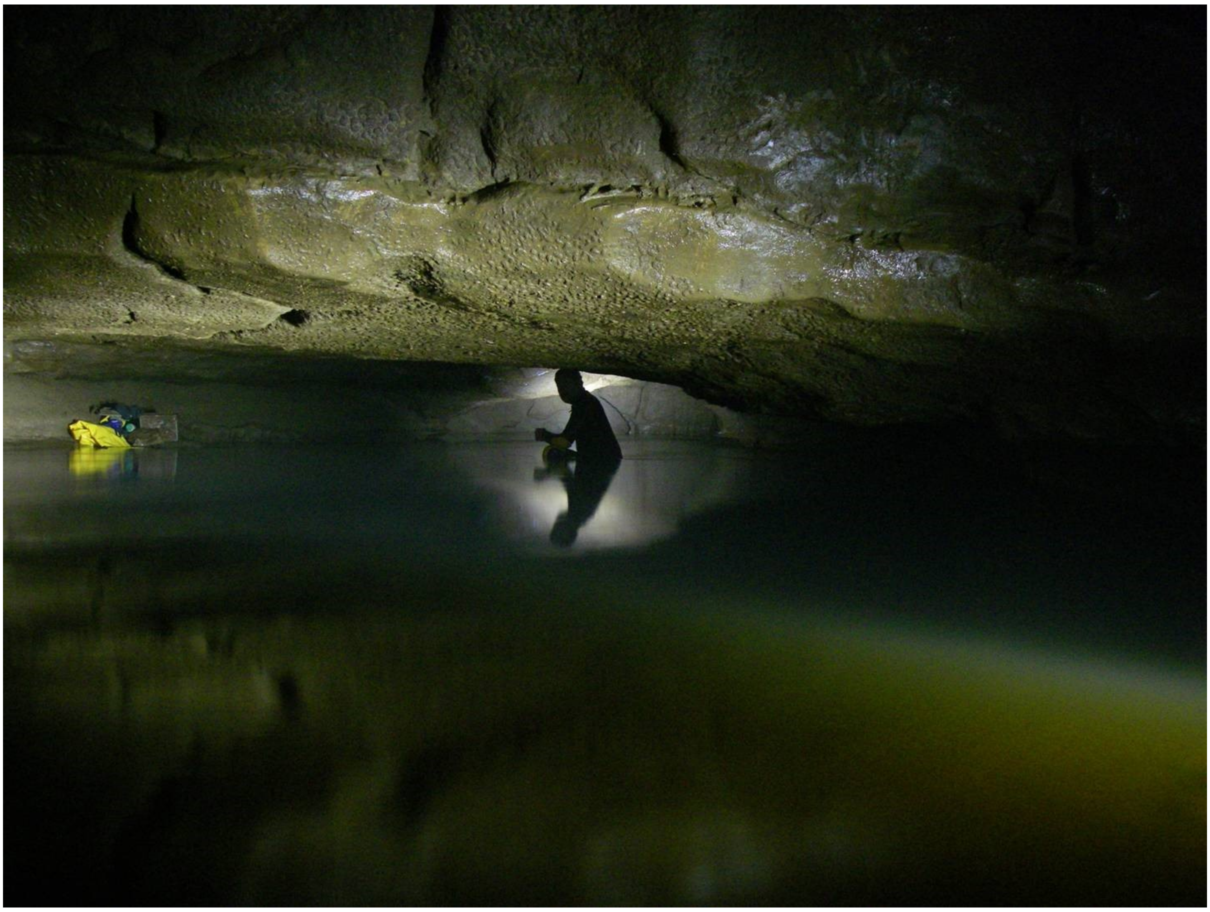

Plate 15. Main river passage in Bogg Hall cave. Photo courtesy of Richard Wilsdon.

Plate 16. Inside Bogg Hall Rising Cave. Photo courtesy of Richard Wilsdon.

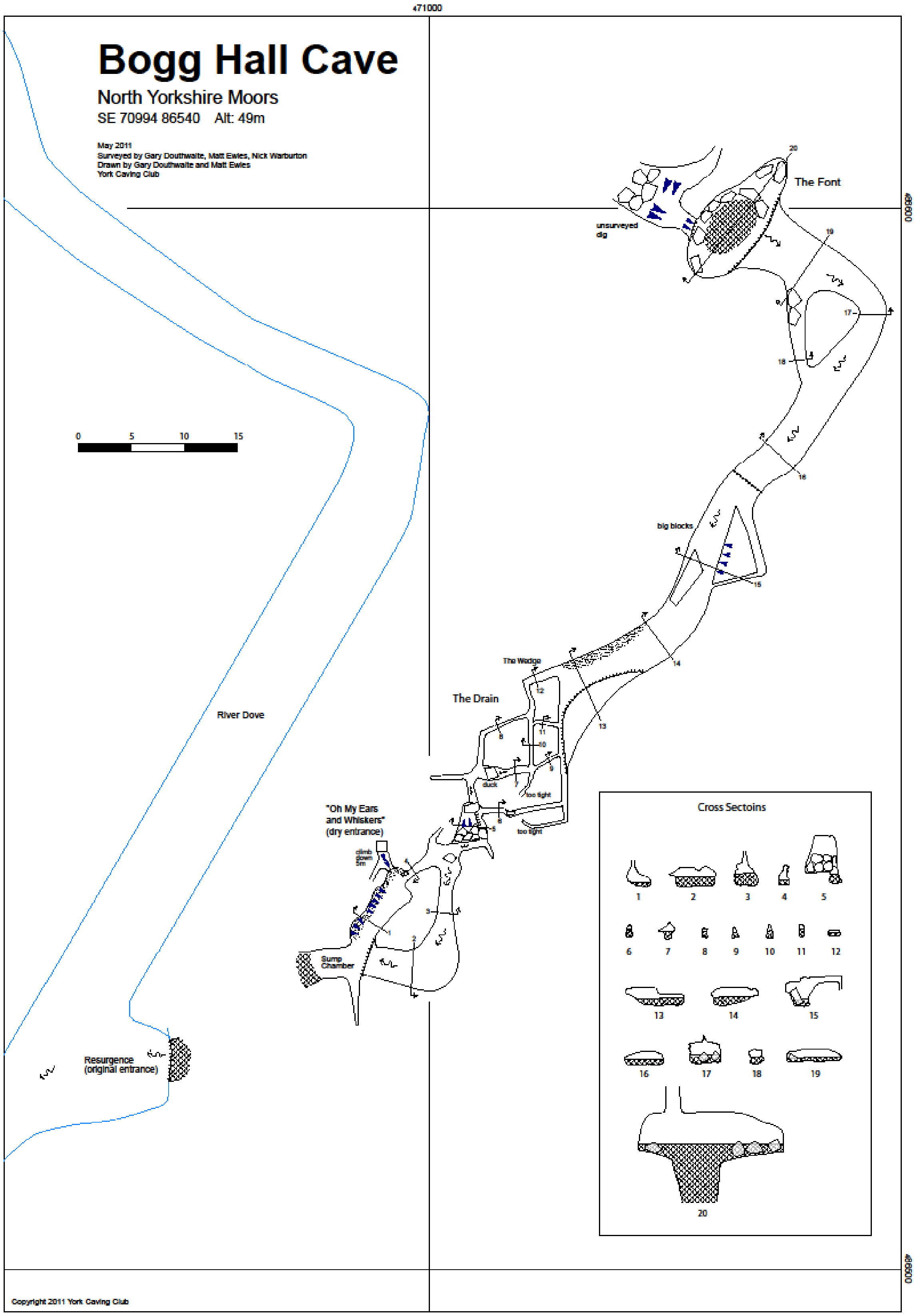

Figure 8. Survey of Bogg Hall Rising. Reproduced with permission from York Caving Club (2022), Douthwaite and Ewles.

2.1.3 Kirkdale Cave

Kirkdale Cave is a 436 m long dry cave located near to the Hodge Beck, near Kirkbymoorside It comprises a largely horizontal network of relict phreatic passages. It was discovered in 1821 and has since been a site of archaeological interest because of the range of fossil fauna found there (McFarlane & Ford, 1988). The cave has been designated as an SSSI (Site of Special Scientific Interest). The cave is associated with the Malton Oolite/Coral Rag boundary.

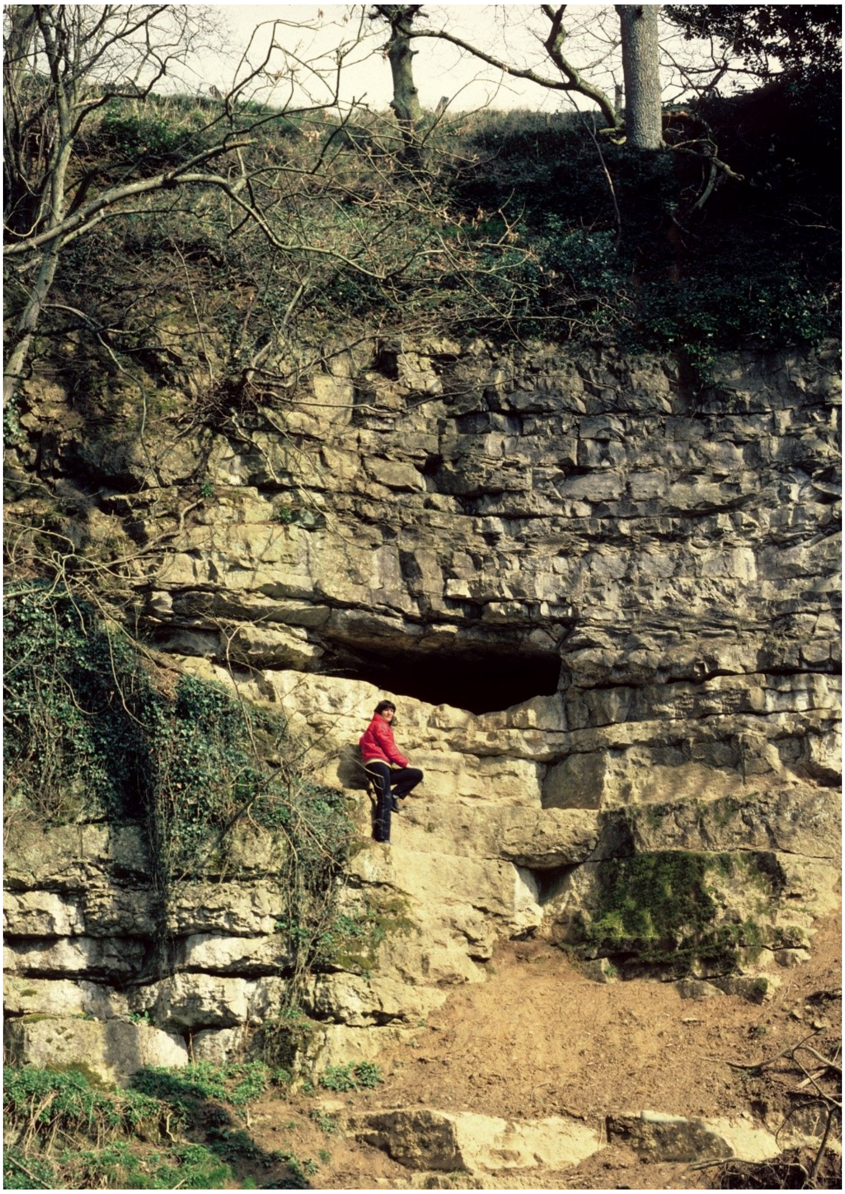

Plate 17. Entrance to Kirkdale Cave in a quarry. Photo courtesy of Tony Waltham Geophotos.

Plate 18. Inside Kirkdale Cave. Photo courtesy of John Dale.

2.1.4 Boltby Quarry Caves

Three caves have been found with entrances in a quarry face east of Boltby on the Hambleton escarpment, with enterable passages up to 25 m in length, and boulder chokes at the ends of the passages (North York Moors Caving Club, 2022). While it has been suggested that these are caves formed by mass movement, the enterable passages show evidence of solutional development such as scallop markings and circular shaped passages (Cooper and Halliwell, 1976). Boltby Quarry is in the Hambleton Oolite Member of the Coralline Oolite Formation. More information on Boltby Quarry Caves can be found in Cooper et al. (1976a & 1976b); Cooper & Halliwell (1976); and in the cave library section of the North York Moors Caving Club website.

2.1.5 Manor Vale caves

Manor Vale is a dry valley located between the River Dove and the Hodge Beck. Caves at this location were first described by Buckland-Reliquiae Diluvianae (1823), see http://nymcc.org.uk/manor-vale/. Two very short caves with a vocal link have been reported on the west side of the valley, one of which contained a “roomy passage” (North York Moors Caving Club, 2022). York Caving Club (2022) note that the bottom of the Manor Vale West Cave takes some water in very wet periods. A longer cave (~30 m) is reported on the east side of the valley (North York Moors Caving Club, 2022, York Caving Club 2010, 2014, 2022). The Manor Vale caves are excellent examples of predominantly dry karstic caves, with classic karst shaped passages (Plates 19-21).

Plate 19. Large open entrance to one of the two caves on the west side of Manor Vale. Photo courtesy of Gary Douthwaite.

Plate 20. Entrance to Manor Vale East cave. Photo courtesy of Gary Douthwaite.

Plate 21. Inside Manor Vale Cave. Photo courtesy of John Dale.

2.1.6 T’une Mouth

T’une Mouth cave is a dry (relict) cave in a cliff above a section of the River Dove which is normally dry (North York Moors Caving Club, 2022). It is a short cave (~ 9 m) but comprises a passage with a classic karstic shape (plates 22 and 23) and evidence of scalloping on the walls, and is therefore evidence of karstic groundwater flow in the geological past. This cave may be developed in the Malton Oolite Formation (York Caving Club, 2010). Further details can also be found in York Caving Club (2014).

Plate 22. T’une Mouth entrance. Photo courtesy of Andy Brennan.

Plate 23. T’une Mouth main passage following excavation of sediment. Photo courtesy of Paul Horner.

2.1.7 Oooh Oooh cave

Oooh Oooh cave is a small, very short (about 4 m) dry (relict) karstic cave in a cliff face in the Derwent Valley near East Ayton (York Caving Club, 2022). The cave appears to be developed on a bedding plane feature and the passage shape suggests a phreatic origin.

Plate 24. Entrance to Oooh Oooh cave. Reproduced with permission from York Caving Club (2022), Douthwaite and Ewles.

Plate 25. Inside Oooh Oooh cave. Reproduced with permission from York Caving Club (2022), Douthwaite and Ewles.

2.1.8 Kirkdale Howl Cave

Kirkdale Howl cave is one of three short dry caves just east of the Hodge Beck, in a valley upstream of Kirkdale Cave; the others being Commode-in-the-hole and Wilmot's Palace (York Caving Club, 2022). The valley is flanked by limestone cliffs which expose these relict caves (York Caving Club, 2022). None of the caves extends more than about 10 m from the cliff face. They are further evidence of past karstic groundwater flow in this area.

Plate 26. Entrance to Kirkdale Howl cave. Photo courtesy of John Dale.

2.1.9 Smaller conduits

There are a number of sites where fissures/smaller conduits have been observed (Figure 4, Table 3), and it is probable that such features are common in the Corallian limestones. Most of these sites are quarries which have intersected karstic conduits, and those recorded in Table 3 are all unsaturated features, which are no longer hydrologically active, but are evidence of karst groundwater flow in the geological past, and demonstrate the karstic nature of the Corallian limestones in this area. Further details are provided here, with grid references for these sites in Table 3, where known.

The PhD thesis from Durham University by Westerman (1981) provides detailed information on solutional features observed in Spaunton Moor quarry, which is about 4 km east of Kirkdale cave. Westerman (1981) provides many photographs of solutional cavities exposed in the quarry. He notes the strong influence of faults and joints on dissolution, and observes that most of the solutional development in this quarry is vertical, but there are horizontal pipes observed near the quarry floor, just above the modern water table. Westerman (1981) also reports "intermediate" sized anastamoses in Yapley quarry adjacent to Bogg Hall resurgence, suggesting that these cavities are smaller than enterable caves.

There is a record in the Natural Cavities database (Applied Geology Ltd, 1993) at NGR SE 795 863 for a "cavity and several fissures" which were identified using investigations (including geophysics) following a collapse at a reservoir.

Cooper and Halliwell (1976) report that at Boltby quarry, more than 12 circular shaped tubes (some partially sediment filled) have been intersected, but note that only seven of these have diameters of more than 20 cm. They also note that these conduits are associated with a shale bed, suggesting that this may act as an inception horizon in this area. There are also a number of sites where karstic fissures/conduits that are too small to enter are documented by North York Moors Caving Club (2022) and York Caving Club (2014). These include conduits observed in a quarry near Levisham (York Caving Club, 2014), that are almost large enough to be termed caves (Plate 27).

Although the conduits documented in Table 3 are not hydrologically active, it is likely that similar hydrologically active solutional conduits and fissures are common in the unsaturated and saturated zones of the Corallian Limestone in Yorkshire. Foley et al. (2012) discuss the potential morphology of the karst networks identified from tracer tests from the Derwent valley swallow holes, and calculate that theoretically a karstic fissure of ~ 30 m width and ~5 cm aperture or a circular conduit of 1.3 m diameter could account for the observed velocities and discharges. It is likely that the karst networks in the aquifer are a mixture of both types of void. Solutional fissures/small conduits have been observed in CCTV images of boreholes (e.g. Tate et al., 1970; Foley, 2006); and it is likely that springs and successful borehole abstractions in the area are supplied by well-developed networks of solutional fissures and conduits, some of which may be of large enough dimensions to be termed caves.

Table 3. Some locations where fissures/smaller conduits have been observed

Name	Easting	Northing	Description	Source
Kirkdale Howl	467500	486600	Fissures and conduits in old quarries of Kirkdale Howl	NYMCC/YCC
Lockton Phreatic Tubes	485800	490100	Conduits up to 2 feet high, clay fill close to roof	NYMCC/YCC
Nunnington Railway cutting	464900	478800	Numerous fissures in railway cutting, some water worn	YCC (2014)
Spaunton Moor Quarry	472000	487200	Solutional cavities	Westerman (1981)
Yapley Quarry, Bogg Hall	470900	486500	Anastomosis in quarry	Westerman (1981)
Reservoir Site	479500	486300	Cavity and several fissures	Natural Cavities Database
Boltby Quarry	450700	486300	Conduits in quarry	Cooper and Halliwell (1976)
Quarry near Levisham	unknown	unknown	Conduits in quarry	YCC (2014)

Plate 27. Conduit intersected by a quarry near Levisham. Photo courtesy of Gary Douthwaite.

2.2 STREAM SINKS

Figure 9 shows the locations of stream sinks recorded in the Corallian limestones. The data are from OS Mastermap; from papers and tracer test reports (Foley, 2006; Foley et al., 2012; Dale & Thomas, 2015; Waters-Marsh, 1984); and from information from York Caving Club (Matt Ewles, personal communication, 2022). Many of the stream sinks shown on Figure 9 have been verified in the field, although those identified from OS Mastermap have not (including those in the far south of the area to the south of the River Derwent, those to the south of the Holbeck, to the west of the Rye, and also those in the Beedale valley). The locations of some large springs are also shown on Figure 9, and some of these may be the outlets for some of the stream sinks. However data on spring discharges are sparse and it is likely that there are more large springs, and that there are many other springs which could be the outlets for stream sinks (see Section 2.3).

Many of the stream sinks in the Corallian Group limestones are in the major river valleys. Most are in the Coralline Oolite Formation. Foley (2006) notes that the Forge Valley swallow holes in the River Derwent are in the Malton Oolite Member, whilst those in the beds of the Hutton Beck, and Dove, Rye and Riccal rivers are in the Hambleton Oolite Member which is lower down in the sequence (Table 1). There are relatively few records of stream sinks in the J1 Jurassic limestone area and it is likely that there are more stream sinks present, particularly within the main river channels. Smaller stream sinks within riverbeds will be difficult to identify.

Most of the streams and rivers draining the North York Moors sink underground where they cross the Corallian limestone outcrop (Dale & Thomas, 2015). However, most sinks cannot take all the flow under moderate to flood conditons. In wetter conditons, the rivers continue across the limestone outcrop, some sinking further downstream in flood sinks. Stream sinks occur in major rivers in the area; the Derwent, the Dove, the Rye, the Riccal and Hutton Beck (Figure 9). These are major sources of recharge to the Corallian aquifer (Foley, 2006; Dale & Thomas, 2015). These, and sinks in other river valleys are described in more detail below from east to west, based on a review of the literature. Some stream sinks discussed below are not included on Figure 9 where grid references were uncertain.

In the east of the area, the Forge Valley swallow holes are major sink points in the bed of the River Derwent, and have been used in tracer tests. Flow rates of more than 375 $l.s^{-1}$ have been recorded for these sinks (Foley, 2006; Foley, 2012; Atkinson, 1999). Carey & Chadha (1998) report that gauging indicates that the River Derwent had losses of 15 to 35 Ml/day (290 to 405 $l.s^{-1}$). They also report that structures were constructed in the 1970s to reduce this leakage. These were not very successful as water sank at alternative points, but Carey & Chadha (1998) suggest that in 1981 the leakage had been reduced by about 20%. Dale & Thomas (2015) suggest that springs at Brompton to the west might have formed a natural outlet for the stream sinks on the River Derwent, as well as for stream sinks in the Dalby Forest, or that perhaps there were natural submarine outlets to the east. Tracer tests have shown that the Forge Valley swallow holes now connect to multiple groundwater abstractions to the south and southeast (Foley, 2006; Foley, 2012, see Section 2.4), and no tracer was detected at Brompton springs during these tests, suggesting that if they did form the natural outlets to the Forge Valley swallow holes in the past, all the flow has been subsequently captured by pumping.

There are some stream sinks in the Gundale Beck which is a small tributary of the Pickering Beck (these are the stream sinks just to the west of the Pickering Beck on Figure 9). Dale & Thomas (2015) report that these sinks (and others in the hills in this area) feed Keld Head and Costa Beck Rising near Pickering to the south. It is not clear if this connection has been proven by tracer testing. They also report that there are multiple small sinks and springs along the River Seven. Thomas (2010) notes that Environment Agency (1997a) suggest that the River Seven and the Gundale Beck are losing rivers, with swallow holes in the bed of the Gundale Beck. York Caving Club (2014) note that there are several stream sinks in the

Gundale Beck, including a major stream sink at [SE 802868], that was in a 4-5 m wide depression 0.5 to 0.6 m deep which took flows of several $l.s^{-1}$.

There are major stream sinks in the beds of the Hutton Beck and the River Dove which resurge at Bogg Hall Spring (Dale & Thomas, 2015; see also Section 3.1 on tracer testing). In the Hutton Beck, water sinks into the Excalibur Pot cave system (Section 2.1.1, Plate 28). The highest stream sink is known as “Top Sink”. The ‘Big Sandy Sink’ is another notable stream sink (Plate 29), and there are several other locations downstream where the water sinks in wet weather. York Caving Club (2021) note that in dry weather all of the water in the River Dove sinks, and that the stream sinks in the River Dove are only about 4-5 metres higher than the elevation of the Bogg Hall Rising, explaining why this conduit system is mostly phreatic (sub-water table). York Caving Club (2021) suggests that around 10-20 % of the water at Bogg Hall Rising comes from Hutton Beck and note that in contrast to the River Dove sinks, the stream sinks in the Hutton Beck are about 40 m higher than the Bogg Hall Rising. This means that much of the conduit system fed by these stream sinks is unsaturated, as observed in the vadose stream passages found in Excalibur Pot (Section 2.1.1). Flow measurements carried out on 18th November 2012 indicated that 138 $l.s^{-1}$ sank in the Hutton Beck, and 543 $l.s^{-1}$ sank in the River Dove; with measurements on 19th July 2013 indicating that 22 $l.s^{-1}$ was sinking in the Hutton Beck and 223 $l.s^{-1}$ was sinking in the River Dove (York Caving Club (2014).

Dale & Thomas (2015) report that the Hodge Beck sinks in Kirk Dale, and suggest that most of this water flows to How Keld springs, although it is not clear if this has been tested with tracers. They also suggest that the River Riccal flows underground for less than a kilometre, and that the River Rye sinks into alluvium at Duncombe Park and flows through the Malton Oolite Member for 2.4 km before emerging through alluvium.

Overall there are a number of substantial stream sinks in the J1 area. However, there is no comprehensive dataset on all the sink points, so there are likely to be many more than shown on Figure 9. A systematic field survey of the area would be useful.

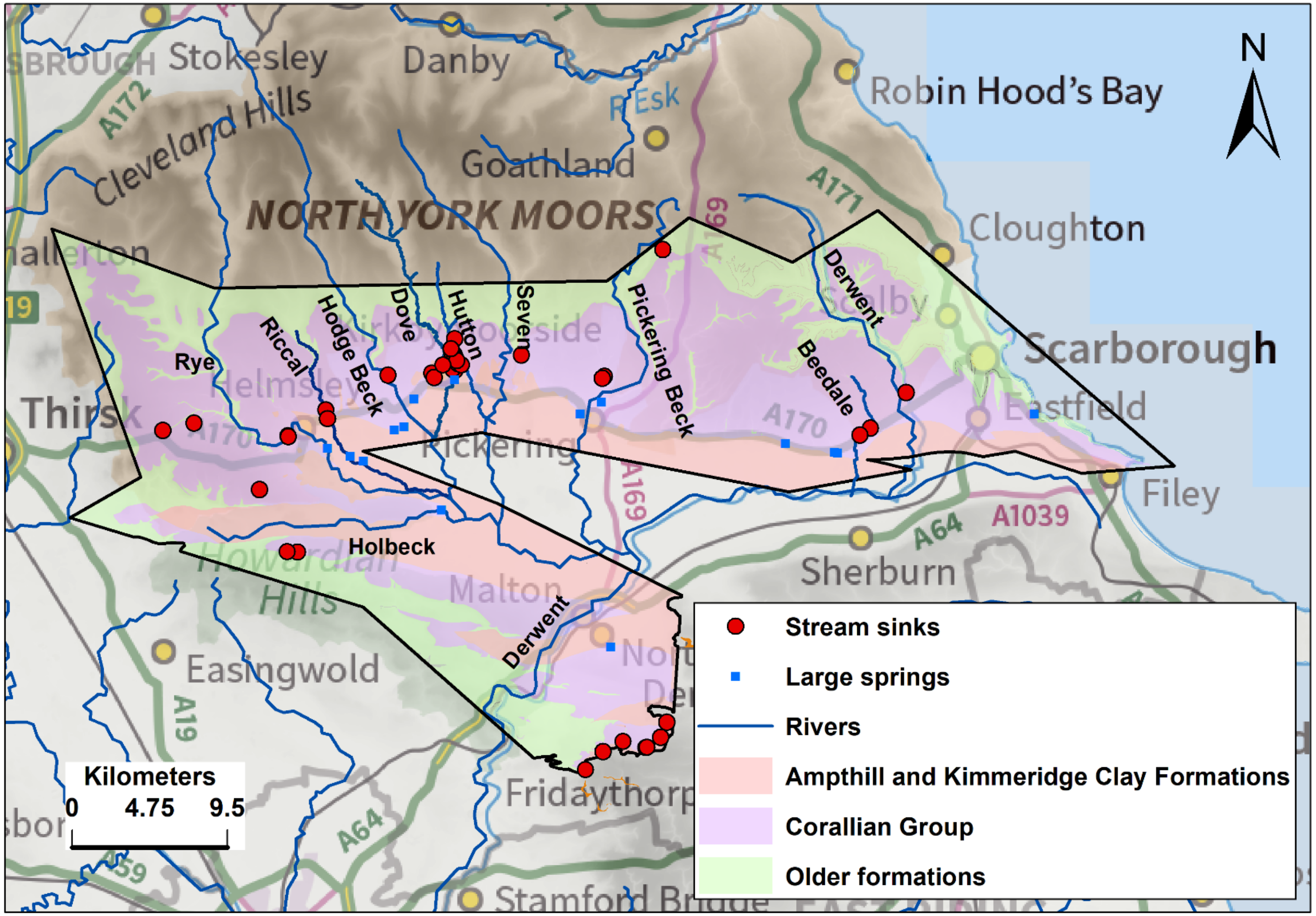

Figure 9. Stream sink locations.

Plate 28. Water sinking at the future site of Excalibur Pot cave entrance (June 2007). Photo courtesy of Gary Douthwaite, York Caving Club.

Plate 29. Large stream sink known as Big Sandy Sink, near Excalibur Pot cave. Photo courtesy of John Dale.

Plate 30. Sink on the River Riccal. Photo courtesy of Gary Douthwaite.

2.3 SPRINGS

There are hundreds of records of springs in the J1 Jurassic limestone area (Figure 10). Records are predominantly from the BGS springs database which is clipped to the Corallian Group in Figure 10. There are a small number of sites recorded in tracer test reports and in the Environment Agency water quality monitoring springs dataset. Springs are widely distributed throughout the area, and the springs shown on Figure 10 do not include all of the springs that are shown on recent or old Ordnance Survey maps, which were not systematically digitised for this study.

Allen et al. (1997) report that there are many small springs located along the northern margin of the outcrop at the contact between the Corallian Group and the underlying Oxford Clay. Large springs occur along the southern, down-dip margin of the outcrop, where water sinking in the various stream sinks resurges. These springs are developed where the Corallian Group limestones dip beneath the overlying Ampthill and Kimmeridge clays, and are often associated with faulting (Reeves et al., 1978; Allen et al. 1997), with major springs on the Helmsley-Filey fault at Brompton and Cayton Bay, and other more minor springs associated with this fault (Foley et al., 2012).

Spring discharge data are generally sparse and it was only possible to identify the locations of 15 springs which are known to be large (Table 4 and red circles on Figure 10). Some other large springs are mentioned in the literature, but without location data. It is probable that many of the other springs (blue circles on Figure 10) are also large; and it is also likely that some spring discharges have declined since the development of water resources for supply. Further information on major springs is provided here, moving from east to west through the northern part of the area, and then considering the southern part of the area.

Cayton Bay springs are the most easterly of the identified major springs and occur on the coast to the south of Scarborough. They are reported to have an average flow of 91 $l.s^{-1}$ (Carey & Chadha, 1998).

Moving west, there are two springs at Brompton (north of Sherburn on Figure 10) which are approximately 200 m apart; one is at the Mill Pond and the other is at Brompton Hall school (Foley, 2006). These springs issue from fissures in the Malton Oolite Member, with those at the Mill Pond extending along the northern edge of the pool over a distance of about 50 m (Foley, 2006). The springs are located on the Ebberston-Filey fault, and have flows ranging from ~ 60 to > 700 $l.s^{-1}$, and an average of 146 $l.s^{-1}$ (Carey & Chadha, 1998). Foley (2006) also reports that there are springs at Welldale between Brompton and Ebberston which have about 25 % of the discharge of Brompton springs, so are clearly substantial.

Moving further west, Keld Held springs have very substantial flows and high turbidity (Thomas, 2010) suggesting karstic sediment transport. These major springs are located about 0.5 miles west of Pickering. Reeves et al. (1978) report low flows from 1972 of 476 $l.s^{-1}$. Thomas (2010) suggests average flows of 45,500 m^3/day (527 $l.s^{-1}$) were reported by the Environment Agency (1997a). Thomas (2010) also notes that Keld Head springs have a fairly constant discharge, which is thought to be because the hydraulic gradient is low and under high flow conditions higher ephemeral springs near Newbridge (approximately 1.5 km to the northeast of Keld Head) are activated. Dale & Thomas (2015) note that Keld Held and Costa Beck rising to the west of Pickering both have flows of up to 300 $l.s^{-1}$, and suggest that the water comes from sinks in the Gundale Beck and other sites in the hills to the north. It is not clear from Ordnance Survey maps where these two different springs are. However, during tracer tests (see Section 3.2), Thomas (2010) monitored two points at Keld Head springs: “Costa Beck east” and “Costa Beck west”. These sites are both within 150 m of the location of the main Keld Head spring on Ordnance Survey maps and presumably represent channels coming from two different spring pools at the Keld Head springs, which may be the two springs referred to by Dale & Thomas (2015). Environment Agency (1997a) also suggest that the Pickering Beck is a gaining river (Thomas, 2010), although no specific springs are described by Thomas (2010). Tracer was detected at a monitoring site in the Pickering Beck (see Section 3.2). This monitoring point is just upstream of the Newbridge overflow springs (Figure 3.4 of Thomas, 2010), suggesting that there are additional springs in the Pickering Beck upstream of this point.

The Bogg Hall Rising is a major spring on the River Dove which is the resurgence for the Excalibur Pot cave system (Section 2.1.1). There are some flow data for Bogg Hall Rising. Waters-Marsh (1984) reports flows of 454 $l.s^{-1}$. York Caving Club (2014) measured flows of 750 $l.s^{-1}$ on 18th November 2012 and flows of 257 $l.s^{-1}$ on 19th July 2013. These were comparable (although 10 and 4.7 % higher respectively) than the combined flows measured sinking into the Hutton Beck and River Dove stream (Section 2.2); and York Caving Club (2014) suggested that most of the water at the Bogg Hall Rising may be derived from the sinks in these two rivers. The difference may be measurement error, although there may be additional groundwater discharge at Bogg Hall Rising, which is also indicated by the additional stream within the Excalibur Pot cave system which comes from the south (Section 2.1.1). Dale & Thomas (2015) note that sometimes there is less water discharged at the Bogg Hall Rising than is sinking in the River Dove and the Hutton Beck, suggesting that there is leakage to the deeper aquifer.

Seven large springs are described by Reeves et al. (1978) who provide some discharges for these springs during low flow conditions in 1972 (Table 4). Despite the low flow conditions these springs all had big flows ranging from 46 to 312 $l.s^{-1}$. These include How Keld spring, to the east of the Hodge Beck. Dale & Thomas (2015) suggest that this spring is fed by stream sinks in Kirk Dale on the Hodge Beck although it is not clear if this has been demonstrated by tracer tests. Wombleton and Welburn springs are located to the west of the Hodge Beck, whilst Red Carr Hill and Harome springs are located in the valley of the River Riccal, and Rye House spring is on the River Rye. Major springs are also described at the heads of the Rye and the Riccal rivers, issuing from the base of the Corallian (Allen et al., 1997). The locations of these large springs are not known although it is likely that they may be some of the springs identified on Figure 10 in the headwaters of these rivers. Dale & Thomas (2015) report that the River Rye flows underground through the Malton Oolite Member before emerging through alluvium, and although no discharge is given, it is likely that this is a substantial spring. They may be referring to Rye House spring reported by Reeves et al. (1978). The seventh large spring reported by Reeves et al. (1978) is at East Ness on the Holbeck, a southern tributary of the River Rye (Figure 10).

A “large” spring is reported at Norton (Allen et al., 1997), although the discharge of this spring is unknown. Carey & Chadha (1998) also report that there are groundwater discharges from the Corallian Limestone along a number of northern escarpment springs, and to the Bee Dale and Swaden Becks, and River Hertford with individual flows of ~ 5 to 35 $l.s^{-1}$, but the locations of these springs are not known.

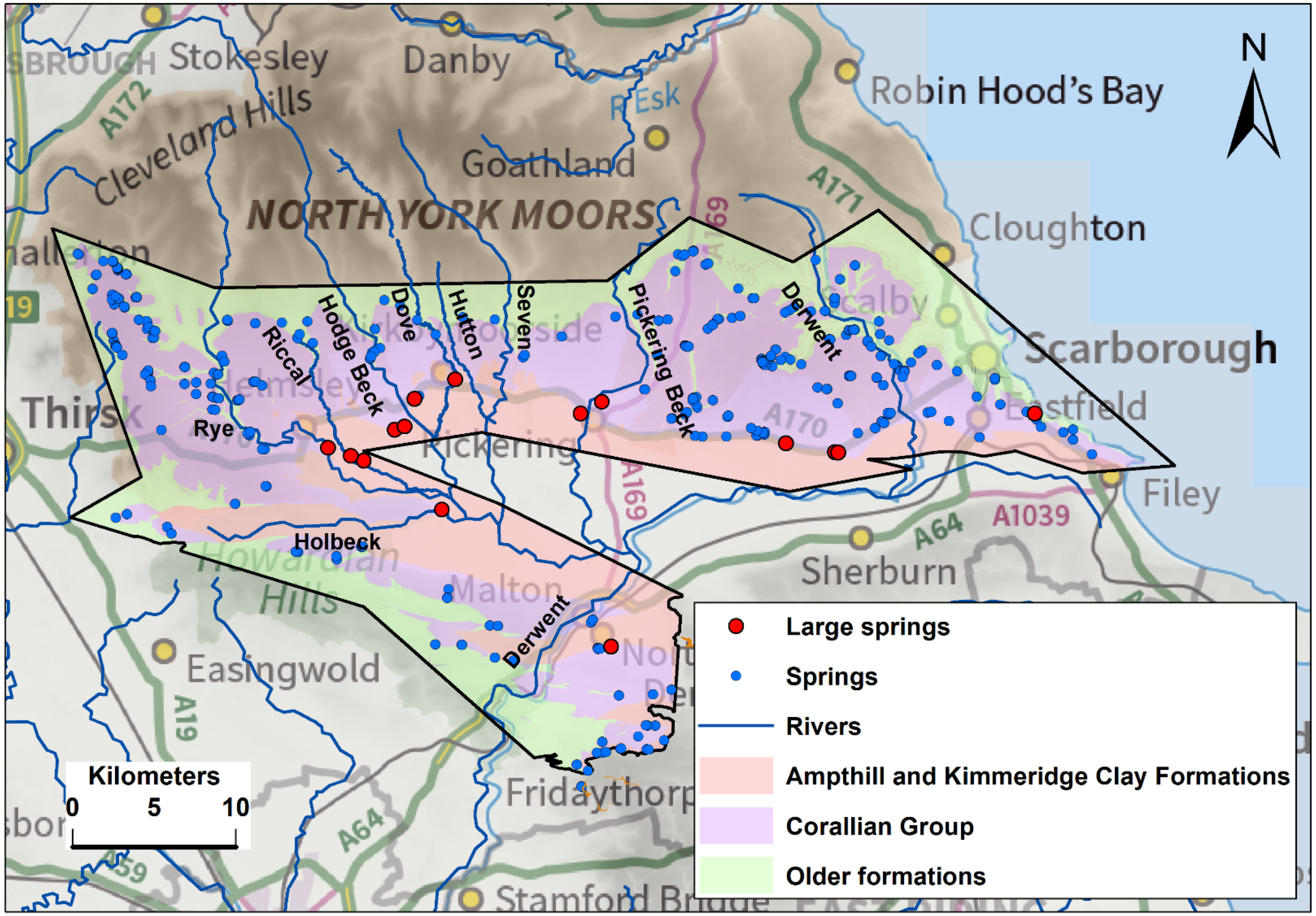

Figure 10. Spring locations.

Table 4. Details of large springs recorded in the J1 Jurassic Limestone area.

Spring	Location	East	North	Discharge ($l.s^{-1}$)	Source
Cayton Bay Springs	Cayton	506600	484500	91 (average)	Foley et al. (2012) location; Carey & Chadha (1998) discharge
Brompton springs	Brompton	494316 494511	482136 482101	~ 60 to > 700, average 146	Foley (2006) locations; Carey & Chadha (1998) discharge
Welldale	Welldale	491317	482683	~ 25% that at Brompton	Discharge: Foley (2006)
Keld Head	Pickering	478708	484512	527; 476*	Discharge: Environment Agency (1997a) reported in Thomas (2010); Reeves et al. (1978)
Keld Head overflow springs	Newbridge	480029	485210	Unknown but tracer test monitoring site	Thomas (2010)
Bogg Hall Spring	Kirkbymoorside	471000	486600	454; 257-750	Waters-Marsh (1984); York Caving Club (2014)
How Keld Mill	East of Hodge Beck	468500	485400	312*	Reeves et al. (1978)
Wombleton/ Welburn	West of Hodge Beck	467300 467900	483500 483700	127*	Reeves et al. (1978)
Red Carr Hill	River Riccal	465400	481600	46*	Reeves et al. (1978)
Harome	River Riccal	464600	481900	104*	Reeves et al. (1978)
Rye House	River Rye	463200	482400	243*	Reeves et al. (1978)
East Ness	Holbeck	470200	478600	162*	Reeves et al. (1978)
Norton	Norton	480600	470200	“large”	Allen et al. (1997)

* summer (low) flows 1972 (from Reeves et al. (1978))

Plate 31.   Cave diver at Bogg Hall spring. Photo courtesy of John Dale.

2.4 DOLINES AND DISSOLUTION PIPES

The BGS karst database has not been completed in this area, and LiDAR data have not been considered for this report. No dolines or dissolution pipes are recorded in the J1 area in either the BGS karst database or the Natural Cavities database which is a legacy dataset held by The British Geological Survey and Peter Brett Associates. This dataset comprises data from a range of sources originally commissioned by the Department of the Environment and by Applied Geology Limited (1993). It is however likely that there are dolines and dissolution pipes in this area, given the high degree of karstification and cave development. York Caving Club (2021) note that surface depressions in the area of the Excalibur Pot cave system were previously thought to be pits of anthropogenic origin, but the discovery of the cave passages directly beneath them suggest that these may be karst dolines. Determining whether surface depressions are karstic in origin can be difficult. For example a surface depression near Levisham (just east of the upper reaches of the Pickering Beck at SE 81982 91867) may be a karst doline or could be a depression caused by a landslip cave, or a mine working (Plate 32). Further work is needed in the J1 area to determine where dolines and dissolution pipes are present.

Plate 32. Depression near Levisham. Photo courtesy of Gary Douthwaite.

3 Tracer tests

Stream sink, borehole and soakaway injection tracer tests have been conducted at a small number of locations on the Corallian Group limestones within the J1 area (Figure 11). These are described below. In addition, Allen et al. (1997) suggest that the National Rivers Authority, Yorkshire Region (1989) reported rapid flow rates of 2 to 3500 m/day through solutionally enlarged fractures at East Ness (located in the south of the J1 area, see Figure 11). It is not clear whether these refer to tracer tests. They also report high transmissivities of > 1700 m^2/day in this East Ness area. It is apparent from Figure 11 that most areas have not been investigated using tracer tests.

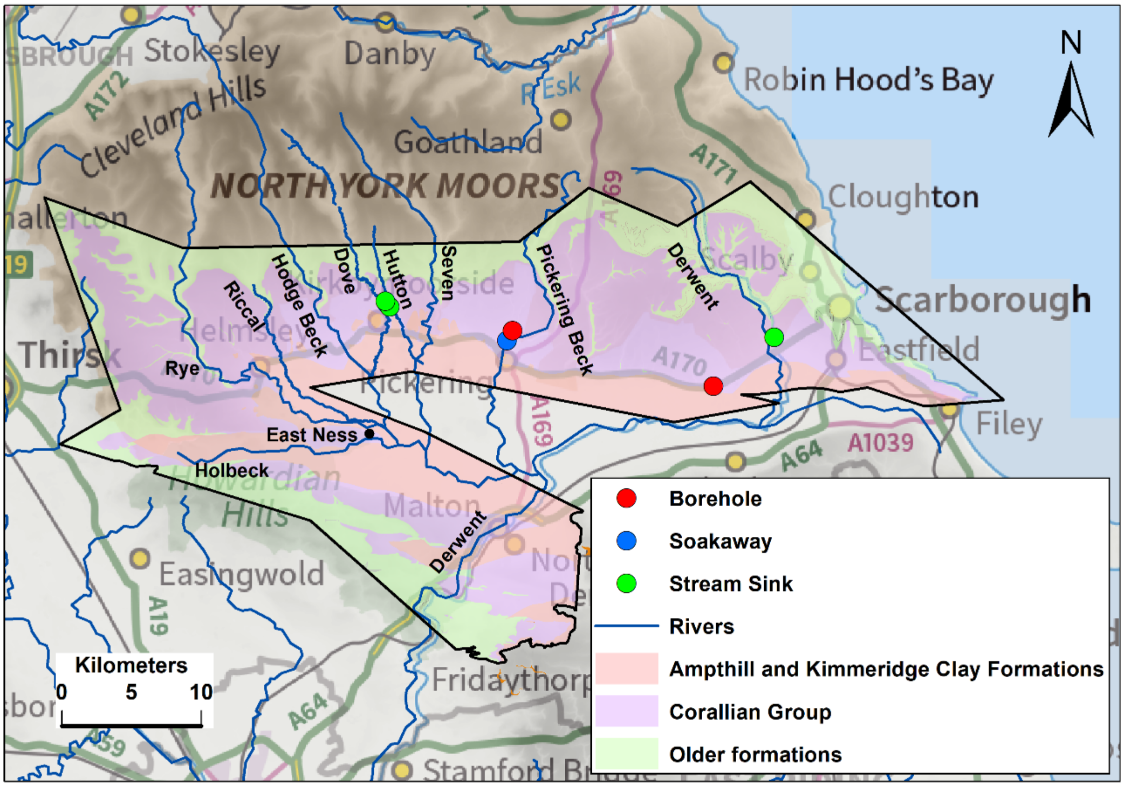

Figure 11. Tracer test injection sites.

3.1 STREAM SINK TRACER TESTS

In the east of the J1 area, tracer tests have been conducted by several authors in the River Derwent catchment since 1908 (Richardson, 1934; Morton, 1938; Environment Agency 1997b; Atkinson, 1999; Foley, 2006; Foley et al., 2012). Using multiple tracers, these tests have demonstrated groundwater flow pathways from the Forge Valley swallow holes to 13 boreholes (Figure 12). The outputs where tracers were detected are predominantly distributed to the south and southeast, with tracer spreading out from the injection site reflecting the recharge mound created by the swallow holes (Foley et al., 2012). No tracer from the Forge Valley swallow holes was detected at Brompton springs or Cayton Bay springs (Foley et al., 2012). Groundwater velocities based on time to peak concentration range from 18 to 13000 m/day over distances of between 18 and 7250 m. The median velocity for these tests is 390 m/day. Foley et al. (2012) note that all groundwater velocities were very rapid, but that those from the swallow holes to the major abstraction at Irton are an order of magnitude higher than velocities to the other monitoring sites. Tracer recoveries have only been calculated for two of these connections (Table 5) and these range from 5 to 49%, suggesting relatively low dilution/attenuation along these two pathways.

The tracer tests conducted by Foley et al. (2012) involved the use of a range of different types of tracer (bacteriophage, SF_6, Sodium Fluorescein and Photine CU), which provide analogues for the transport of different types of contaminants (Foley et al., 2012). The use of the gas SF_6 as a groundwater tracer over large geographical scales is probably the first such application, with the development of an innovative tracer injection system (for details see Foley, 2006). Breakthrough curves for many of these tests show a rapid initial breakthrough, quite a rapid drop to low concentrations and an elongated tail (e.g. Figure 13). The tracer tests demonstrated that tracer was discharged for a month at Irton, and for 30-50 days at sites within 2 km of the injection site, demonstrating the potential for fairly prolonged contaminant discharge in the event of a pollution incident in the River Derwent. The long tails in the tracer breakthrough curves were thought to be due to advection-dispersion and diffusion between the karstic network and the unmodified fracture network that is extensive within the limestone. Foley et al. (2012) provide details of the implications of the tracer testing for understanding the hydrogeology of the area, and the implications of the karst for groundwater management, highlighting the limitations of groundwater modelling in karst without information from tracer tests. The results of the tracer tests were used to re-define the Source Protection Zones in the Scarborough area (see Section 4).

Near Kirkbymoorside, connections from two stream sinks (one in the Hutton Beck, and one in the River Dove) to the Bogg Hall Risings were demonstrated by tracer tests (Kendrick, 1979; Waters-Marsh, 1983). Westerman (1981) discusses tracer tests carried out by Kendrick (1979) between the Hutton Beck and Bogg Hall that resulted in a “diffuse” tracer peak which was interpreted as “multiple overlapping peaks”. It was suggested that minor N-S trending faults were guiding the flow in the Corallian aquifer. These flow paths are in fact characterised by both very rapid groundwater flow and low attenuation of tracer. Rapid velocities of 4500 m/day over 1500 m, and 4000 m/day over 1000 m (based on the time taken to reach peak tracer concentration) were observed in tracer tests from the Hutton Beck and the River Dove by Waters-Marsh (1983). The tracer recoveries were high, 99.7% and 55% (Table 5). More recent tracer testing has been carried out here by cavers. These suggest that water entering the River Dove stream sinks flow via two other short caves (Guinevere’s Slit and The Well) en-route to Bogg Hall. Similarly, the flood overflow sinks in Hutton Beck do not join the main steamway in Excalibur Pot, but take an independent route to the spring (York Caving Club, 2021). The tracer tests by cavers are reported by York Caving Club (2014) and Matt Ewles (personal communication, 2022). Tracer injected at Excalibur top sink arrived at Bogg Hall risings between 2.5 and 3 hours later, indicating a velocity of at least 12 km/day over a 1550 m distance. Tracer injected in a sink near the Jenga Pot entrance reached Bogg Hall in 5 to 5.5 hours indicating a velocity of approximately 5 km/day over the 1200 m distance (see Figure 14). York caving club also did a ‘tracer test’ at Excalibur Pot by diverting water into a relict sink on the surface and observing where it entered the cave system (York Caving Club, 2014).

The rapid velocities indicated by the tracer tests in the Corallian limestone in this area suggest very low effective porosity. Worthington et al. (2019) suggest an effective porosity of 0.000147 based on the River Derwent tracer tests of Foley (2006).

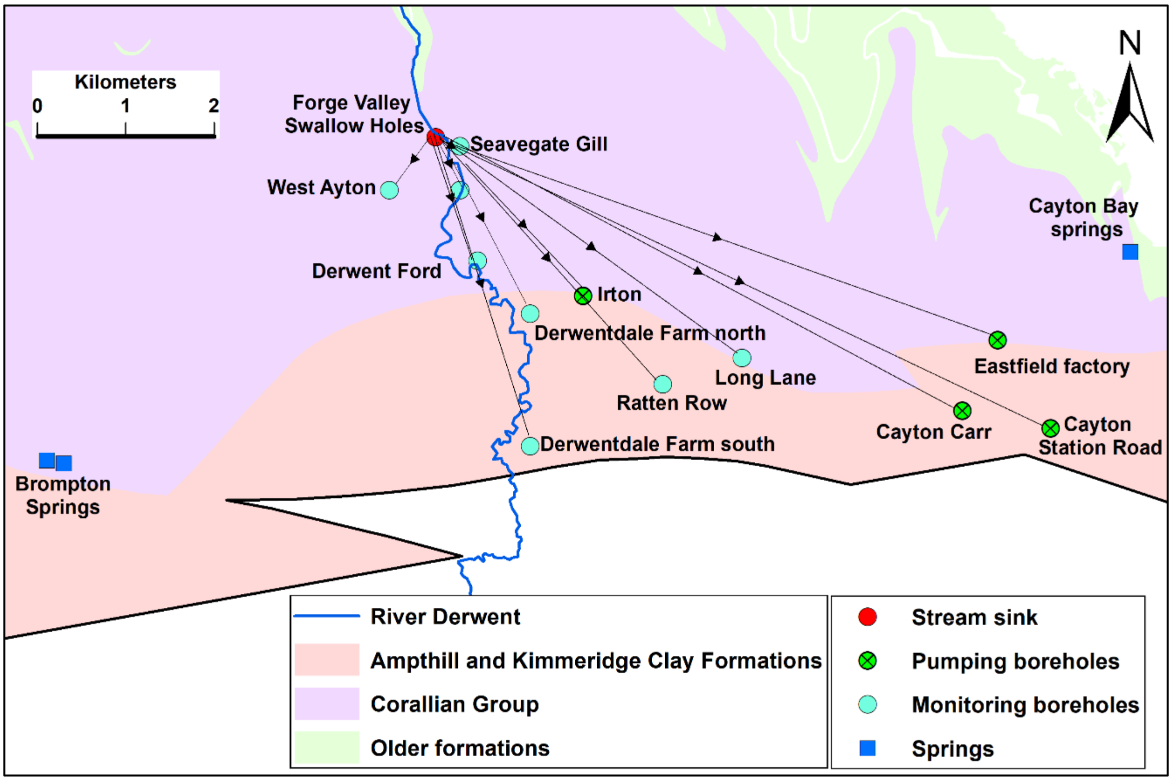

Figure 12. Groundwater flow pathways from tracer tests by Foley (2006), Foley et al. (2012), Morton (1938) and Atkinson (1999) in the Derwent Catchment.

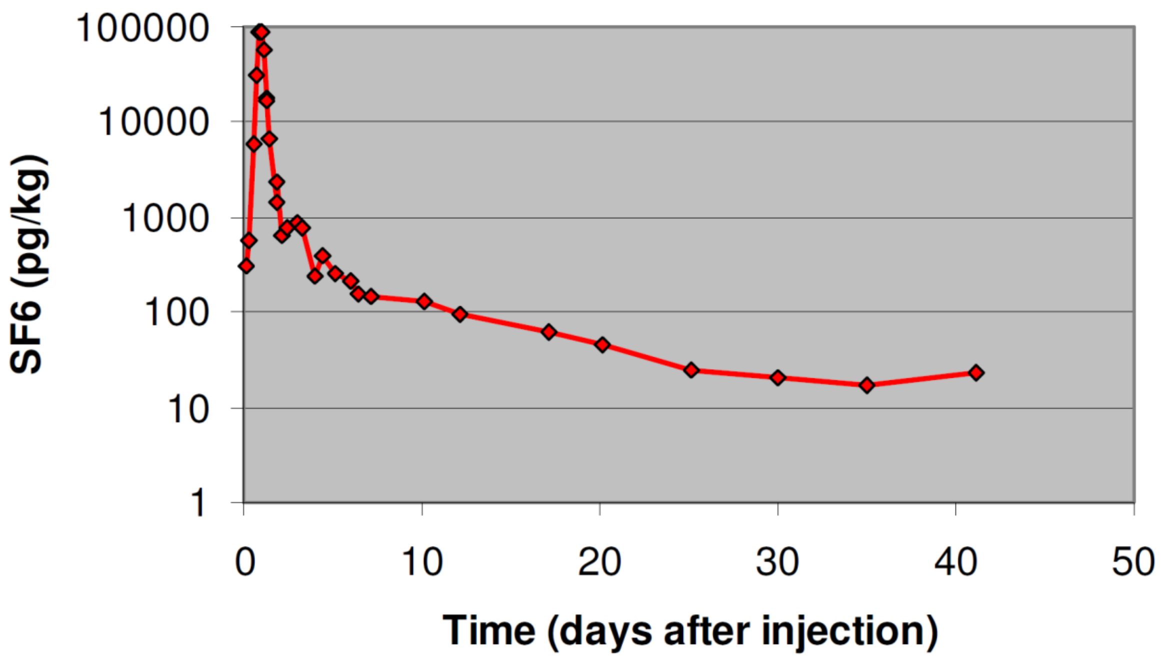

Figure 13. Example of sulphur hexafluoride breakthrough curve at Derwentdale Farm North from injection at Forge Valley swallow holes. (from Foley, 2006. Reproduced with permission).

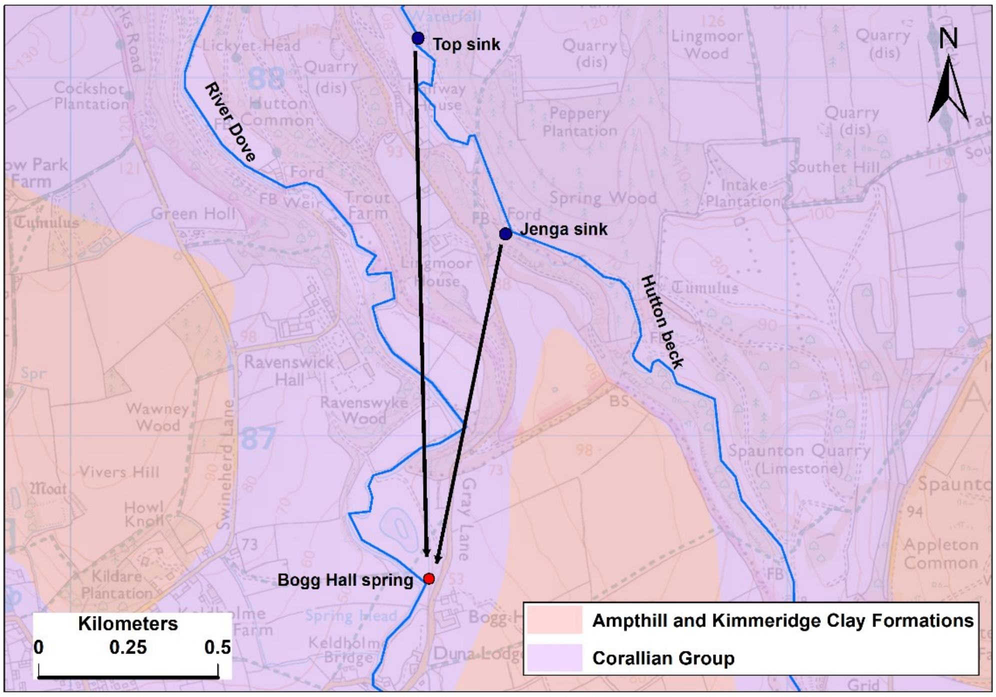

Figure 14. Tracer connections demonstrated by York Caving Club.

3.2 BOREHOLE AND SOAKAWAY TRACER TESTS

Qualitative tracer tests in Brompton demonstrated two borehole to spring connections (Mottram, 2003; Foley, 2006). Tracer was recovered at the Brompton Mill Pond and Brompton Hall School springs. Velocities based on time to peak concentration of 190 and 100 m/day were measured over 190 and 200 m respectively.

At a quarry near Pickering, bacteriophage tracers were injected into one soakaway and one borehole (Thomas, 2010). MS2 bacteriophage from the soakaway was detected at Keld Head springs (Costa Beck East and Costa Beck West) and the Pickering Beck, but no tracer was detected at the Keld Head abstraction borehole (Figure 15). *Serratia Marcescens* injected into a borehole at the quarry was detected at Keld Head borehole 63 days after injection. These tracer tests indicated fairly rapid groundwater flows of 35 to 175 m/day over distances of 770 to 2200 m (Table 5). For the tracer test from the soakaway, in calculating the groundwater velocities, Thomas (2010) assumed that there was no movement of tracer until the first rainfall after the tracer injection which occurred 17 days later (and therefore the travel time was 8 days to Keld Head springs (Costa Beck east and Costa Beck West), and 11 days to the Pickering Beck).

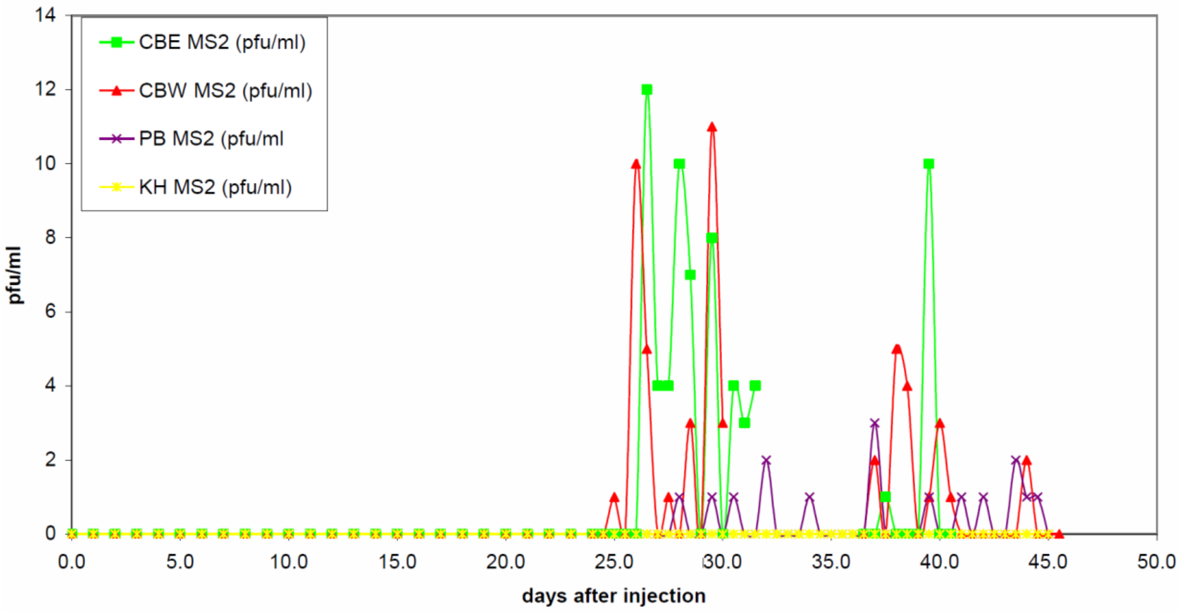

Figure 15. Tracer breakthroughs from soakaway injection near Pickering (from Thomas, 2010. Reproduced with permission).

CBE = Costa Beck east, CBW = Costa Beck west, PB = Pickering Beck, KH = Keld Head abstraction borehole.

3.3 SINGLE BOREHOLE DILUTION TESTS

Foley (2006) undertook single borehole dilution tests in 7 observation boreholes (three in the vicinity of the Forge Valley Swallow Holes, two to the southwest at Brompton and two in between). In all boreholes there was rapid dilution of tracer with concentrations generally returning to near background levels within hours, suggesting rapid groundwater flow in the aquifer. In some boreholes, dilution was extremely rapid at specific horizons, with tracer returning to background within a few minutes or tens of minutes (Foley, 2006).

Table 5. Summary of tracer tests conducted in the J1 area, velocities are based on the time taken to reach peak tracer concentration (S = spring; B = borehole)

Authors	Area	Input	Output	Injection type	Distance	Velocity	Recovery
Waters-Marsh (1984)	Kirkbymoorside	Hutton Beck swallow hole	Bogg Hall Spring (S)	Stream sink	1500 m	4500 m/day	99.70%
		River Dove swallow hole	Bogg Hall Spring (S)	Stream sink	1000 m	4000 m/day	55.00%
Foley (2006); Foley et al. (2012); Morton (1938); Atkinson (1999)	Derwent catchment	Forge Valley swallow holes	Irton PWS (B)	Stream sink	1950 m	9100 - 13000 m/day	5 - 49 %
			Augmentation borehole (B)	Stream sink	18 m	18 m/day	N/A
			Derwent Ford (B)	Stream sink	1000 m	260 m/day	N/A
			Swallow-holes (B)	Stream sink	10 m	170 - 190 m/day	N/A
			West Ayton (B)	Stream sink	875 m	1140 m/day	N/A
			Eastfield factory (B)	Stream sink	6250 m	520 m/day	N/A
			Cayton Carr PWS (B)	Stream sink	6250 m	600 m/day	N/A
			Long Lane (B)	Stream sink	3650 m	240 m/day	N/A
			Ratten Row (B)	Stream sink	3200 m	N/A	N/A
			Seavegate Gill (B)	Stream sink	500 m	100 - 250 m/day	N/A
			Derwentdale Farm North (B)	Stream sink	1750 m	2210 m/day	34%
			Derwentdale Farm South (B)	Stream sink	3000 m	75 m/day	N/A
			Cayton Station Road PWS (B)	Stream sink	7250 m	2320 m/day	N/A
Mottram (2003)	Brompton	Brompton-by-Sawdon shallow borehole	Brompton Mill Pond Spring (S)	Borehole	190 m	190 m/day	N/A
			Brompton Hall School Spring (S)	Borehole	200 m	100 m/day	N/A
Thomas (2010)	Pickering	Pickering Quarry borehole	Keld Head abstraction borehole	Borehole	2200 m	35 m/d	N/A
		Pickering Quarry soakaway	Keld head (Costa Beck West) (S)	Soakaway	1400 m	175 m/day	7.1%
			Keld Head (Costa Beck East) (S)	Soakaway	1400 m	175 m/day	13.1%
			Pickering Beck (S)	Soakaway	770 m	70 m/day	3.3%

4 Other evidence of karst and rapid flow

There is considerable evidence of karst from boreholes in the J1 Corallian limestone area. Transmissivity is very variable (Figure 16), but there are some high (and in some places exceptionally high) transmissivities suggesting that there are extensive networks of solutional fissures and conduits. The data are predominantly from the British Geological Survey aquifer properties database (Allen et al., 1997), in which the “best” estimate of transmissivity was estimated from pumping test reports. Other data are from a table in Foley (2006) reporting transmissivity values from Barker & Courchee (1982) and Aspinwall & Co (1994,1995). This is reproduced here in Table 6, with some comparisons to the aquifer properties database where data are available from both sources. For some sites Foley (2006) reports a range of transmissivity values from the original sources, and the minimum reported value is used in Figure 16.

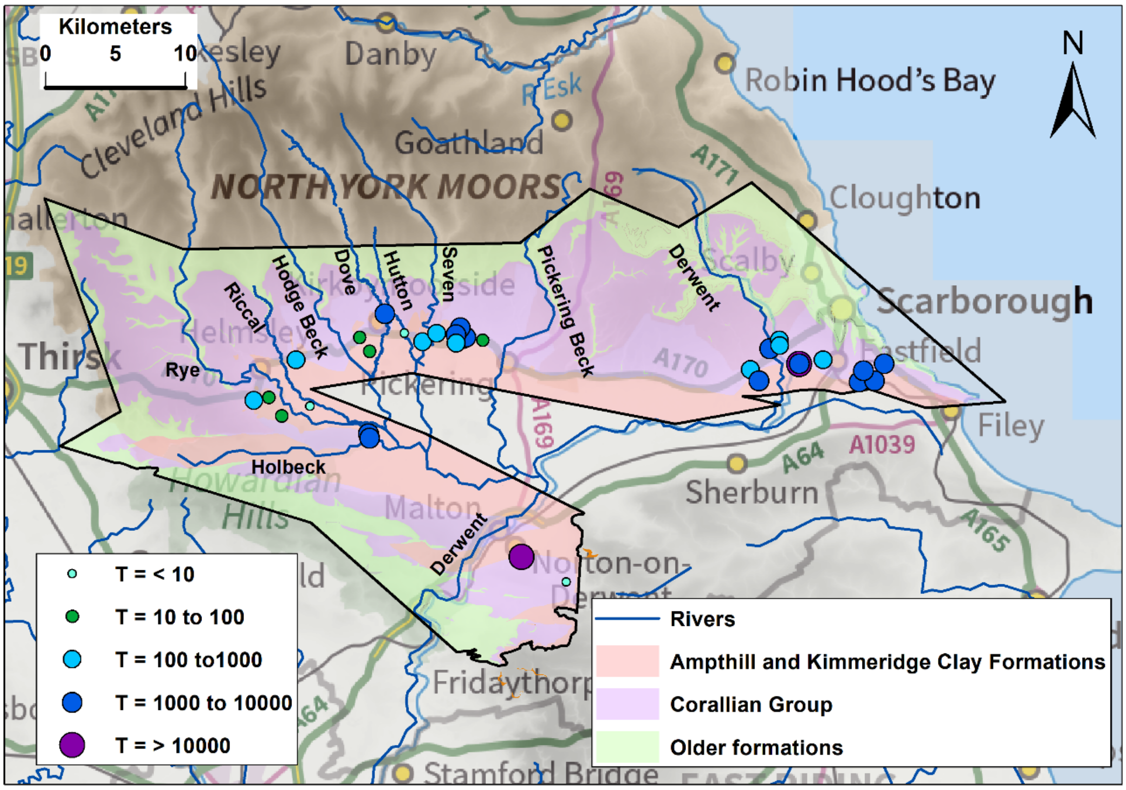

Figure 16. Transmissivity (T) in m^2/day in the J1 Jurassic Limestone area

Name	East	North	T	Reference reported by Foley (2006)	BGS aquifer properties T
Irton old well	500400	484000	5640-6980	Barker & Courchee (1982); Aspinwall and Co. (1994 and 1995)	6300
Irton new well	500400	484000	36500	Barker & Courchee (1982); Aspinwall and Co. (1994 and 1995)	no data
Irton OBH	500400	484000	9290	Aspinwall and Co. (1994 and 1995)	no data
Cayton station road	504700	482700	3558-12450	Aspinwall and Co. (1994 and 1995)	8000
Osgodby pumping station	506500	484000	3285	Aspinwall and Co. (1994 and 1995)	no data
McCains	505000	483500	4115-40349	Aspinwall and Co. (1994 and 1995)	3400
Seavegate Gill	498987	485707	35-80	Barker & Courchee (1982)	420
Swallowholes BH	499000	485300	800-1000	Barker & Courchee (1982)	no data
West Ayton quarry	498200	485200	1400	Barker & Courchee (1982)	1500
Wykeham village hall	496900	483600	200	Aspinwall and Co. (1994 and 1995)	no data
Tetherings plump	497500	482800	10000	Aspinwall and Co. (1994 and 1995)	no data

Table 6. Transmissivity (T) in m^2/day reported by Foley (2006) with comparative data from the BGS aquifer properties database (Allen et al., 1997) for some sites

Allen et al. (1997) report that for the Corallian limestones of the Cleveland Basin there are 29 locations with transmissivity data, ranging from 0.2 to 16,000 m^2/day with a geometric mean of 318 m^2/day. They note that some transmissivity values are from boreholes which were drilled to investigate geological structure, rather than boreholes aimed at obtaining the highest yields. This may account for the lower values compared to many areas with aquifer properties data in England, where transmissivity data are more biased to high yielding sites. Allen et al. (1997) report that transmissivity was usually very low for the main aquifer outcrop because of the small saturated thickness, with much higher transmissivity near the confined aquifer. They also note that Yorkshire River Authority (1973) reported that boreholes near to large springs at Keld Head and Norton have very large specific capacities and are therefore likely to have high transmissivities; and that Monkhouse & Richards (1982) suggest that there are high yields close to faults; as well as reporting a high pumping rate of 158 $l.s^{-1}$ in a single borehole at Irton, which is indicative of flow from karstic networks.

Groundwater in the Corallian limestone responds rapidly to rainfall with rapid changes in groundwater head (Allen et al., 1997), and storage in the aquifer is low (Reeves et al., 1978). In the report on tracer testing in the Brompton area (Mottram, 2003), very similar patterns in discharge data from the Brompton Beck and nearby groundwater levels in an observation borehole are shown, suggesting good connectivity between the river and groundwater. The data also show that these sites have a rapid response to rainfall.

Several borehole geophysical logging studies have demonstrated that flow to boreholes is through a small number of karstic solutional fissures (Tate et al., 1970; Reeves et al., 1978; Foley, 2006; Buckley & Howlett, 2014). Borehole investigations (including logging, CCTV and the use of saline tracers) were conducted in two wells at Irton (Tate et al., 1970). Strong inflows were identified, with saline tracers indicating very rapid vertical flows of ~ 2 to 20 m/s within the wells. In Irton "Old Well" there were two major inflows visible on CCTV (as well as apparent from the other logs) at 115 feet (35m) and 184 feet (56 m) depth, with most flow from the upper horizon (a bit less than 50 $l.s^{-1}$). Foley et al. (2012) report that this upper flow horizon was the main source of tracer during tracer tests to this site, with downward flow from this inflow and no/very little evidence of tracer above this. Reeves et al. (1978) note that geophysical logging at four boreholes in the Corallian limestones indicated fissure flow, for example at the South Ings artesian borehole, where two thirds of the flow came from a fissure ~64 m below ground level, and the rest from a fissure at ~73.5 m. Geophysical logging (including CCTV imaging and flow logging with and without pumping of the nearby abstraction) of a borehole drilled at Cayton Carr in the 1990s identified flow horizons in the Malton Oolite, Coral Rag and Hambleton Oolite Members (Buckley & Howlett, 2014). A major flow zone was found at the same stratigraphical horizon as the West Ayton swallow holes. Pumping tests (pumping at 57.0, 84.5 and 128 $l.s^{-1}$) are discussed by Buckley & Howlett (2014) who reported that from 5 minutes into the test, water was derived from an approximately linear feature. From the logging and pumping tests at Cayton Carr, Buckley & Howlett (2014) concluded that very rapid flow in karstic conduits occurs in both the oolite members. Most of the flow at Cayton Carr Standby borehole was from a conduit system in the deeper Hambleton Oolite Member fed by some longer time residence water; with the remaining flow in the Malton Oolite and Coral Rag members directly from the River Derwent at West Ayton. The geophysical logging that has been undertaken in the area is reviewed by Foley (2006) who also reports logging at three new boreholes in the vicinity of the Forge valley swallow holes; where inflowing, outflowing and crossflowing horizons were identified.

There is clear evidence of karstic systems in the Jurassic limestones in this area which are comparable to highly karstic aquifers, with a high proportion of rapid recharge at some groundwater outlets. For example, Foley et al. (2012) estimate that 80-95% of water at Irton is river water, based on tracer tests, major ion chemistry and previous studies of tritium reported by Tate et al. (1970). At Cayton Carr abstraction, it was estimated that 36.3 % of the water was recent recharge (Buckley & Howlett, 2014). Water quality indicators of rapid groundwater flow at 6 groundwater abstraction sites in the Jurassic limestones are variable (knowledge exchange with Yorkshire Water). Five of these sites show some evidence of a rapid groundwater flow component. This ranges from a strong indication of rapid flow, to sites where indicators of rapid groundwater flow are sometimes present, but at low levels, perhaps suggesting attenuation/dilution with longer residence time groundwater.

Karst data and the results of tracer tests (Foley, 2006; Foley et al., 2012) were used by Buckley & Howlett (2014) to develop a bespoke karst methodology to redefine the groundwater Source Protection Zones (SPZs) for four abstractions in the Scarborough area (Irton, Cayton Carr Lane, Cayton Station Road and McCains). The SPZs for these abstractions were previously defined with MODFLOW modelling which could not represent the karstic nature of the aquifer (Foley, 2006; Foley et al., 2012; Buckley & Howlett, 2014). This resulted in very small areas for SPZ1 (the area in which groundwater takes 50 days to travel through the saturated zone, see Figure 17). The report by Buckley & Howlett (2014) describes the lines of evidence that were used to justify the new SPZs, which have large SPZ1s that include the rivers which sink into karst features supplying the abstractions with very rapid travel times. The revised SPZs for Irton are shown in Figure 18. The general principles of the Environment Agency approach to SPZ delineation in karst are outlined in Environment Agency (2019), where the Scarborough example is also presented. The karst hydrogeology of the area is discussed in detail in Foley (2006) and Foley et al. (2012).

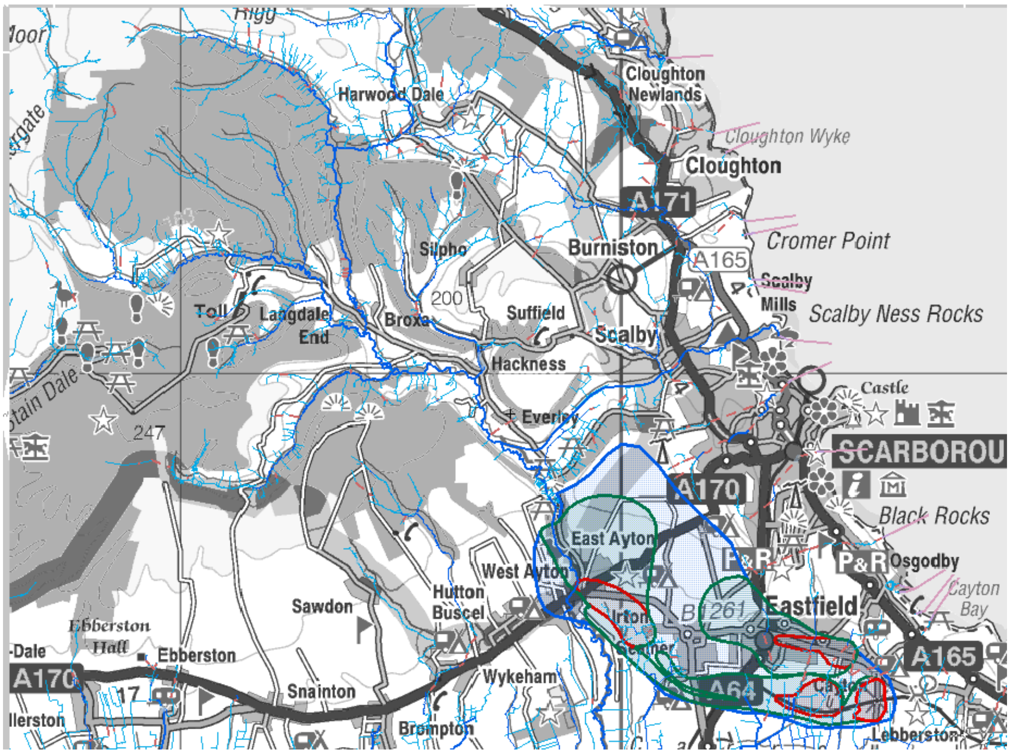

Figure 17. Previous SPZs in the Scarborough area based on MODFLOW modelling (red = SPZ1); from Buckley & Howlett (2014). Permissions courtesy of Ruth Buckley, Environment Agency. Contains Ordnance Survey data © Crown copyright and database rights [2022]

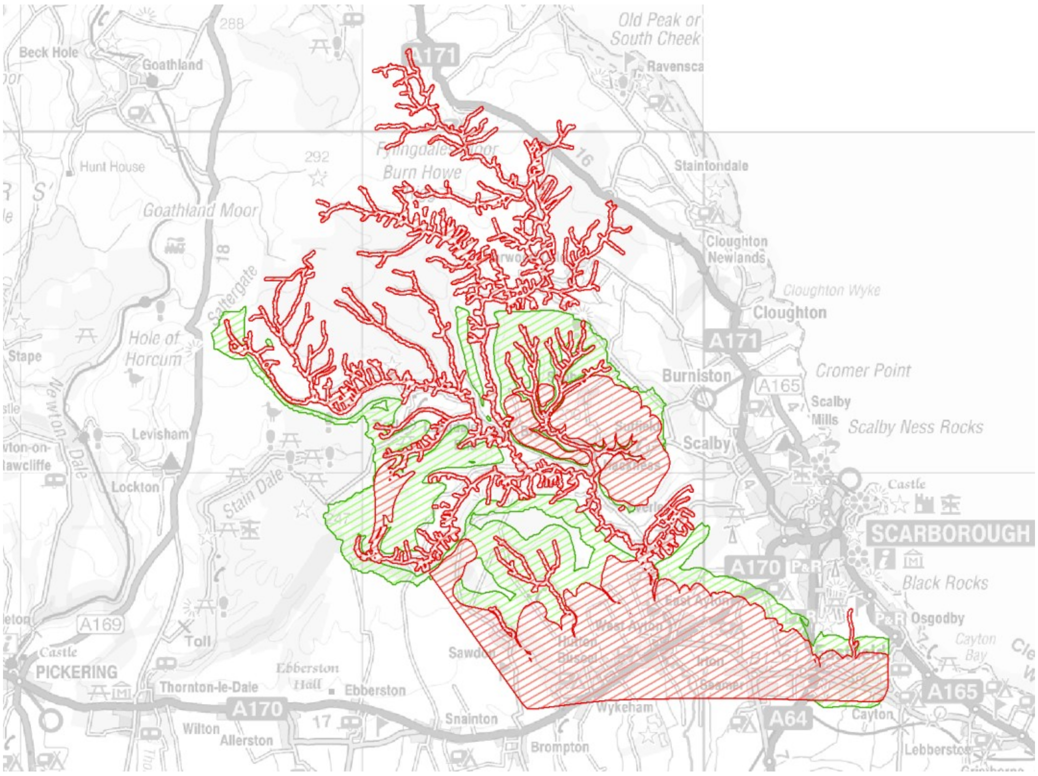

Figure 18. SPZ 1 (red) and SPZ 2 (green) for Irton abstraction (from Buckley & Howlett, 2014). Permissions courtesy of Ruth Buckley, Environment Agency. Contains Ordnance Survey data © Crown copyright and database rights [2022]

5 Summary

- The Corallian limestones of the North York Moors are highly karstic.
- There are a number of karst caves recorded in the area. Three are over 100 m in length, and the longest is 3.8 km. There is the potential for other significant cave systems associated with the major river valleys.
- There is strong evidence for cave development in the Hambleton Oolite Member (Excalibur pot) and the Malton Oolite Member (Bogg Hall Rising and some of the inactive caves).
- Karst data are sparse and have not been systematically collected, but there are records of stream sinks and springs.
- Most of the major rivers in the area have substantial karst sinks where they cross the Corallian outcrop, including the Forge Valley Swallow holes on the River Derwent, which can provide direct recharge of more than 375 $l.s^{-1}$.
- There are records of hundreds of springs in the area, in most cases their discharge and characteristics are unknown. Some natural spring discharges are likely to have been reduced as a result of the development of water resources.
- Whilst spring discharge data are sparse, there are fifteen which are known to be substantial, including three with discharges of more than 450 $l.s^{-1}$.
- There are no records of dolines, although surface depressions previously thought to be old pits which are above known cave systems are likely to be karst dolines, and there are likely to be others in the J1 area.
- There are no records of dissolution pipes, but they may be present in the area.
- Tracer tests have identified 21 pathways from six injection points. The results demonstrate very rapid flow velocities, ranging from 0.018 to 13 km/day over distances of 0.018 to 7.25 km.
- Tracer recoveries ranged from 3.3 to 99.7%, indicating very low attenuation at some sites.
- Long tailing in some tracer breakthrough curves over weeks suggests dispersive/diffusive processes within the aquifer.
- Tracer tests indicate complex karstic flowpaths with convergent and divergent flow over long distances.
- Hydrogeological information from boreholes provides further evidence of karst with some high transmissivities, high yields, rapid responses of monitoring boreholes to rainfall, and logging indicating karstic fissure flows.
- A bespoke method of Source Protection Zone delineation has been used in the Scarborough area due to the highly karstic nature of the Corallian limestone aquifer.
- Further work is needed to develop better datasets on karst in the area and improve understanding of the karst. This could include tracer testing; monitoring spring discharges; improving datasets on stream sinks, caves and dolines (and updating them as more are discovered); use of LiDAR data, investigating the impact of karst on abstractions in the area; and investigating the details of local karstic networks.

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.

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

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

Fissure: An enlarged fracture with aperture of ~ 0.5 to > 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.

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

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

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

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

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

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.

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