BGS Karst report Series: J2. Karst in the Jurassic limestones of central England

Environmental Change, Adaptation & Resilience Programme

Open Report OR/21/060

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BGS Karst report Series: J2. Karst in the Jurassic limestones of central England

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Front cover

Easton Wood stream sink during a dye tracer injection 21st Feb 1977. Photo by T. Atkinson

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Executive Summary

This report documents the evidence for karst and rapid groundwater flow in the Jurassic limestones of central England. It is part of the BGS karst report series 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”. 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, 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. 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 and consultants.

This report shows that in the Jurassic limestones of central England there is extensive evidence for karst, with surface geomorphology, tracer tests and hydrogeological studies all highlighting the role of karstic solutional development in the aquifers. Karst is best documented in the Grantham to Stamford area, associated with the East Glen, West Glen and Witham rivers; but there is evidence for karst throughout the area. Karst is particularly developed in the Lincolnshire Limestone Formation, but there is also evidence of karst in the limestones of the Great Oolite Group.

Stream sinks, dolines, dissolution pipes, and springs are all present. There are many stream sinks, and several major rivers in the area have large losses to the aquifer as they cross the limestone. Some stream sinks are very substantial with inflows of 200-300 l/s. There are also many springs, and some have large reported discharges of up to 355 l/s. Several tracer tests indicate rapid groundwater flow velocities ranging from 21 to 10000 m/day over distances of up to 11.9 km. Tracer tests demonstrate connections to multiple outlets over a wide area, suggesting that the karst comprises complex networks with divergent and convergent flow. Some tracer breakthrough curves had very long tails, with tracer discharged for more than 100 days following injection indicating high attenuation via dispersion and/or diffusion. Hydrogeological studies in the area also indicate the importance of karstic solutional development including evidence from rapid water level responses in monitoring boreholes, and powerful artesian boreholes with large discharges.

Further work is needed in the area to improve understanding of karst: Data on spring discharges are very sparse, and for most springs there discharge is unknown. There is almost no information on long term variations in spring discharges or how they respond to rainfall. Further studies of dolines and stream sinks, and further tracer testing would also be useful. Indicators of karst at abstraction boreholes (e.g. conduits observed in borehole images; water quality indicators of rapid groundwater flow) have not been considered for this report, and would enable understanding of the impacts of karst on groundwater abstractions. Although karstic caves have not been identified in this area, conduits are observed in quarries and unexplored small karstic caves may be present. The Jurassic limestones of central England are karstic in nature with extensive solutional networks of conduits and fissures. Karst is an important factor that should be considered in hydrogeological studies, and which affects groundwater protection and management in this area.

Introduction to the BGS Karst Report Series

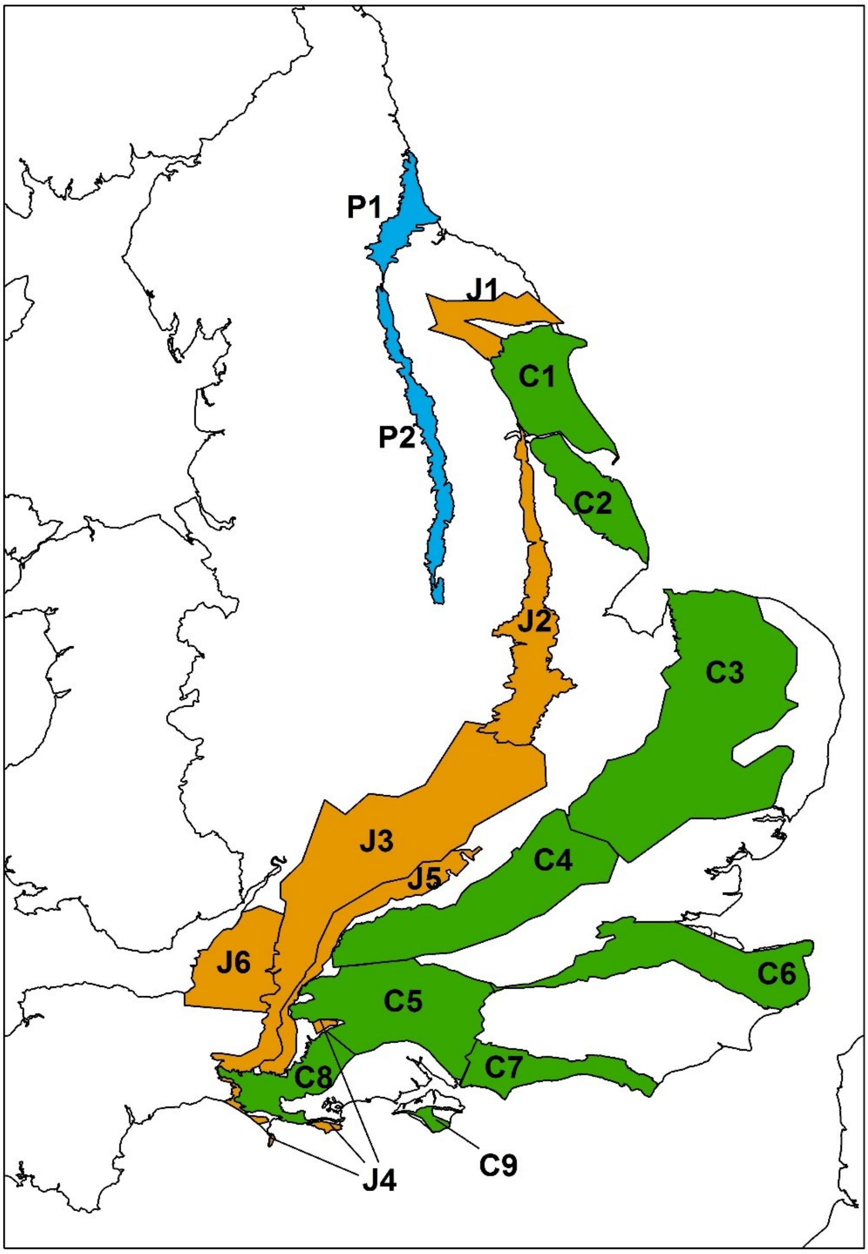
The BGS karst report series is focused on karst aquifers in England in which cave development is limited – The Chalk and the Jurassic and Permian limestones. The series is the main output of the NERC funded Knowledge Exchange fellowship “Karst knowledge exchange to improve protection of groundwater resources” 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 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 and consultants. The data are not complete and further research and knowledge exchange is needed to obtain a fuller picture of karst development in these aquifers, and to investigate the detail of local catchments. The reports provide an initial overview of the evidence for karst and demonstrate that surface karst features are much more widespread in these aquifers than previously thought, and that rapid groundwater flow is common. Consideration of karst and rapid groundwater flow in these aquifers will improve understanding of how these aquifers function, and these reports provide a basis for further investigations of karst to enable improved management and protection of groundwater resources.

The reports are structured to provide an introduction to the area and geology, evidence of karst geomorphological features in the area (caves, conduits, stream sinks, dolines 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. Many sites have not been verified in the field. Stream sink records are predominantly from the BGS karst database in which many were identified by desk study and geological mapping. Several stream sink field surveys have also been carried out, predominantly in areas of the Chalk in Southern England. Some additional records were obtained through knowledge exchange.

Most streams that sink have multiple sink points over distances of 10s to 1000s of metres. The sink point varies depending on flow conditions and also as some holes become blocked with detritus and others open up. Each individual sink point provides recharge into a solutional void in the underlying carbonate aquifer, and their locations therefore provide direct evidence of the locations of subsurface solutional features enabling rapid recharge. The sink points range from 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 is comprised of data from a range of sources originally commissioned by the Department of the Environment and reported by Applied Geology Limited (1993). In some areas dolines and dissolution pipes are not distinguished in the Natural Cavities database. Information from reports and papers with information on dissolution pipes in the area are summarised.

Springs

Large springs are indicative of connected networks of karstic voids 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 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 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 and Allen, 2001) are presented.

Knowledge exchange with water companies highlighted that in many areas water supply abstractions and springs have some characteristics that are indicative of karst. In some areas abstractions have indicators of 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 students Ian Booker, Emma King, Simon Little, Paul Barnes and Robert Barnes, all former MSc students at the University of East Anglia (UEA), for their work on tracer tests in this area under the supervision of Tim Atkinson in the 1970s and the 1990s. We also acknowledge the extensive work of former UEA research student Ian Booker who mapped stream sink and doline locations and conducted tracer tests in collaboration with Ed Smith and David Burgess of the Anglian Water Authority in the 1970s. We thank Richard Morgan, Cat Finch, Jim Branson and Paul Sherman from the Environment Agency for discussion and provision of some stream sink, spring and wild bore location data; and Simon Eyre from Anglian Water for discussion. We thank Melinda Lewis at BGS for reviewing the report and Carole Sharratt for help with formatting. 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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FIGURES

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1 Introduction

1.1 AREA/GEOLOGY

The J2 Jurassic limestone area of central England encompasses a North-South strip from the Humber in East Yorkshire to just south of Kettering in Northamptonshire (Figure 1; Figure 2). The major rivers are the Nene, the Welland, the Witham and the West and East Glen Rivers, which all drain the south of the area and flow to the Wash on the east coast. The Witham and the West and East Glen Rivers are aligned approximately parallel to the strike of the limestone formations (Figure 2).

The stratigraphy is summarised in Table 1 (Powell, 1998). The limestones are underlain by a succession of three older non karstic formations, the Whitby Mudstone Formation of the Lias Group which outcrops to the west and southwest and around the river Nene in the southeast; the permeable Northampton Sands Formation, and in places the thin Grantham Formation which predominantly comprises mudstones. In places the Northampton Sands Formation may be in hydraulic connection with the overlying limestones where the intervening low-permeability mudstones of the Grantham Formation are absent (Allen et al., 1997).

The limestones comprise the Lincolnshire Limestone Formation, and the overlying Great Oolite Group which contains two units of fine-grained oolitic limestones separated by mudstones (Table 1). The Rutland Formation (mudstone) lies at the base of the Great Oolite Group, with the Blisworth Limestone, Blisworth Clay and Cornbrash (limestone) formations above. The Great Oolite Group is overlain by the Kellaways and Oxford Clay Formations, which are non-karstic, and make up part of the Ancholme Group, outcropping in the east and southeast (Figure 2; Table 1).

The superficial geology predominantly comprises tills that blanket much of the interfluve areas (Figure 3). In the major river valleys alluvium and sand and gravel river terrace deposits are present. There are glacio-lacustrine and blown sand deposits in the northernmost parts of the area.

Table 1. Simplified stratigraphy in the J2 Jurassic Limestone area (Powell, 1998; Downing & Williams, 1969; Allen et al., 1997)

Group	Formation	Lithology	Thickness
Ancholme Group	Oxford Clay Formation	Mudstone	120 m
	Kellaways Formation	Mudstone, sandstone and interbedded sandstone and siltstone	14 m
Great Oolite Group	Cornbrash Formation	Limestone	0.3-3 m
	Blisworth Clay Formation	Mudstone	2-12 m
	Blisworth Limestone Formation	Limestone	2.5-8 m
	Rutland Formation (formerly Upper Estuarine Series)	Argillaceous rocks with subordinate sandstone and limestone	4.5-14 m
Inferior Oolite Group	Lincolnshire Limestone Formation	Limestone	0-40 m
	Grantham Formation (formerly Lower Estuarine Series)	Mudstone, siltstone and sandstone	0-9 m
	Northampton Sand Formation	Ferruginous sandstone and ironstone	0-11 m
Lias Group	Whitby Mudstone Formation	Mudstone	22-106 m

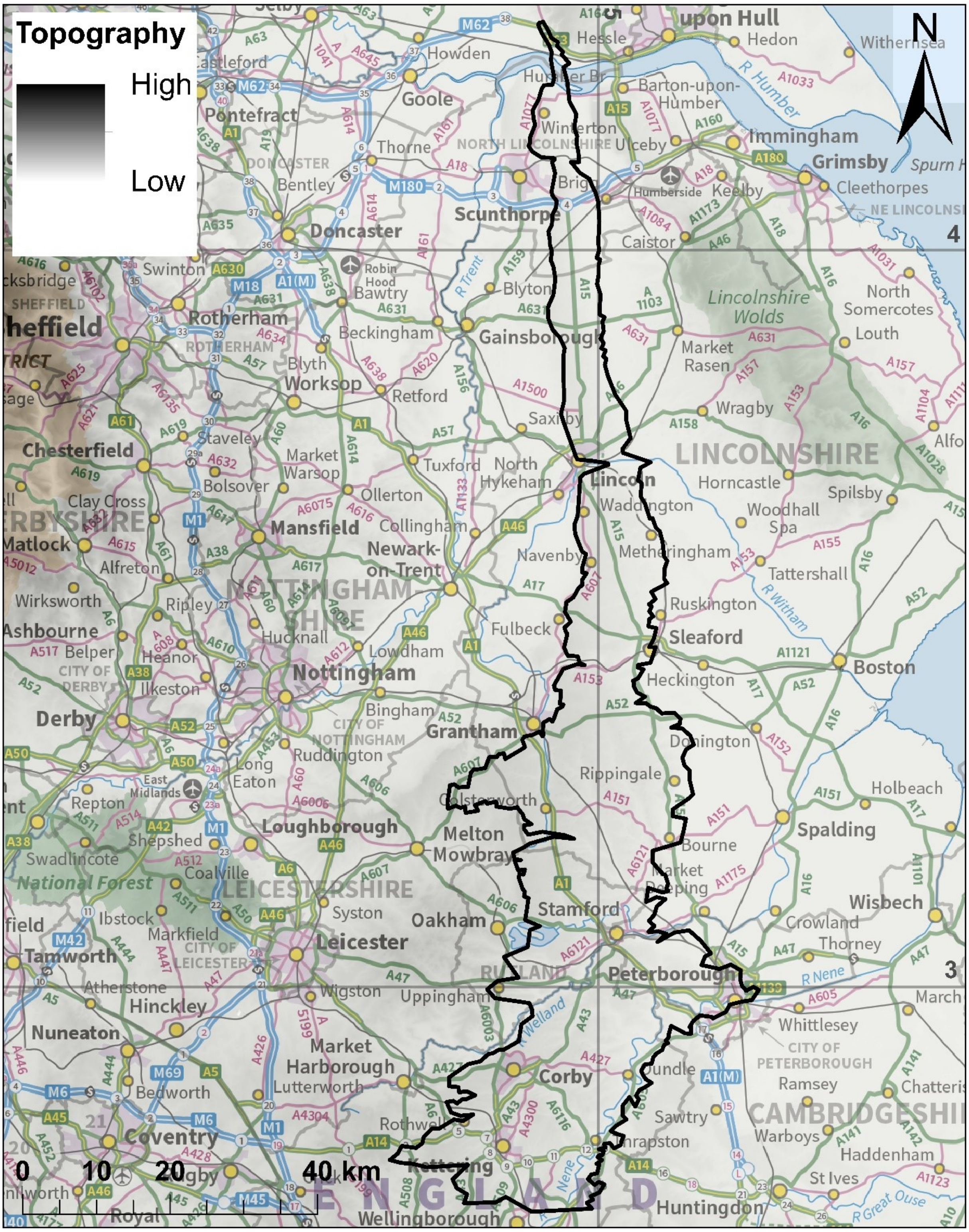

Figure 1. The J2 Jurassic Limestone area.

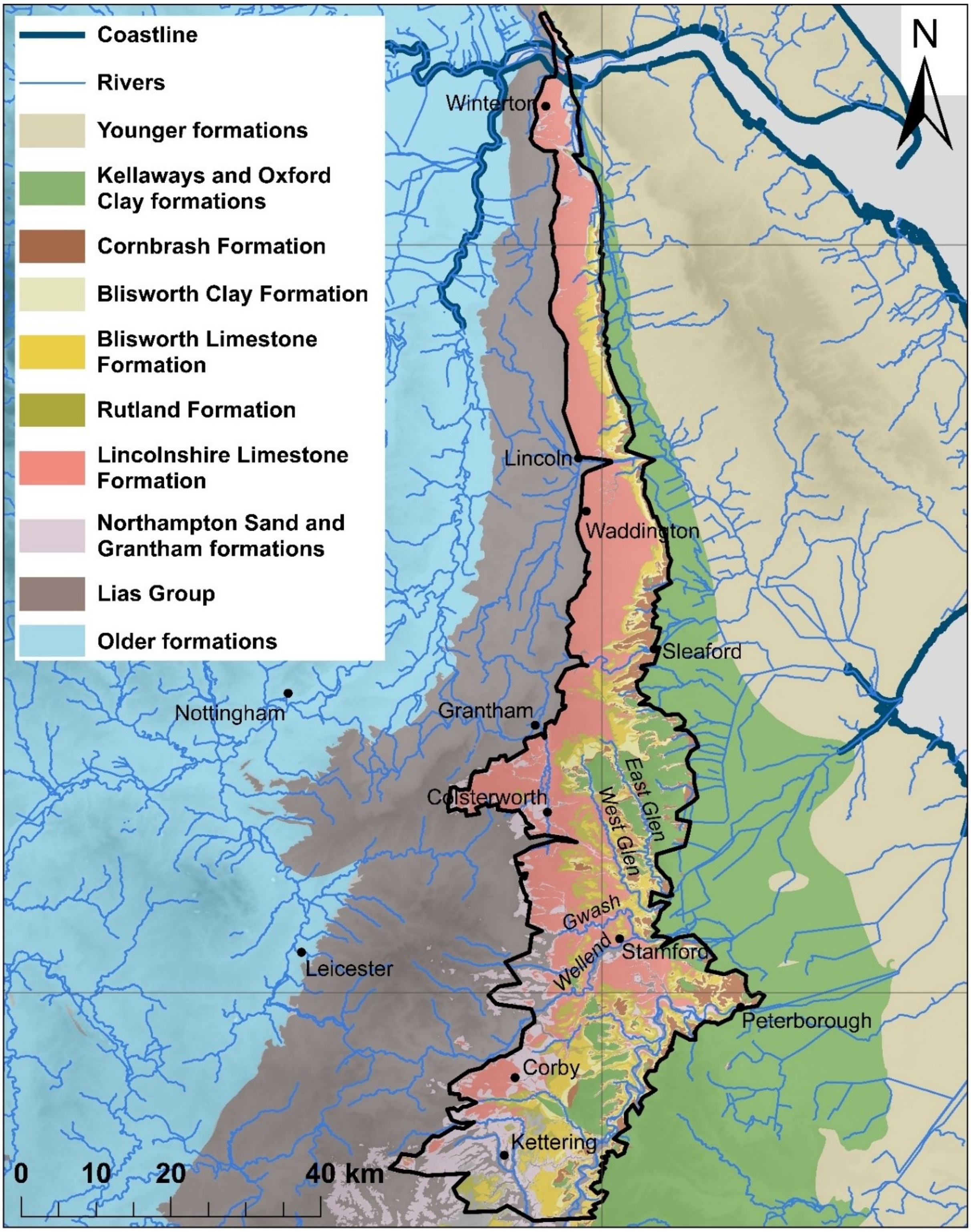

Figure 2. Bedrock geology and rivers.

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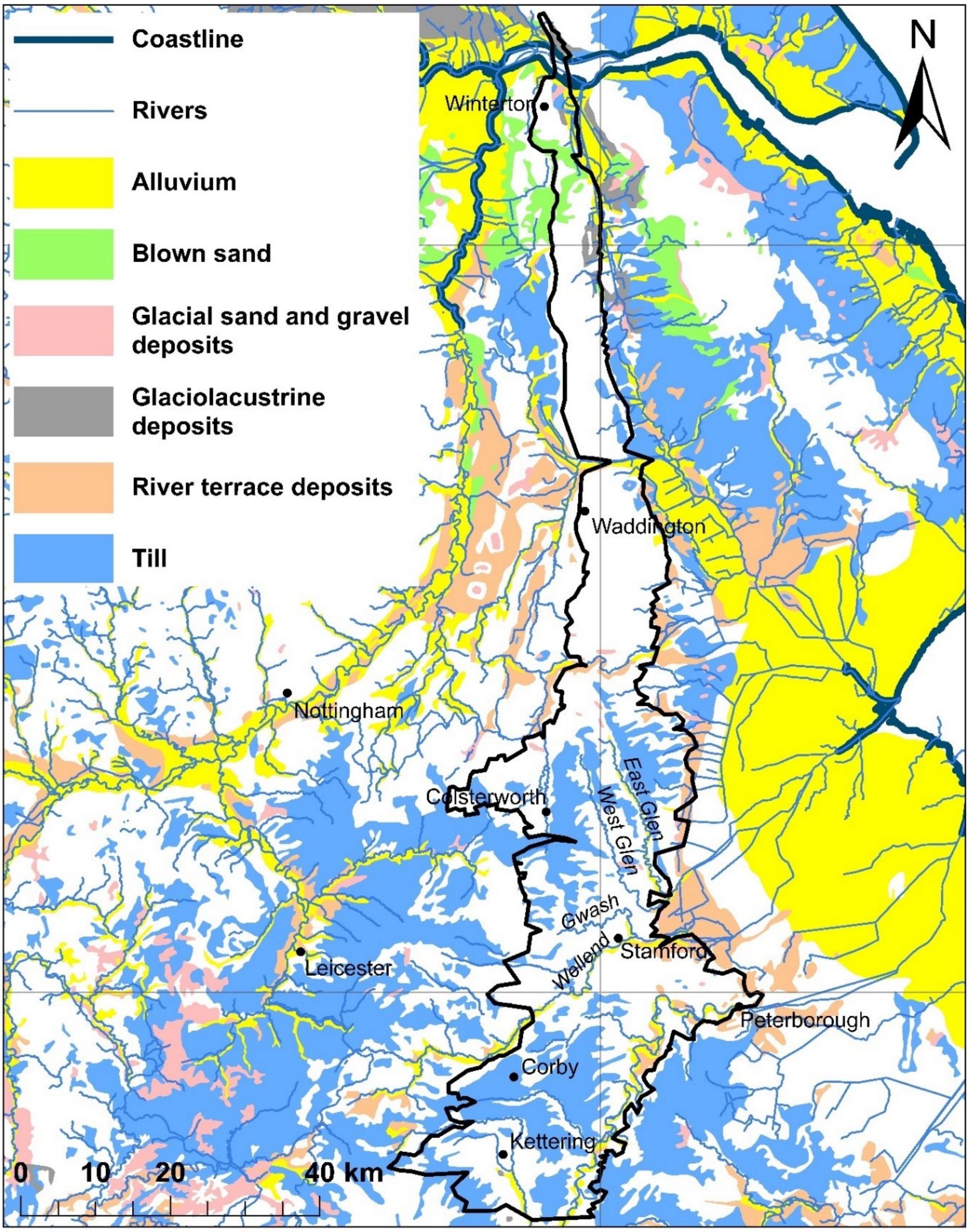

Figure 3. Superficial geology.

1.2 WATER PROVIDERS AND REGULATORS

Anglian Water is the main water provider in the J2 Jurassic limestone area (Figure 4). Severn Trent Water and Yorkshire Water are responsible for supply in small parts in the west and north, respectively. The area mainly lies within the Lincolnshire and Northamptonshire Environment Agency area (Figure 5).

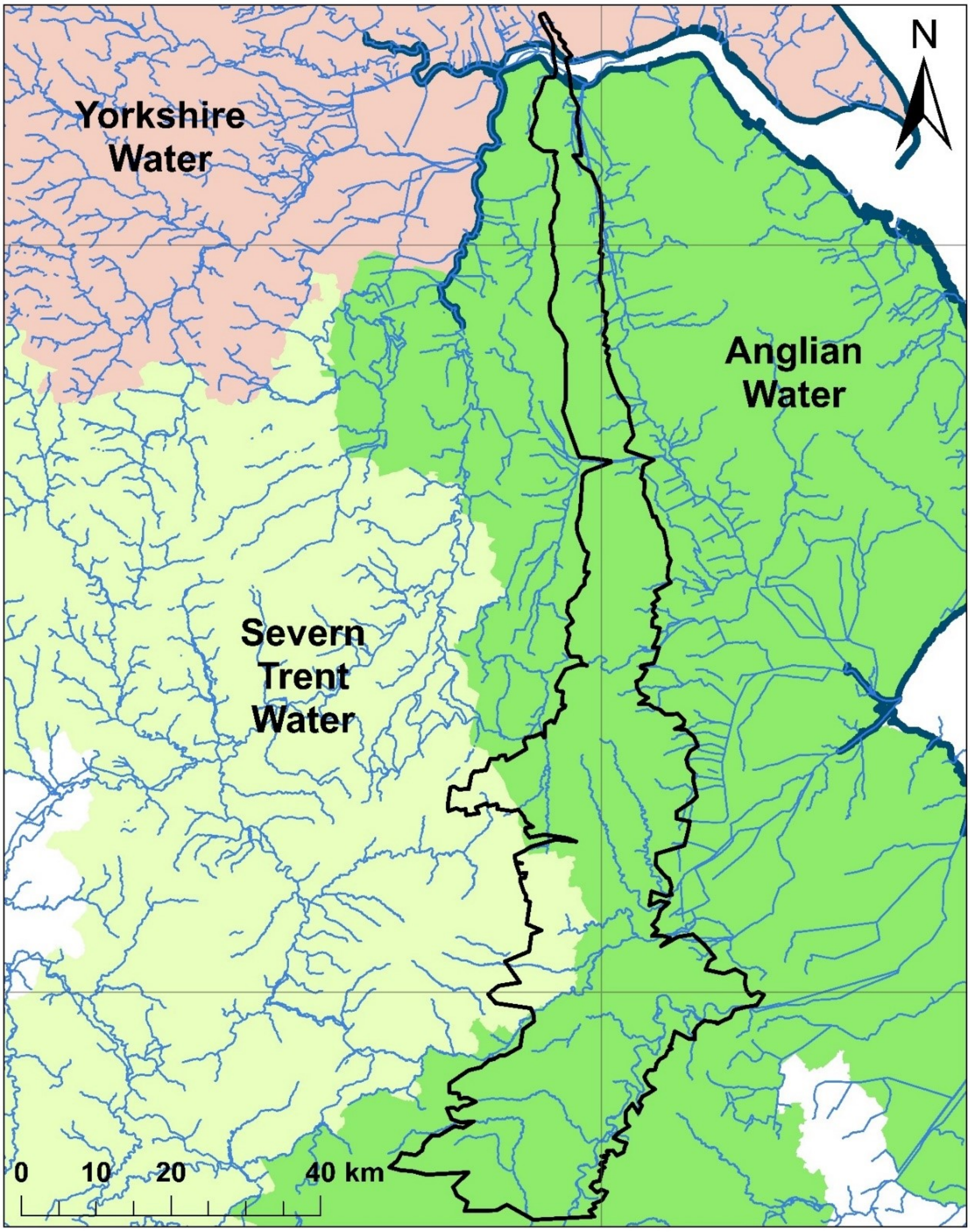

Figure 4. Water providers in the J2 Jurassic Limestone area.

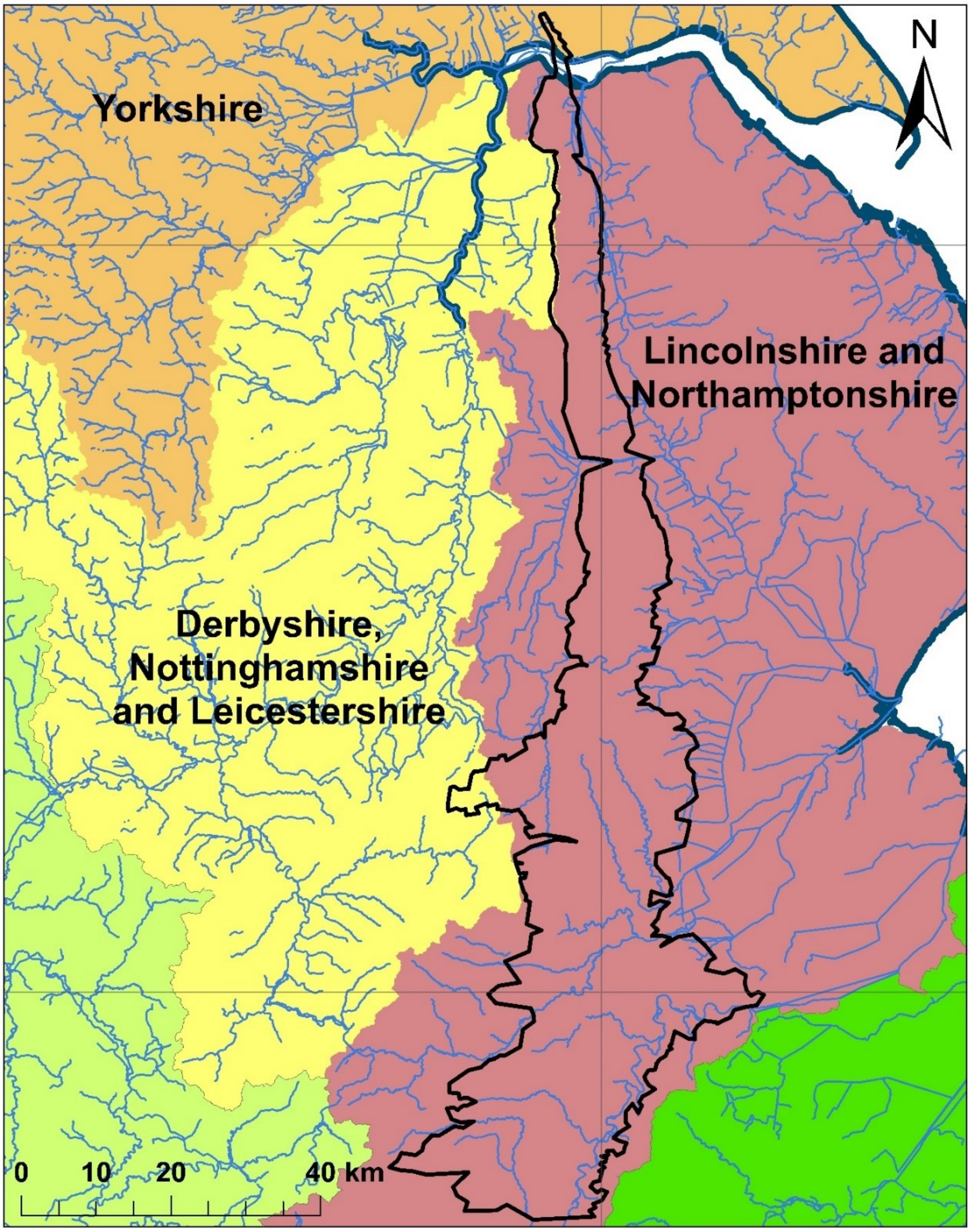

Figure 5. Environment Agency areas in the J2 Jurassic Limestone area.

2 Karst geomorphology

2.1 CAVES AND CONDUITS

There are no recorded enterable caves in the J2 Jurassic limestone area. Conduits and solutional fissures have been observed in quarries and in abstraction boreholes. For example, Atkinson and Farrant (2015) describe conduits in Medwells Quarry (NGR 498600 315900) and Clipsham Quarry (NGR 496700 315400). Both quarries are near Clipsham and are located at the boundary between the Upper Lincolnshire Limestone and the Rutland Formation of the Great Oolite Group, and their locations are shown in Figure 6. Booker (1977) also mentions conduits in Clipsham Quarry which are up to 15 cm wide, and observed where horizontal and vertical joints intersect. There were solutional flutes and scallops inside the joint faces indicating karstic flow. Pictures of karstic solutional fissures and conduits observed at Medwells Quarry in 1978 are shown in Figure 7, Figure 8, and Figure 9; with examples of solutional scallops indicating past subterranean water flow in Figure 8 and Figure 9. A karstic conduit observed in the late 1970s in a quarry near Stainby is shown in Figure 10.

The British Cave Research Association fieldtrip in March 2013 visited Clipsham quarry and at that time there were few larger solutional fissures exposed although one large, potentially cave sized void was observed half way up a quarry face (Maurice, 2013). During this field trip many large fissures with evidence of dissolution were observed at Medwells quarry (Maurice, 2013).

Mason (2015) reports the development of voids and collapse in the lower part of three boreholes drilled at a proposed landfill site near King’s Cliffe. This is likely to have been due to the breakdown of the sandstone beneath the Lincolnshire Limestone due to drilling activities rather than karst cavities in the limestone (MJCA, personal communication, 2022; and Scott Doherty Associates, 1998). Mason (2015) also reports that a void of 20 cm was reported in another borehole at Kings Cliffe, and that a floodlit well at NGR 501400 299110 reveals moving groundwater at depth within the Lincolnshire Limestone.

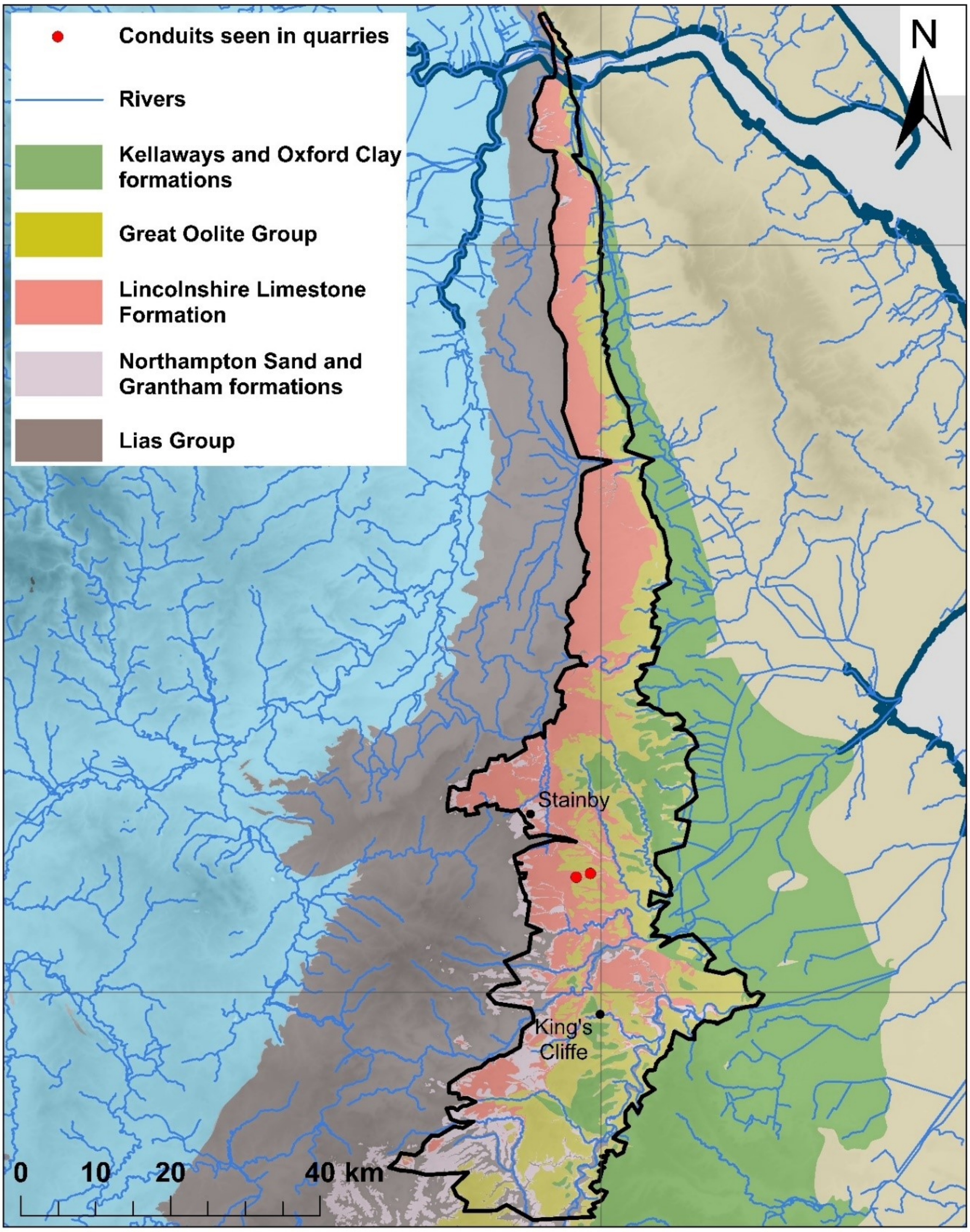

Figure 6. Locations of quarries with reports of fissures/conduits.

Figure 7. Solutional fissures observed in 1978 at Medwells quarry, Clipsham. Photos by T. Atkinson.

Figure 8. Solutional fissure observed in 1978 at Medwells Quarry, Clipsham with scallops indicating past water flow. Photos by T. Atkinson.

Figure 9. Solutional fissure with conduit observed in 1978 at Medwells Quarry, Clipsham (left) with scallops indicating past water flow (right). Photos by T. Atkinson.

Figure 10: Conduits observed in a quarry near Stainsby. Photo by T.Atkinson.

2.2 STREAM SINKS

The 93 recorded stream sinks in the J2 area are shown in Figure 11 and Figure 12. Fifty-seven records are from the BGS karst database, sixteen are from records held by the Environment Agency, and the remaining stream sinks are identified in Roberts (1997), a report on a proposed landfill site near King's Cliffe (Mason, 2012), and in tracer test reports by Atkinson (1978) and Booker (1977; 1982). The stream sinks recorded in the BGS karst database are predominantly from Hindley (1965), with some from historic maps and BGS fieldslips. Atkinson and Farrant (2015) provide the original map from Hindley (1965) showing the locations of stream sinks and depressions. The unpublished manuscripts by Booker (1977; 1982) contain an exhaustive survey of almost all the sinks and depressions within the topographic catchment of the West Glen river, roughly the area between the West Glen itself and the A1 road. Those that were described as having water flow are included in Figure 11. Stream sinks in the J2 area are also discussed in Downing and Williams (1969) and Rushton et al. (1993).

The BGS karst database is incomplete in this area. Apart from two recorded stream sinks south of the River Welland, the recorded sinks all cluster in the western part of the area, just north of Stamford – which is the area that was investigated in detail by Hindley (1965) and Booker (1977, 1982). The stream sink records shown in Figure 11 reflect areas where studies have been undertaken, and there may be other stream sinks present elsewhere which could be identified by systematic desk and field studies. For example, old Ordnance survey maps and LiDAR (https://maps.nls.uk/geo/explore/side-by-side/) suggest that there may be stream sinks near Welby at NGR 498195 338342 and at NGR 499022 340042.

The stream sinks are mostly located on till deposits near the boundary between the till and bedrock (Figure 12). Others are located near the base of the Rutland Formation in the Great Oolite Group which overlies the Lincolnshire Limestone Formation. Some also appear to be located near the base of the Lincolnshire Limestone Formation. Most of the recorded stream sinks in the J2 area are in the catchments of the West Glen and Witham Rivers (Figure 12). Rushton et al. (1993) suggest that there are also sinking sections in the Grimsthorpe Brook and Irnham Brook, which are tributaries of the East Glen.

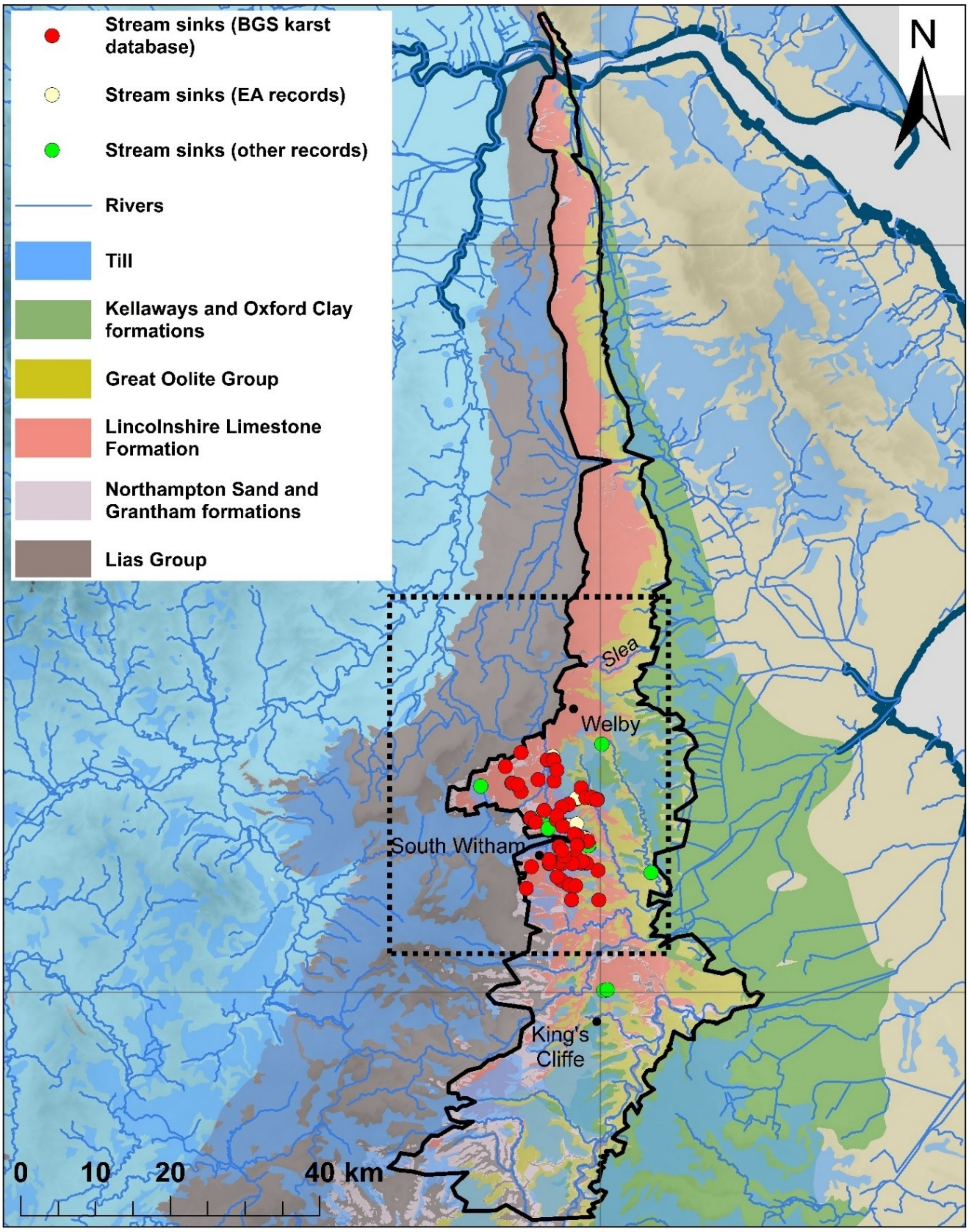

Figure 11. Recorded stream sink locations.

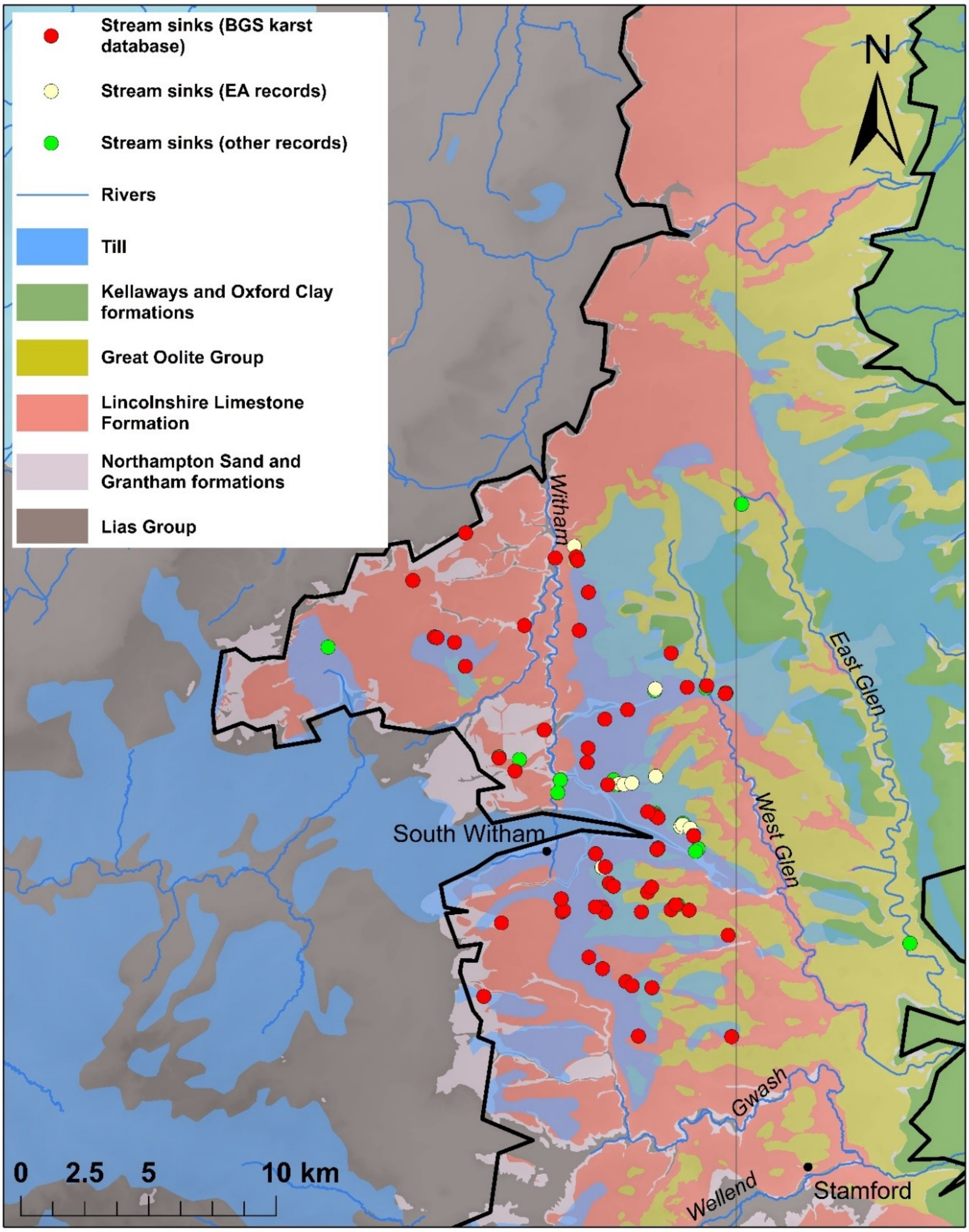

Figure 12. Magnified view of stream sink locations.

Figure 13 shows details of the Easton Wood stream sink in the West Glen catchment near Burton le Coggles (NGR 496830 325950), as recorded in the notes of a field geologist in 1941 (also reproduced in a paper by Farrant and Cooper, 2008). Tracer testing was conducted from this stream sink in February 1977 (see Section 3) and this is pictured on the front cover of this report. The stream sink is also shown below in Figure 14 which shows how the stream turbidity that occurs in high flow conditions enables transport of sediment into the subsurface.

Atkinson and Farrant (2015) also report that just east of Burton-le-Coggles (NGR 498800 326000) there are several sink points in the bed of the West Glen river, which have been used as injection points for a series of tracer tests (see Section 3). One of these sink points, known as the Burton Coggles stream sink took substantial flow in the past (Figure 15). However, when it was visited during the March 2013 British Cave Research Assoication field trip the water had long since been diverted away from the stream sink which was no longer evident (Maurice 2013).

Booker (1977; 1982) mapped 120 “swallow holes” in the J2 area (Figure 16). Within this category Booker included stream sinks, where sinking streams or trickles recharge the aquifer, dolines (i.e. karstic hollows formed by a combination of limestone dissolution and removal of overlying deposits via the subsurface), and closed depressions of uncertain origin, which may in some cases have been man-made. Some of the dolines and other depressions have been used to direct outlets from field drains into the subsurface. One of the stream sinks mapped by Booker (1977; 1982) is the Rodbecks stream sink which is a substantial karst feature shown in photographs in Atkinson at Farrant (2015). This large feature can also be seen in aerial images on google maps (Figure 17).

In addition, two stream sinks were identified near King’s Cliffe to the south of Stamford (Figure 11), in a written objection to a proposal for potentially hazardous waste storage in the Rutland Formation in Northamptonshire (Mason, 2012). The larger of the two stream sinks is described as a 15 m by 25 m pit, extending 5 m into the ground. Many dolines can be seen on LiDAR in this area (Figure 18).

Hawker et al. (1993) report that the River Slea (Figure 11) loses flow to groundwater downstream from Wilsford, and that the channel was frequently dry at the Rauceby golf course. Downing and Williams (1969) also report that the River Slea is influent where it crosses the Lincolnshire Limestone outcrop. They state that “where the Upper Slea flows for some six miles across the limestone outcrop above Rauceby station, considerable loss of water occurs despite an apparently naturally sealed river bed” and that “the influent condition is reflected in the flow measurements taken at various times”. They provide a table of river flows and spring flows for the River Slea. The river flow data in this table provide an indication of the losses that occur as the river crosses the Lincolnshire Limestone. For example, the data suggest that in November 1966 the river flow decreased from 17 l/s to 5 l/s implying losses of 12 l/s. The flow then increased to 21 l/s where the river meets the margin of the Lincolnshire Limestone outcrop again.

There is some other information on the discharge of stream sinks. Downing and Williams (1969) report that the swallow hole in the riverbed east of Burton-le-Coggles had an inflow of 200 l/s. They also report that the total losses over a distance of 1.5 km from the West Glen River between Burton-le-Coggles and Corby Glen was 420 l/s in January 1968. To the west of this, Atkinson and Farrant (2015) report that the Easton Wood stream sink (NGR 496800 326000) can take in water up to 300 l/s, and forms a lake at rates greater than this, sometimes flooding the roads when flow is high. Both the Burton Coggles stream sink and the Easton Wood stream sink are in the Upper Lincolnshire Limestone Formation (Atkinson and Farrant, 2015), and their locations are shown on Figure 26 in Section 3 below. In the East Glen catchment, Rushton et al. (1993) suggest springs of 2 to 4 Ml/day (~20 to 50 l/s) sink about 100 m downstream in the Irnham Brook; with 2 to 5 Ml/day (~20 to 60 l/s) springflow infiltrating the Grimsthorpe Brook; and 3 to 12 Ml/day (~12 to 140 l/s) of infiltration at the Caudles. Bradbury and Rushton (1998) developed a runoff-recharge model for the West Glen and East Glen catchments that accounted for recharge to the limestone from surface runoff on adjacent low permeability strata.

Downing and Williams (1969) report that 2300 m^3/day (equivalent to ~27 l/s) of minewater was discharged into a normally dry swallow hole at South Witham (see Figure 12 for location of South Witham). Downing and Wiliams (1969) provide further information on the swallow holes in the

Upper Witham and Glen catchments and note that swallow holes seem to be associated with (a) faults in the Lincolnshire Limestone (b) the junction between till and limestone and (c) the outcrop at the base of the Rutland Formation.

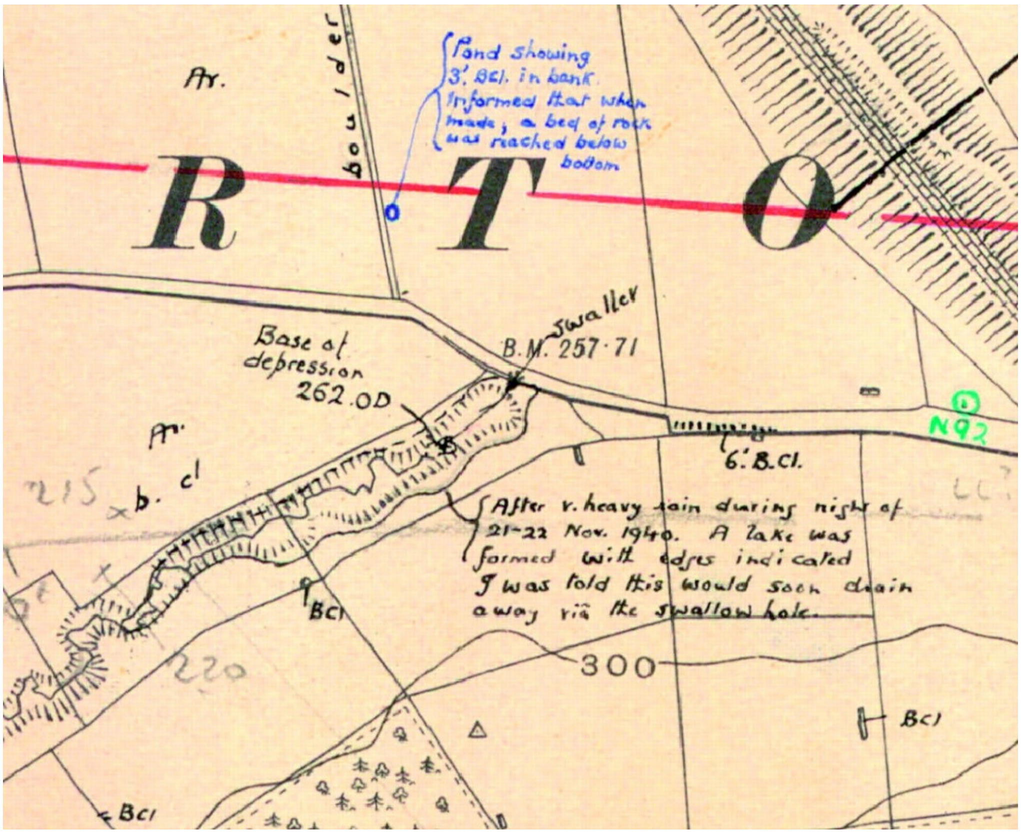

Figure 13. Field slip by F. B. A. Welch, 1941 detailing the Easton Wood stream sink near Burton-le-Coggles.

Figure 14. Easton Wood stream sink taking a large turbid flow in 1977. Photo by T. Atkinson

Figure 15. Burton Coggles stream sink near the West Glen River, pictured in 1977. Photo by T. Atkinson.

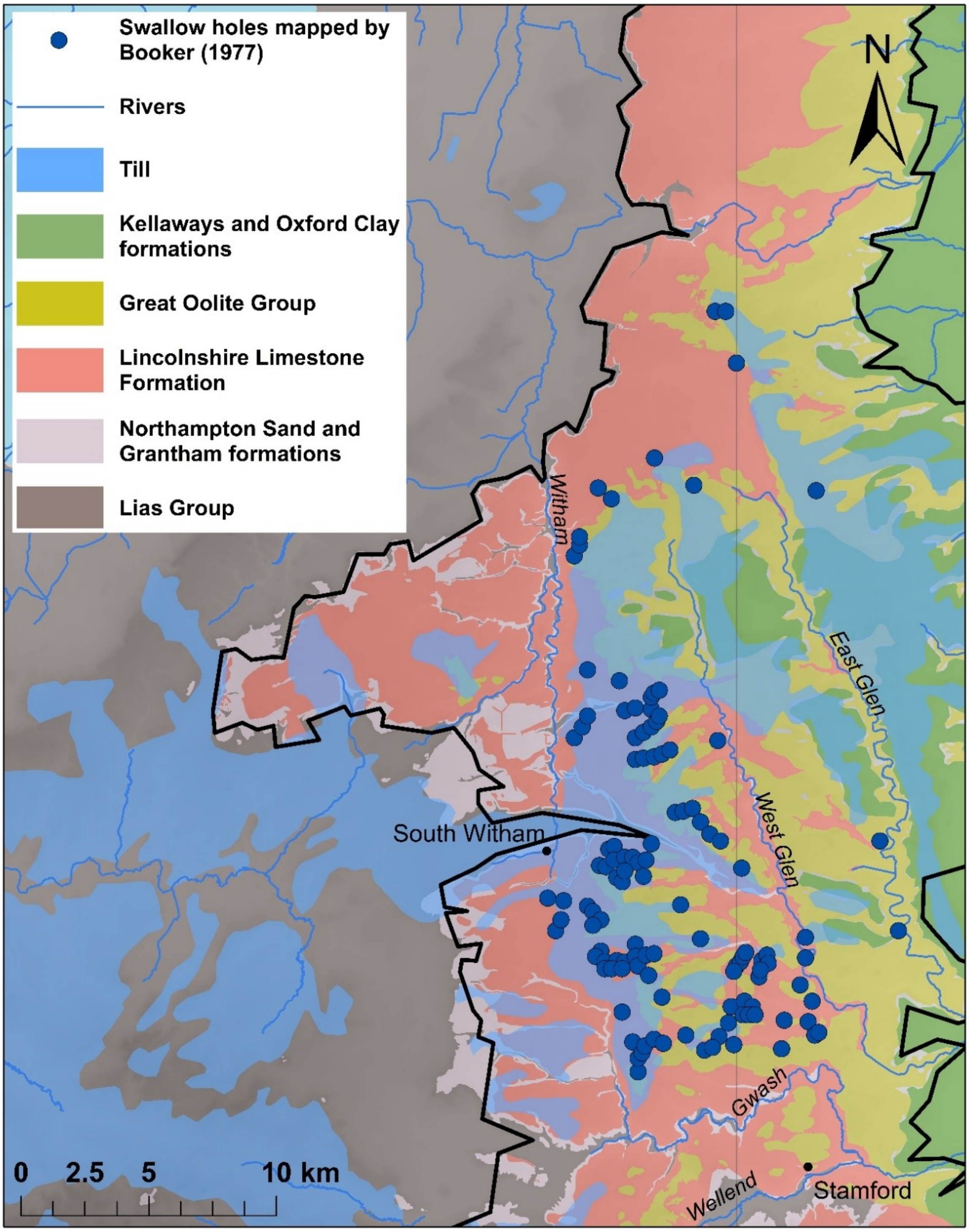

Figure 16. Swallow holes mapped by Booker (1977).

Figure 17. Aerial image of Rodbecks stream sink

(https://goo.gl/maps/CNq6sqDUXB32).

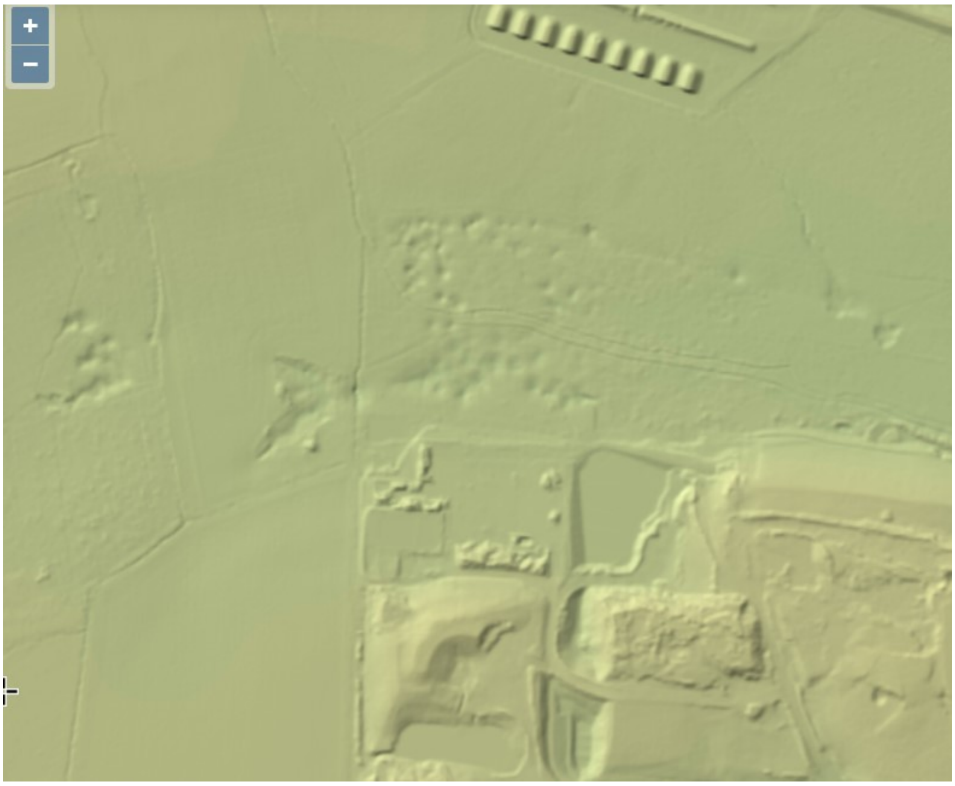

Figure 18. Dolines on LiDAR, north of King’s Cliffe

(https://maps.nls.uk/geo/explore/side-by-side/#zoom=15&lat=52.59509&lon=-0.51429&layers=10&right=LIDAR_DTM_2m)

2.3 DOLINES AND DISSOLUTION PIPES

Dissolution pipes have been widely recorded across the south of the area, mainly within the Lincolnshire Limestone Formation, but also in the Great Oolite Group (Figure 19). The dissolution pipe records are from the Natural Cavities database which is a legacy dataset held by the British Geological Survey and Peter Brett Associates. It was originally commissioned by the UK Department of Environment and by Applied Geology Limited (1993) and contains data from a wide range of sources.

Most recorded dolines are in a north-south trending area located on Glacial Till deposits to the west of the West Glen River, and close to the geological boundary between the Lincolnshire Limestome Formation and the overlying Great Oolite Group (Figure 19). The dolines shown in Figure 19 are from the British Geological Survey karst database, the Natural Cavities database discussed above, and several west of the West Glen that can be seen from satellite images. Dolines of several tens of metres in diameter in the King's Cliffe area are also mentioned in the Northamptonshire Resource Management Facility report (Mason, 2012), but the exact locations are not reported. The features mapped by Ian Booker (Figure 16) also include dolines as well as active stream sinks.

The patterns observed in Figure 19 reflect the small areas which have been investigated, and there are likely to be other dolines and dissolution pipes. LiDAR data reveal many other dolines, for example north of King's Cliffe (Figure 18); at Greetham Wood approximately 10 km northwest of Stamford (Figure 20); and at Old Wood near Tickencote (Figure 21); and a systematic survey would reveal more.

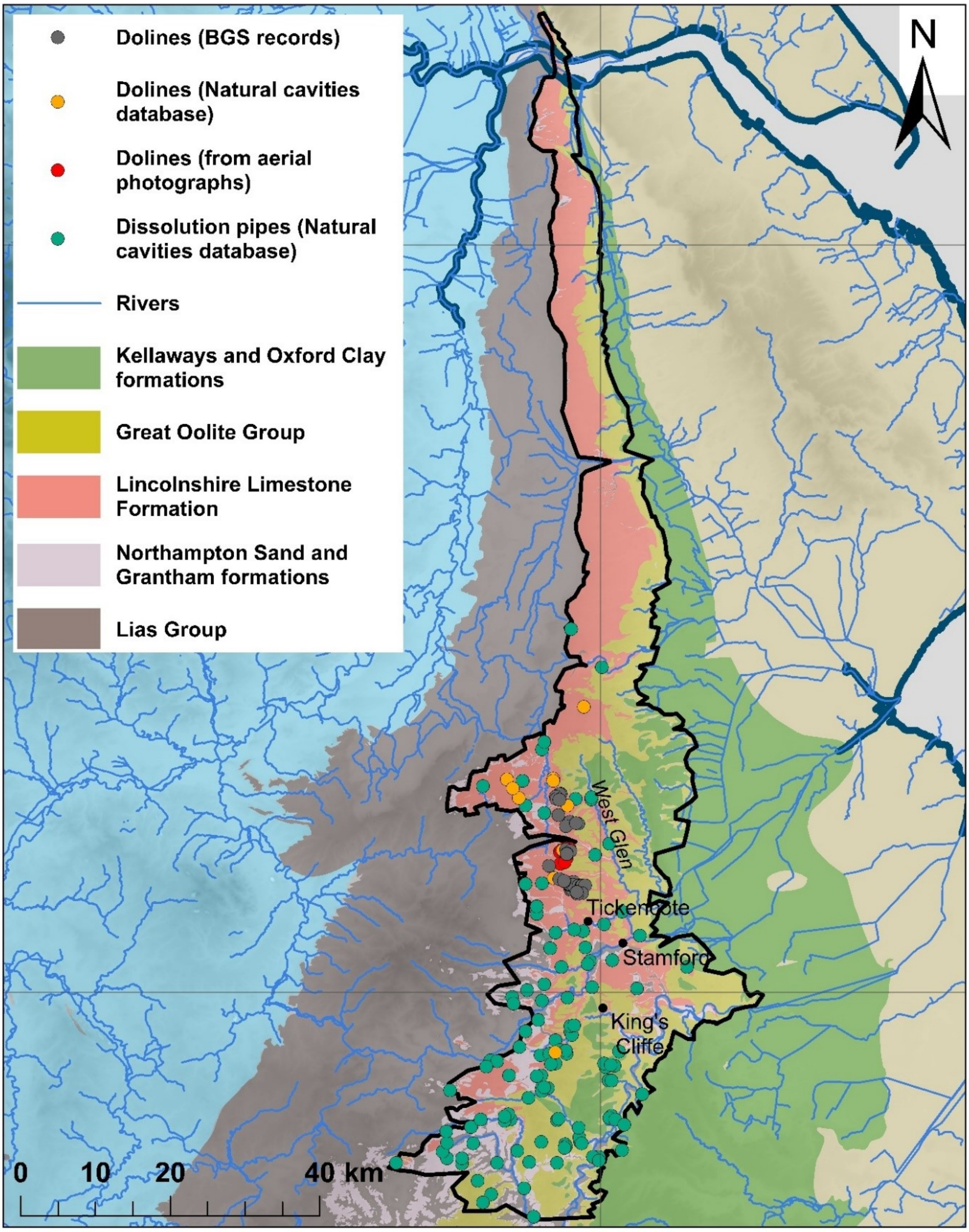

Figure 19. Locations of dolines and dissolution pipes.

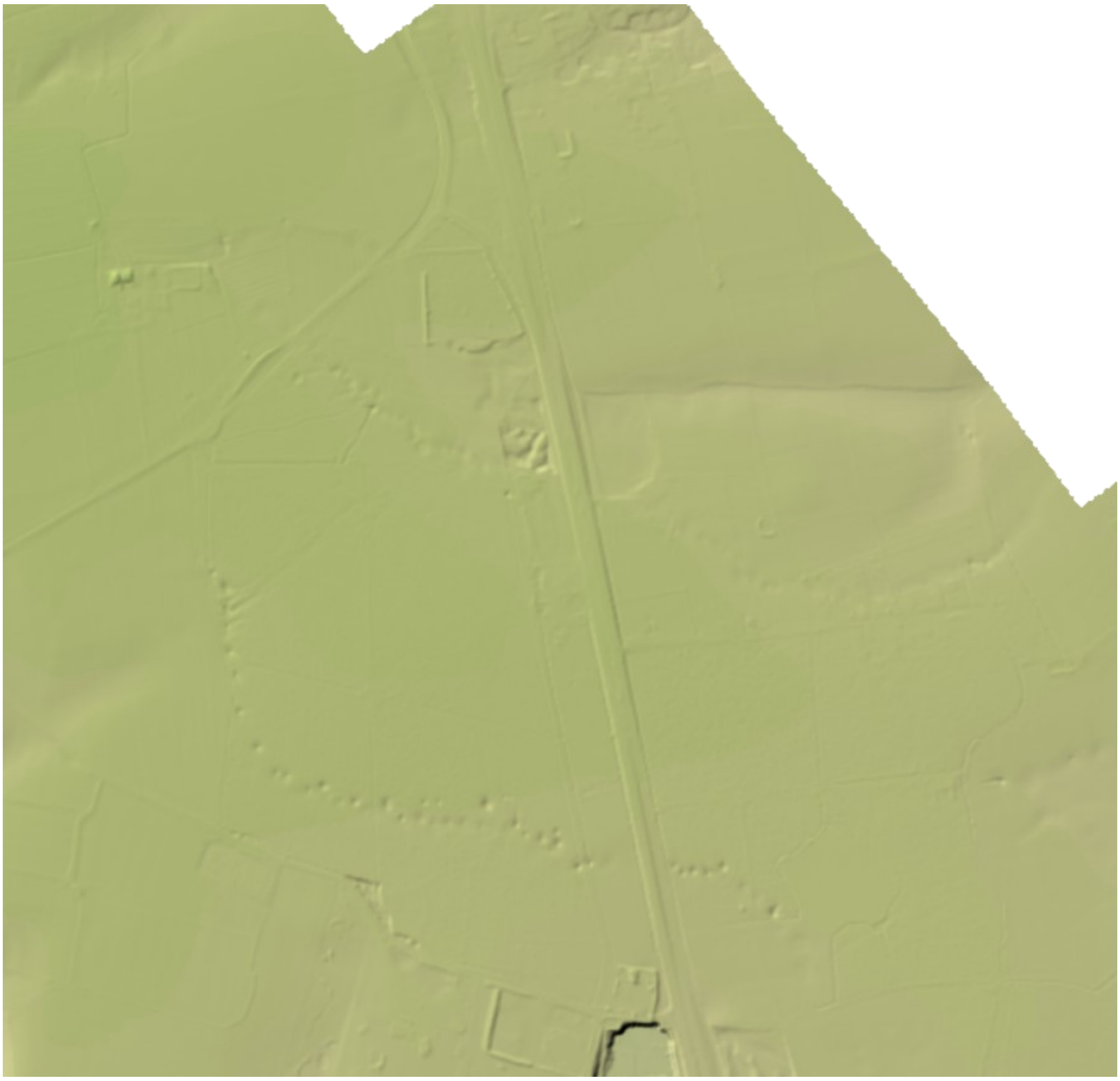

Figure 20. Dolines apparent on LiDAR, at Greetham Wood, approximately 10 km northwest of Stamford

(https://maps.nls.uk/geo/explore/side-by-side/#zoom=15&lat=52.72368&lon=-0.59707&layers=10&right=LIDAR_DTM_2m)

Figure 21. Dolines apparent on LiDAR, at Old Wood near Tickencote, approximately 6 km northwest of Stamford

(https://maps.nls.uk/geo/explore/side-by-side/#zoom=16&lat=52.68404&lon=-0.57830&layers=10&right=LIDAR_DTM_2m)

2.4 SPRINGS

In total there are 589 records of springs in the J2 Jurassic Limestone area (Figure 22). Data are from the BGS springs records, the Environment Agency, tracer test reports (Booker, 1977; King, 1994; Booker & Atkinson, 1980; Atkinson, 1978; Barnes, 1993) and general hydrogeological texts on the area (Roberts, 1999; Bowyer & Finn, 1973). There are also data from the BGS karst database which include springs recorded on Ordnance Survey maps and spring locations from Hindley (1965). Springs are widely distributed throughout the whole area, but generally concentrated in the south around the major rivers. They are also present at the boundaries between the Inferior Oolite Group and the Lias Group in the west, as well as between the Kellaways/Oxford Clay Formations and the Great Oolite Group in the east. Figure 22 shows the springs in the area labelled by source of the record as well as the geology at the surface, with 165 springs on the Lincolnshire Limestone Formation and 196 on the Great Oolite Group. Springs in the Kellaways and Oxford Clay formations are likely to issue from the Jurassic aquifers and not from the clays. As mentioned earlier, in some areas the Northampton Sands Formation is in hydraulic continuity with the Lincolnshire Limestone Formation and the springs located on the Northampton Sands Formation are included in Figure 22.

For many of these springs there is no information on discharge. However, there are 25 springs in the area which have recorded discharges that at times exceed 10 l/s, or that were monitoring sites during tracer tests and are therefore likely to have substantial flows (Figure 23). None of these springs are located further north than Sleaford or further south than Peterborough. Along the eastern margin of the J2 area, most of the recorded large springs are located around the boundary between the Kellaways/Oxford Clay Formations and the Great Oolite Group, whilst in the west large springs occur in the Lincolnshire Limestone around Great Ponton, Colsterworth, Little Bytham and Stamford. Two of the larger springs have recorded discharges of more than 300 l/s (Table 2). It is likely that springs flows are substantially reduced compared to their natural discharges prior to the onset of the development of water supplies. A brief literature review of further information on springs in the area is provided below:

Downing and Williams (1969) provide information on springs in the Lincolnshire Limestone Formation and report spring flow data between 1965 and 1967, which are included here in Table 2. Springs in the Lincolnshire Limestone Formation are described as falling into two categories; those issuing from the base of the aquifer where it overlies low permeability formations, and those at the top of the aquifer where it is overlain by low permeability muds and clays (Downing and Williams, 1969). The discharges vary across the aquifer, and there is significant seasonal variation in individual spring flows.

Hawker et al. (1993) note that the River Slea is fed by springs along the base of the Lincolnshire Limestone escarpment and that these springs sometimes failed causing the river to dry up. Downstream from Wilsford there is a losing section (see Section 2.2) beyond which three major springs discharge from the contact between the Lincolnshire Limestone and the Rutland Formation clays, west of Sleaford (Hawker et al., 1993). These three are the Boiling Wells spring, 3 km upstream from Sleaford which discharges 1900 Ml/year (equivalent to a constant discharge of ~60 l/s), and the Guildhall and Cobblers Hole springs 1.5 km upstream from Sleaford with a combined discharge of 10800 Ml/year, equivalent to a constant discharge of approximately 340 l/s (Hawker et al., 1993). Hawker et al. (1993) also report that at this time annual abstraction was about 3400 Ml/a, which would presumably have been discharged from the natural outlets prior to abstraction. These large spring discharges suggest well developed karstic solutional networks in the Sleaford area.

Atkinson (1978) describes springs near Colsterworth (Stainby No. 1 Gullet and Easton Park Springs) issuing from the Lower Lincolnshire Limestone with discharges of up to 12 l/s at Easton Park springs. Stainby No. 1 Gullet has been used as a monitoring point during tracer tests (Section 3).

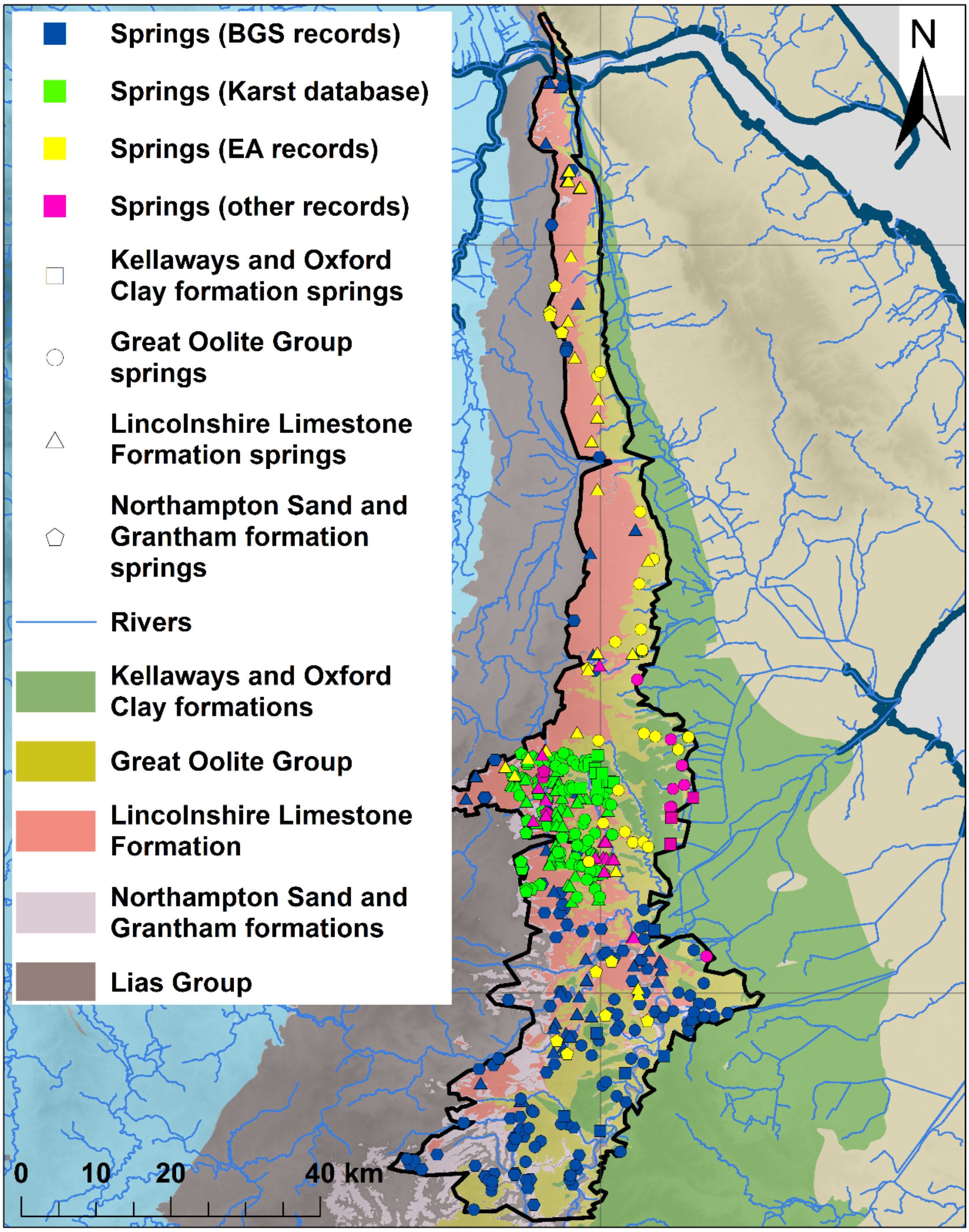

Figure 22. Locations of recorded limestone springs of known and unknown discharge.

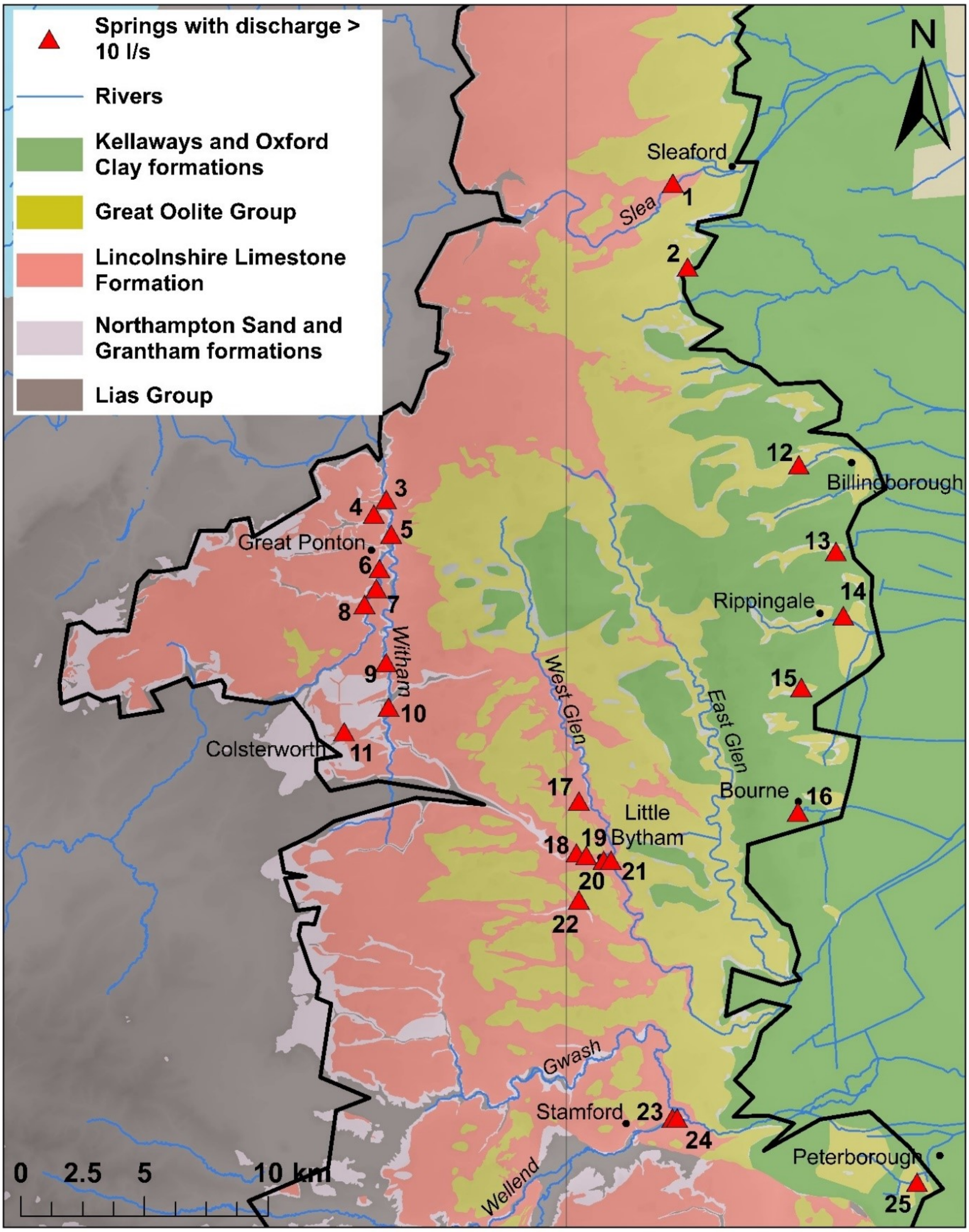

Figure 23. Locations of large springs.

Table 2. Details of the larger springs recorded in the area, those with no discharge data are assumed to be substantial due to their use as monitored outlets in tracer tests

Map no.	Name	Location	Discharge	Source	Geology at surface
1	Boiling Wells	Sleaford	0 - 355 l/s	Downing & Williams (1969)	Lincolnshire Limestone
2	Cliff Beck	Sleaford	19 l/s	Bowyer & Finn (1973)	Great Oolite Group
3	Bath Spring	Great Ponton	4 - 13.3 l/s	Downing & Williams (1969)	Lincolnshire Limestone
4	Little Ponton	Great Ponton	0 - 18.5 l/s	Downing & Williams (1969)	Lincolnshire Limestone
5	Great Ponton Mill	Great Ponton	8.7 - 45.1 l/s	Downing & Williams (1969)	Northampton Sand and Grantham formations
6	Great Ponton	Great Ponton	2.3 - 11.6 l/s	Downing & Williams (1969)	Northampton Sand and Grantham formations
7	Stoke Rochford 2	Great Ponton	3.5 - 22.0 l/s	Downing & Williams (1969)	Northampton Sand and Grantham formations
8	Stoke Rochford 1	Great Ponton	29.5 - 86.8 l/s	Downing & Williams (1969)	Northampton Sand and Grantham formations
9	Easton Park Springs	Colsterworth	3.5 - 12 l/s	Atkinson (1978)	Lincolnshire Limestone
10	Colsterworth Priory	Colsterworth	2.3 - 16.8 l/s	Downing & Williams (1969)	Northampton Sand and Grantham formations
11	Stainby No.1 Gullet	Colsterworth	N/A	Atkinson (1978)	Lincolnshire Limestone
12	Folkingham Beck	Billingborough	42 l/s	Bowyer & Finn (1973)	Great Oolite Group
13	Little Dowsby Spring	Rippingale	19.7 l/s	Barton & Perkins (1994)	Great Oolite Group
14	Old Beck	Rippingale	26 l/s	Bowyer & Finn (1973)	Great Oolite Group
15	Bourne Eau	Bourne	N/A	Booker & Atkinson (1980)	Great Oolite Group
16	Bourne Spring	Bourne	240 l/s in 1874	Addy (1882)	Kellaways and Oxford Clay formations
17	Creeton Springs	Little Bytham	N/A	Booker (1977)	Lincolnshire Limestone
18	Glebe Farm 1	Little Bytham	N/A	Booker (1977)	Lincolnshire Limestone
19	Glebe Farm 2	Little Bytham	N/A	King (1994)	Lincolnshire Limestone
20	Little Bytham	Little Bytham	N/A	King (1994)	Lincolnshire Limestone
21	River Tham	Little Bytham	N/A	King (1994)	Lincolnshire Limestone
22	Holywell	Little Bytham	N/A	Booker (1977)	Lincolnshire Limestone
23	Hudd's Mill Spring	Stamford	N/A	Barnes (1993)	Lincolnshire Limestone
24	Small Spring	Stamford	N/A	Barnes (1993)	Lincolnshire Limestone
25	Etton	Peterborough	397.78 l/s	BGS records (springs)	Great Oolite Group

Smith (1979) provides some information on springs in the Lincolnshire Limestone including a conceptual model of karstic flow to springs in the Holywell Brook catchment (Figure 24). The Holywell Brook is a small tributary of the West Glen river, and these springs are number 22 on Figure 23. Smith (1979) suggests that high flow velocities in fissures in the Upper Lincolnshire Limestone affect discharge from springs which consequently have a rapid response to large recharge events. Smith (1979) relates the high transmissivity (2500 to 10000 m^2/day) and low storativity (10^{-4}), particularly in the upper portion of the limestone, to karstic features which also result in rapid responses to recharge in borehole piezometers. Smith (1979) also reports many artesian overflows of boreholes of approximately 50 to 250 l/s in the confined Lincolnshire Limestone Formation. Whilst these are not natural springs, the large volumes involved are indicative of concentrated karstic flows. Artesian flows are also described by Barton and Perkins (1994) in relation to managing uncontrolled loss of groundwater from artesian springs and boreholes. Barton and Perkins (1994) describe several artesian springs located between Peterborough and Sleaford with discharges of 2.3 to 19.7 l/s. Downing and Williams (1969) also discuss artesian flow in wells in the Lincolnshire Limestone Formation, and the importance of groundwater flow through solutionally enhanced fractures.

The Bourne Eau is a natural artesian spring in the town of Bourne (Figure 23), and there are also natural springs a few kilometres to the northeast of Bourne at Dyke, and springs known as the Caudles a few kilometres southwest of Bourne in the East Glen valley (Atkinson and Farrant, 2015). In the 19th and 20th centuries abstraction from artesian wells caused the Caudles to become estavelles rather than permanently discharging springs, and by the 1970s there was rarely any discharge from the Caudles (Burgess and Smith, 1979; reported in Atkinson and Farrant, 2015). Addy (1882) reports that natural springs at Bourne had a discharge of 4,600,000 gallons in 24 hours which is roughly 240 l/s. Addy (1882) also reports that there is another spring of note at Horbling.

There are some other observations of springs in the area. In the mid-1990s Atkinson observed a spring of several l/s at NGR 492700 323800 (near Colsterworth) which may flow to the River Witham. Mason (2012) notes that there are more than 9 springs emerging from the base of the Lincolnshire Limestone at King's Cliffe and within the Willow Brook (~ 10 km west of Peterborough), "some strongly flowing throughout the year". Rushton et al. (1993) also provide information on springs in the J2 area. In the West Glen catchment, springs provide approximately 95% of the baseflow at various points along the river and tributaries, and during the dry months, this figure increases with the springs providing essentially all of the flow (Downing and Williams, 1969; Rushton et al. 1993).

Further information on springs in the area can also be found in Woodward et al. (1904), although no grid references are provided. They discuss several springs including (i) springs at Dunston with discharges of 105,000 to 2800,000 gallons, although it is not clear what timescale this is over (ii) "strong springs" at Welton (iii) Norcliff Spring at Wilsford, near Sleaford (iv) The Lady Well at Ancastre (v) The Holy Well at fulbreck between Grantham and Lincoln and (vi) a Spring at Stoke Rochford, near Colsterworth with a flow of 303 l/s).

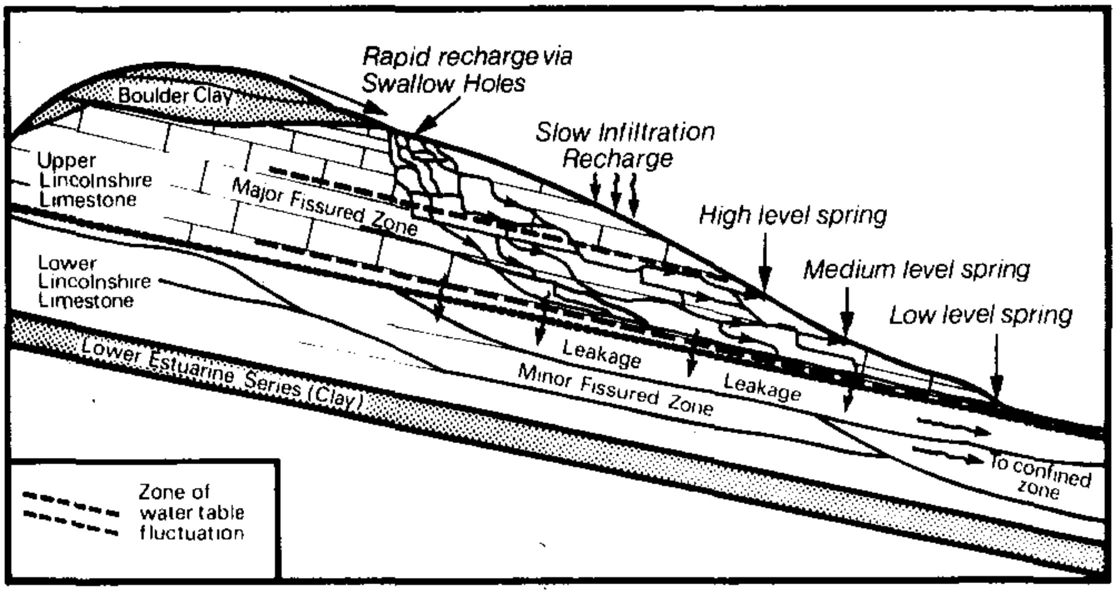

Figure 24. Conceptual model of flow to springs in the Holywell Brook catchment from Smith (1979)

Smith, J.E. 1979. Spring Discharge in Relation to Rapid Fissure Flow. *Groundwater* 17, no. 4: 346-350. (Figure 2a). Reprinted from Groundwater with permission of the National Ground Water Association. Copyright 1979.

3 Tracer tests

In the J2 Jurassic Limestone area there have been 18 tracer injections into stream sinks and 21 borehole injections (Figure 25; Table 3).

Much of the tracer testing was carried out in the West and East Glen catchments by Ian Booker and other students from the University of East Anglia, under supervision from Tim Atkinson. These are reported by Booker (1977; 1982), King (1994), and in an unpublished manuscript (Booker & Atkinson, 1980); and details of all the tracer testing that was conducted are summarised in Atkinson and Farrant (2015). The injection sites for these tests were stream sinks and boreholes in either the Lower or Upper Lincolnshire Limestone members of the Inferior Oolite Group or the Rutland or Blisworth Limestone formations in the Great Oolite Group. In some of the tracer tests only a small number of samples had concentrations of the tracer above background.

Sixteen different connections were proven between stream sink or borehole injection points in the West Glen catchment, and spring or borehole monitoring points to the east (Figure 26; Table 3). These tests were conducted over distances of between 500 and 9830 m. The front cover of this report shows a tracer injection into Easton Wood stream sink. The tracer tests demonstrated rapid to extremely rapid groundwater velocities ranging from 100 to 10000 m/day. However, at some sites tracer continued to be discharged for long periods, indicating a range of travel velocities along different pathways, with a part of the tracer showing residence times of 100 to 200 days (Figure 27). Some tracer tests demonstrated divergent flow with tracer detected at multiple sites over a wide area (Figure 26). For example, tracer injected at Easton Wood was detected at 9 different monitoring locations. Tracer recoveries were only estimated for three connections and ranged from 0.01 % to 22.45 %. These recoveries suggest some dilution and/or attenuation, and may be due to the extensive flow path branching. A tracer injection was also carried out in a borehole in the East Glen catchment which demonstrated flow to four abstraction boreholes and one spring over distances of 600 to 5690 m. Groundwater velocities of 6000 and 7500 m/day were reported for two of the five connections (Booker & Atkinson, 1980). No tracer recoveries were reported. The tracer tests from Burton Coggles to Elsthorpe borehole and from the latter to sites around Bourne Pumping Station demonstrate rapid flow for over 12 km along a flow path from outcrop to an area in the confined zone in which there are major abstractions for water supply.

Figure 28 is a conceptual model of the karstic flow in the East and West Glen catchments which has been demonstrated by tracer tests and was drawn around 1980. In the figure the yellow shows areas of glacial deposits (mainly till) and the pale brown indicates strata overlying the Lincolnshire Limestone Formation.

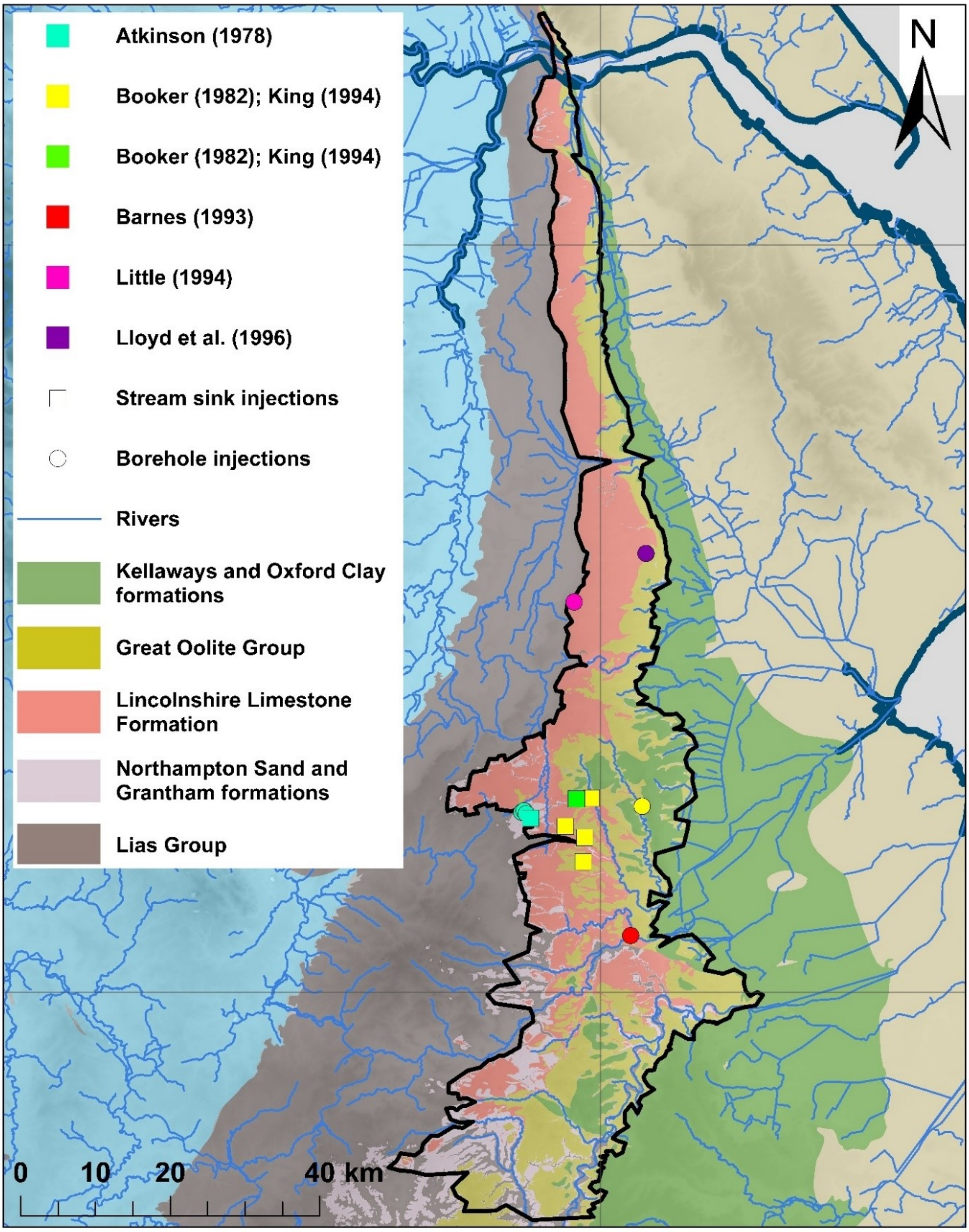

Figure 25. Tracer test injection points in the J2 Jurassic Limestone area.

Table 3. Tracer test summay details; velocities based on the time to peak tracer concentration (B = borehole; S = spring)

Authors	Area	Input	Output	Injection type	Distance (m)	Velocity (m/d)	Recovery (%)
Booker (1982); King (1994)	West Glen catchment	Easton Wood	Potato & Allied Services Ltd. (B)	Stream sink	500	263	0.01
			Creeton Springs (S)	Stream sink	7000	3365	2.70
			Glebe Farm 1 (S)	Stream sink	8500	2833	22.45
			Glebe Farm 2 (S)	Stream sink	8600	7370	N/A
			Castle Bytham Large (S)	Stream sink	7600	7350	N/A
			Castle Bytham Small (S)	Stream sink	7600	2760	N/A
			Little Bytham (S)	Stream sink	9250	1890	N/A
			Tham/West Glen (S)	Stream sink	9500	1830	N/A
			Swayfield (B)	Stream sink	3970	N/A	N/A
			Elsthorpe (B)	Stream sink	8860	N/A	N/A
Booker & Atkinson (1980)	West Glen catchment	Cabbage Hill	Careby (B)	Stream sink	7010	100	N/A
		Porter's Farm	Irnam (B)	Stream sink	9830	N/A	N/A
			Elsthorpe (B)	Stream sink	11870	5000	N/A
		Rodbecks	Holywell (S)	Stream sink	3050	10000	N/A
			Careby (B)	Stream sink	5290	100	N/A
		West Glen at Burton Coggles	Elsthorpe (B)	Stream sink	6890	3000	N/A
Atkinson (1978)	West of the River Witham	Glebe Farm Swallow Hole	Stainby No.1 gullet (S)	Stream sink	360	350	0.25
			Motherford Spring (S)	Stream sink	2460	34	N/A
		B2 Glebe Farm	Glebe Farm well (B)	Borehole	960	80	N/A
		B3 Glebe Farm	Foxhole Spring (S)	Borehole	2000	170	0.17
			Motherford Spring (S)	Borehole	2380	24	0.60
Booker & Atkinson (1980)	East Glen catchment	Elsthorpe	Bourne Eau (S)	Borehole	3900	7500	N/A
			Hanthorpe (B)	Borehole	2510	N/A	N/A
			Elsthorpe Grange (B)	Borehole	600	N/A	N/A
			Pasture Hil (B)	Borehole	4900	6000	N/A
			Bourne Woodland Nurseries (B)	Borehole	5690	N/A	N/A
Lloyd et al. (1996)	Metheringham	BH 1	BH 2 (B)	Borehole	7.8	4490	63.50
			BH 5 (B)	Borehole	3.6	650	63.00
			BH 9 (B)	Borehole	6	N/A	68.00
			BH 11 (B)	Borehole	3	1080	84.90
			BH 12 (B)	Borehole	2	640	95.00
Riley et al. (2001)	Metheringham	BH 14	BH 1 (B)	Borehole	20.6	1020	74.40
		BH 6		Borehole	19.6	850	98.60
		BH 15		Borehole	41.2	650	55.00
		BH 16		Borehole	40.3	120	88.30
Little (1994)	Leadenham	LFG 12 Leadenham	BH 4 Leadenham (B)	Borehole	317	N/A	N/A
Barnes (1993)	River Welland/ Gwash junction	Gilmans Borehole	Sample Point R (B)	Borehole	180	21	N/A
			Hudd's Mill Spring (S)	Borehole	260	284	N/A
			Small Spring (S)	Borehole	430	86	N/A

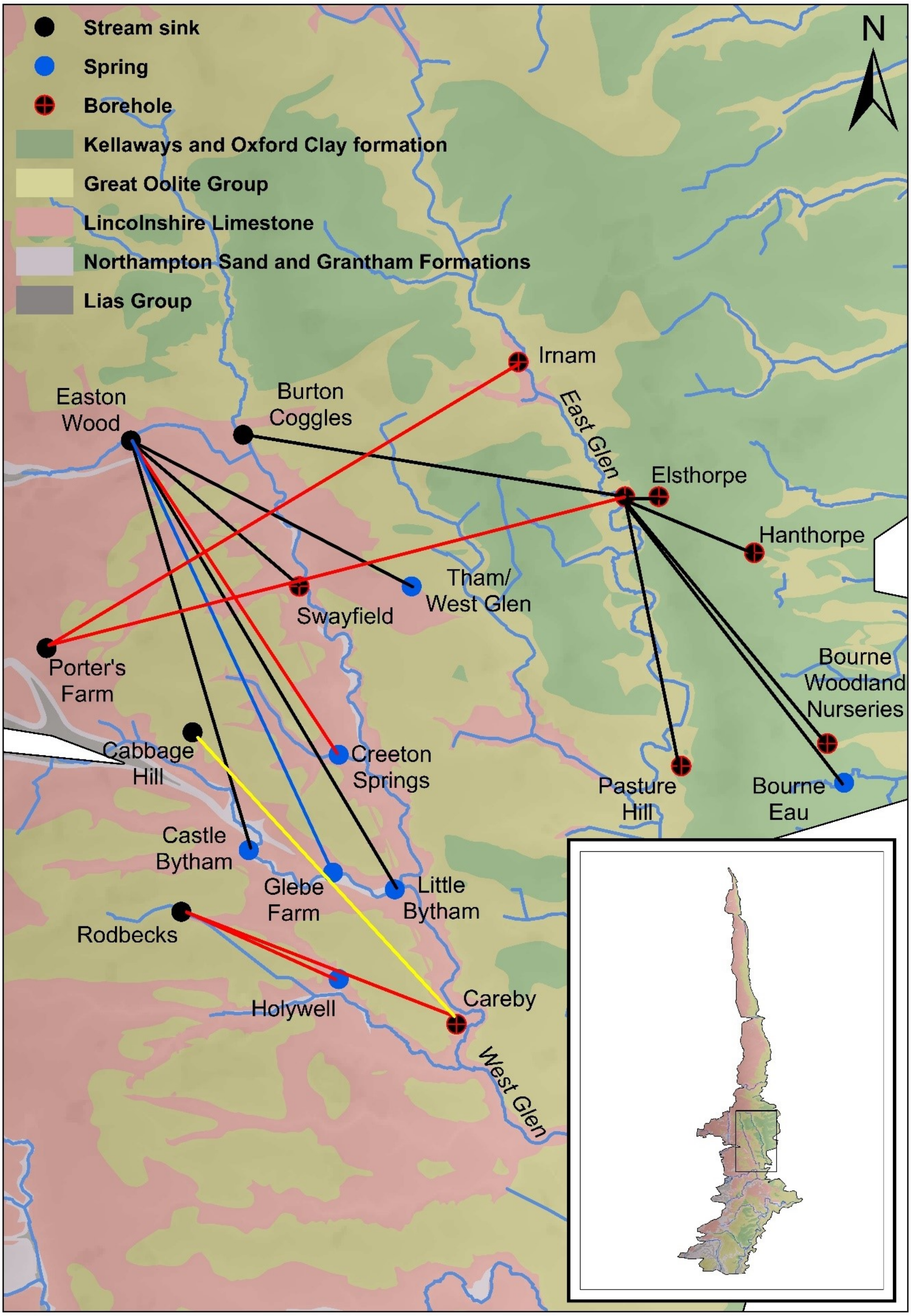

Figure 26. Tracer test connections in West and East Glen catchments based on Table 1 in Atkinson and Farrant (2015). Red lines indicate connections proven using Rhodamine WT, blue lines Photine CU, yellow lines Lissamine 7FF and black lines Sodium Fluorescein.

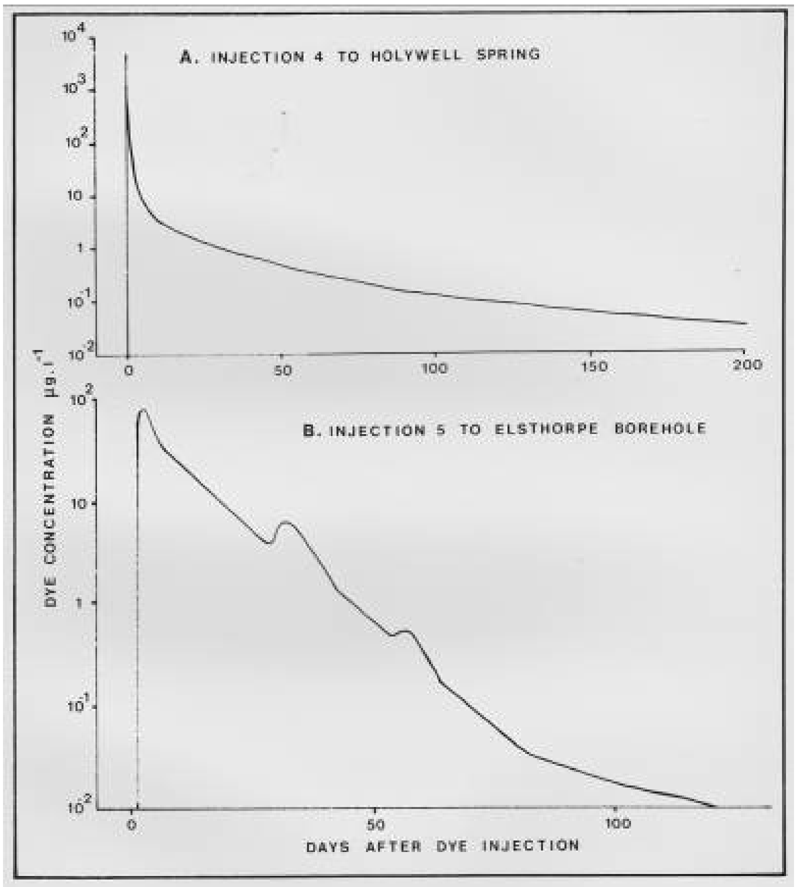

Figure 27. Breakthrough curves for tracer tests in the West Glen catchment (from unpublished manuscript by Booker and Atkinson, 1980)

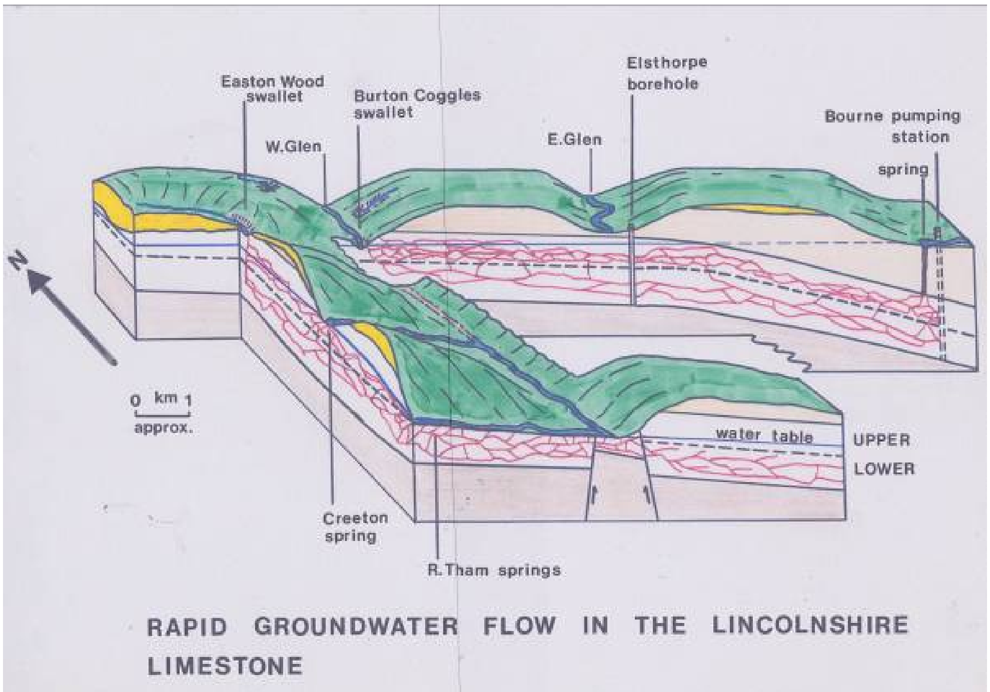

Figure 28. Conceptual model explaining the rapid flow velocities of groundwater due to karstification in East and West Glen catchments from Atkinson and Farrant (2015)

West of the River Witham, tracers were injected into one stream sink and two boreholes and were monitored and detected at four springs and one borehole (Atkinson, 1978); see Figure 25 for location. Travel distances ranged from 360 to 2460 m and the measured velocities based on the time taken to reach peak tracer concentration ranged from 24 to 350 m/day. These velocities are rapid, but lower than those demonstrated in other tracer tests in the J2 area. Tracer recoveries were quite low for these tests, ranging from 0.17 to 0.60%. This may be due to dispersal of tracer to unmonitored outlets, or attenuation along the flowpath.

In Metheringham, small-scale tracer tests from one injection borehole to five abstraction boreholes are reported by Lloyd et al. (1996); see Figure 25 for location. These proved connections over very short distances ranging from 2 to 7.8 m (Figure 29). Very rapid groundwater flow velocities were measured, from 640 to 4490 m/day. The breakthrough curves for these tests showed very rapid breakthroughs (tracer arriving within a few minutes of injection), distinctive peaks, and varied amounts of tailing (tracer continuing to be discharged at low levels for between about 1 and 4 hours at the different boreholes). Lloyd et al. (1996) suggest that the breakthrough curves may represent rapid movement of groundwater along large fissures/conduits, with some slower migration through more restricted fissures and/or diffusion causing the tailing. Tracer recoveries were high, ranging from 63 to 95%, which suggests that overall there is low attenuation and that most of the tracer was discharged at the monitored outlets.

At the same site further tests were conducted by Riley et al. (2001), which demonstrated a further four connections to BH1, which was the injection site for the Lloyd et al. (1996) tests (Figure 29). The distances between the injection sites to BH1 range from 19.6 to 41.2 m and the velocities based on time to peak concentration over these distances ranged from 120 to 1020 m/day. Tracer recoveries were very high, ranging from 55.0 to 98.6%.

In Leadenham, tracer testing demonstrated a connection between two boreholes over a distance of 317 m in the Lower Lincolnshire Limestone (Little, 1994); see Figure 25 for location. No details of travel time, velocity or tracer recovery are recorded.

At the junction where the River Welland meets the River Gwash, three connections were identified from one injection borehole to one observation borehole and two springs over distances of 180 to 430 m (Barnes, 1993) - see Figure 25 for the general location. Groundwater flow velocities of 21 to 284 m/day (based on time to peak concentration) were recorded. Tracer recovery was not measured in these tests.

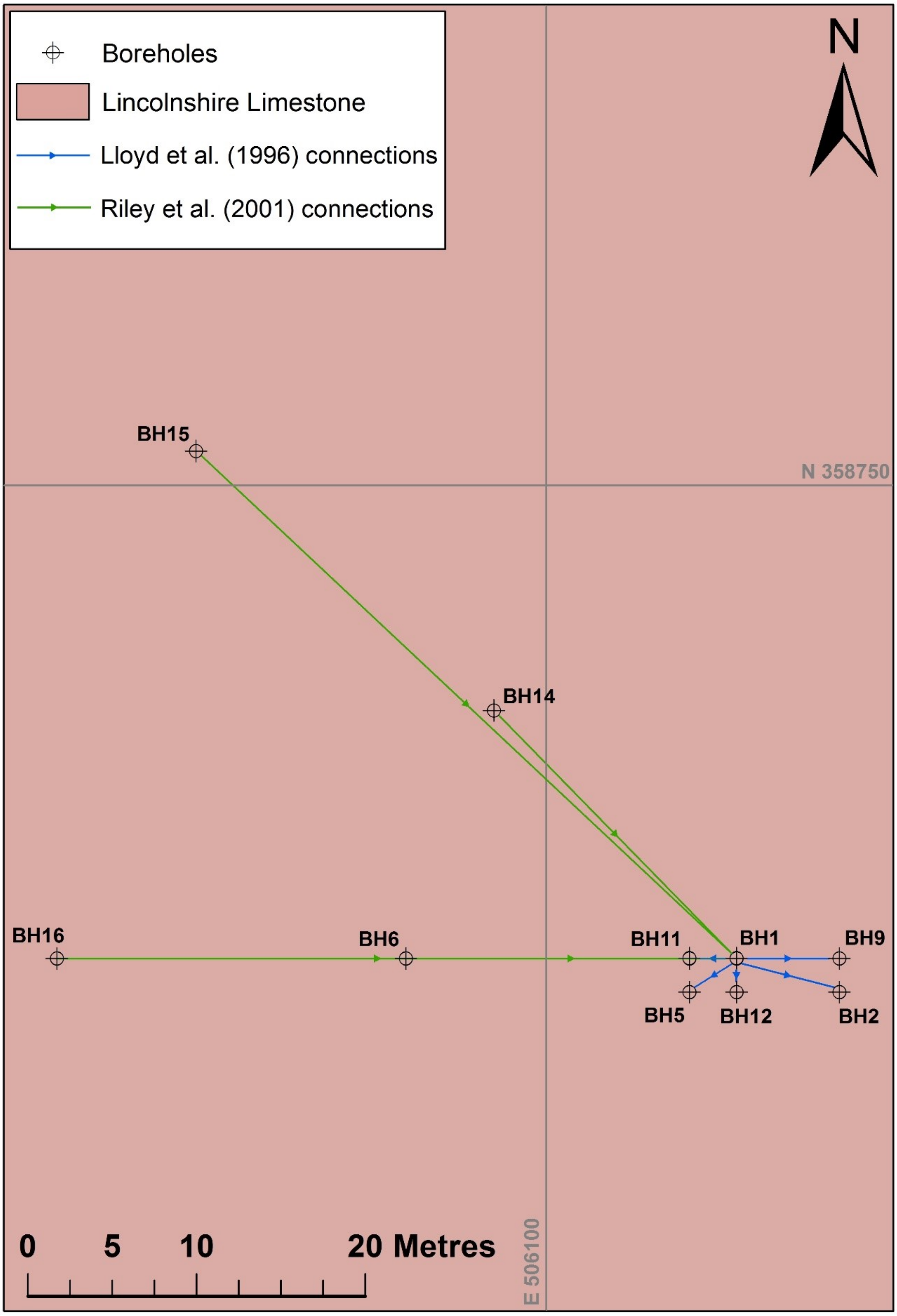

Figure 29. Tracer test pathways demonstrated by Lloyd et al. (1996) and Riley (2001) in the Metheringham area.

4 Other hydrogeological evidence of karst and rapid flow

High transmissivities of more than 1000 m^2/day are reported in the area (Allen et al., 1997; Figure 30), indicating the presence of well-connected networks of solutional fissures and conduits supplying the abstractions. There are boreholes with very high transmissivity (5800 to 14000 m^2/day) around Sleaford. Figure 30 shows the locations of 63 transmissivity measurements, of which 30 values are from outside of the nominal J2 area boundary. They have been included as they are measurements from within the confined area of the Jurassic aquifers; and show that high transmissivity (and hence subsurface karstic development) extend many kilometres into the confined aquifer to the east of the limestone outcrops.

Fox and Rushton (1976) also note that there are transmissivities of up to 10000 m^2/day in the confined Lincolnshire Limestone in this area. They also discuss large piezometric head variations in confined boreholes around Aslackby in the south east of the J2 area, and note that rapid bypass recharge is needed in groundwater models in order to simulate these variations. Transmissivities of up to 10,000 m^2/day have also been suggested for three abstractions in the confined limestones in the Bourne area (Downing and Williams, 1969; reported by Atkinson and Farrant, 2015).

The high transmissivity in the confined aquifer is observed through artesian boreholes with high flow rates (see Section 2.4). Addy (1882) notes that a bore at Bourne sometimes “has water rising to 40 feet [12 m] above the average level of town”. The problem of “wild bores” or loss of groundwater due to artesian discharge was increasingly recognised and one of the large wild bores (at Aslackby) had losses of ~ 40 l/s in the 1970s (Barton and Perkins, 1994). The locations of some “wild bores” in the confined aquifer (from Environment Agency records) are shown on Figure 30.

Atkinson and Farrant (2015) report an “accidental” tracer test discovered by Booker (1982). When Booker conducted background monitoring of optical brightener in 1976-1977 prior to injecting tracer at the Porters Farm stream sink, he found a colourant that was thought to be derived from a disused WW2 airfield site at Twyford Wood, and was able to track it moving from borehole to borehole indicating velocities of 30 to 160 m/day. Whilst these are slower than the very rapid flows indicated by the injected tracer tests in this area (Section 3), these flows are still rapid, and would suggest that groundwater within the karstic solutional fissure network in the aquifer is likely to travel many kilometres over 50 days (the travel time for inner source protection zones). Atkinson and Farrant (2015) also report groundwater flow velocities of tens of metres per day based on changing nitrate and chloride concentrations in groundwater observed by Booker, who assumed that the sources of these ions were fertiliser applications to the limestone outcrop area and road salt applied to the A1 road, respectively. Atkinson and Farrant (2015) note that these velocities of tens of metres per day are consistent with the long tailing observed in some of the breakthrough curves following tracer injections (e.g. Figure 27).

During the 1990s investigations of pesticide pollution of the Etton public water supply found the source to be waste pesticides in landfill sites in the Lincolnshire Limestone Formation approximately 3 km away (Sweeney et al., 1998). Whilst the pollutant travel times are not reported and the work did not demonstrate rapid groundwater flow, the pollution incident illustrates the vulnerability of the aquifer, with connectivity between the fissures supplying the abstraction and a pollutant source some distance away.

Indicators of karst at abstraction boreholes (e.g. conduits observed in borehole images; water quality indicators of rapid groundwater flow) have not been considered for this report, although some abstractions in the area have some of these characteristics indicative of karst (knowledge exchange meetings with the Environment Agency and water companies in 2016; Rushton et al., 1993).

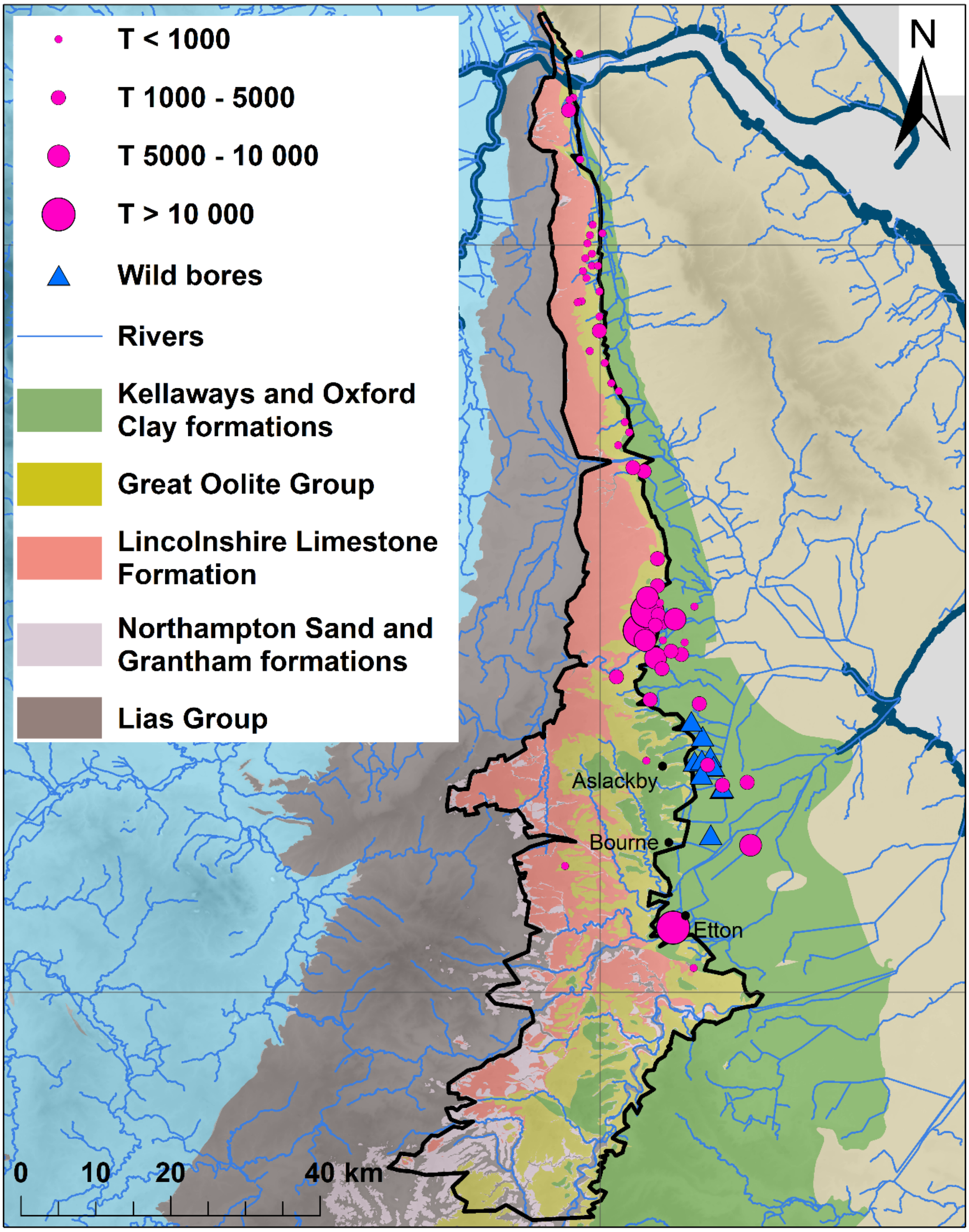

Figure 30. Recorded values of transmissivity (m^2/day) from the BGS aquifer properties database and "wild bores" from Environment Agency records.

5 Summary

- There is considerable evidence for karst in the J2 Jurassic limestone area.
- Karst is particularly developed in the Lincolnshire Limestone Formation, but there is also evidence of karst in the limestones of the Great Oolite Group.
- Many surface karst features have been recorded including dolines, stream sinks and springs, although there are no recorded enterable caves.
- Stream sinks and doline records are concentrated in the central western part of the area, which could suggest that this area has more surface karst. However, records reflect areas where studies have been undertaken and there has been no systematic study of karst features throughout the J2 area and therefore there could be other unrecorded features.
- Some stream sinks in the area have the capacity to take very large inflows of 200 to 300 l/s.
- There are 589 recorded springs in the area with 165 on the Lincolnshire Limestone, 196 in the Great Oolite and the remaining in the overlying Kellaways and Oxford Clay formations, or the underlying Northampton Sand.
- There is little spring discharge data, but there is evidence that at least 25 of them are substantial, and the largest recorded discharge is 355 l/s.
- Artesian springs in the western part of the confined aquifer formed the natural outlets for the karstic networks.
- Very high transmissivities (up to 10,000 m^2/day) are also found in abstractions from the western part of the confined aquifer.
- High transmissivities (and hence subsurface karstic flowpaths) extend many kilometres into the confined aquifer to the east of the limestone outcrops.
- Several tracer tests reveal rapid groundwater flow velocities ranging from 21 to 10000 m/day over distances of up to 11.9 km.
- Tracer tests demonstrate connections to multiple outlets over a wide area, suggesting that the karst comprises complex networks with divergent and convergent flow.
- Some tracer breakthrough curves had very long tails, with tracer discharged for more than 100 days following injection indicating high attenuation via dispersion and/or diffusion.
- Tracer recoveries ranged from 0.01 to 98.60 %. High tracer recoveries suggest low attenuation and extremely high vulnerability to pollution. Tracer tests with lower recoveries suggest flow paths are complex with attenuation (dispersion and diffusion) and dilution within the aquifer.
- Karst is an important factor that should be considered in hydrogeological studies, and which affects groundwater protection and management in this area.
- Further work is needed to improve understanding of the karstic nature of the aquifers and the implications for groundwater protection. This could include the development of improved datasets on springs and other surface karst features; consideration of the impact of karst on abstractions; and further tracer testing.

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 in the subsurface, often with no surface expression.

Estavelle: A karst feature in a doline, stream or river bed that acts as a spring when groundwater levels are high but is a sink for surface water when groundwater levels are low.

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

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

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

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