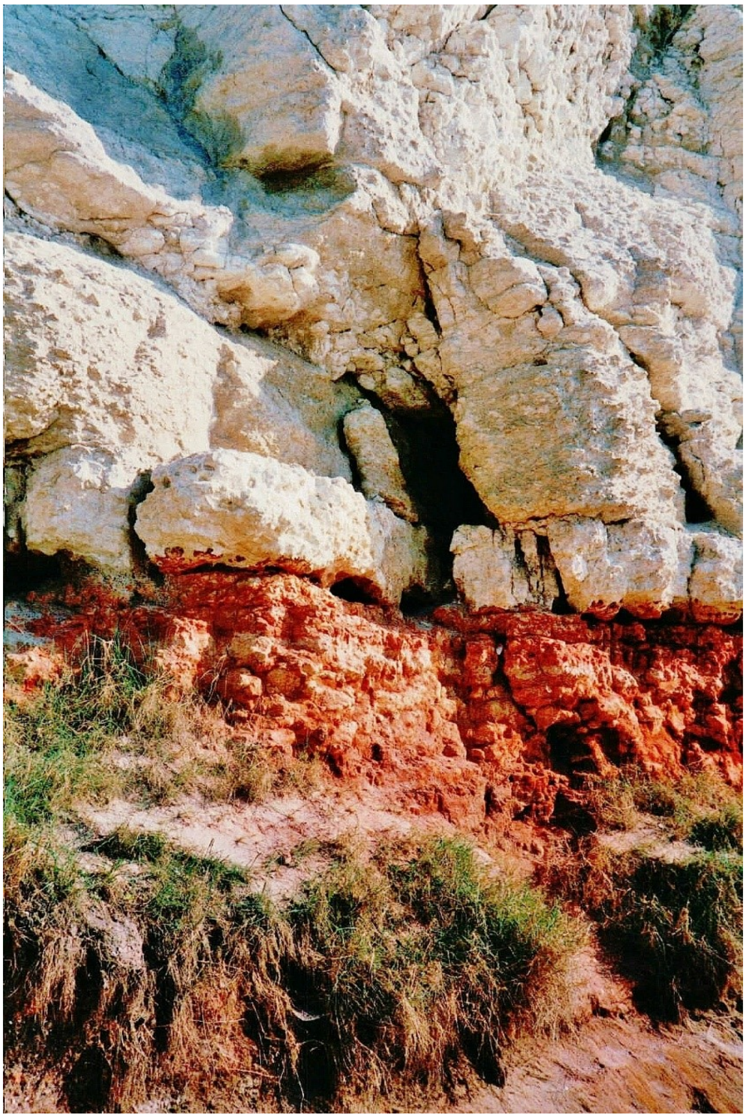
BGS Karst Report Series: C3. Karst in the Chalk of East Anglia

Environmental Change, Adaptation and Resilience Programme

Open Report OR/22/062



BRITISH GEOLOGICAL SURVEY

ENVIRONMENTAL CHANGE, ADAPTATION AND RESILIENCE PROGRAMME

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BGS Karst Report Series: C3. Karst in the Chalk of East Anglia

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

Keywords

Chalk, Karst, groundwater, East Anglia.

Front cover

Karst cave at Hunstanton. Photo courtesy of Terry Reeve.

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British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG
Tel 0115 936 3100

BGS Central Enquiries Desk
Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales
Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP
Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
London SW7 5BD
Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT
Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB
Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw,
Belfast, BT4 3SB
Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House,
North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
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Executive Summary

This report documents the evidence for karst and rapid groundwater flow in the Chalk of East Anglia. 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 report shows that there is a surprising amount of evidence for karst in East Anglia, despite the extensive and often thick superficial deposits that cover much of the Chalk following the Anglian glaciation. Paleokarstic features provide evidence of karstification prior to the Anglian glaciation, and post Anglian karst development is also occurring. Although there are only a few studies of karst specifically, considering the different strands of evidence, it is clear that karst processes impact the Chalk throughout the area.

A small karst cave is present in the Chalk at one location on the north coast, and other small caves may be present beneath the superficial cover. Karst networks in the area are likely to comprise fissures and conduits, and the extent to which some of these are enlarged to form small caves is difficult to assess given the limited outcrops and exposures. Dissolution pipes are common, many are large, and some provide evidence of paleokarst that pre-dates the Anglian glaciation. Extremely high densities of surface depressions occur, and it is often difficult to determine if they are of periglacial, anthropogenic, or karstic origin. However, it is clear that many are anthropogenic and that some are likely to be karst dolines. Stream sinks occur, with some classic chalk karst stream sinks in the south of the area associated with the Chalk-Paleogene boundary. Many stream sinks are associated with the Chalk-glacial till boundary, and although these are small scale features, collectively they may be important for recharge in some areas. Some streams on the Chalk (and where there is thin permeable cover) have losing sections and/or exhibit bourne behaviour.

Karstic recharge is unlikely over large parts of East Anglia where there are thick deposits of glacial till overlying the Chalk. Nevertheless, there are areas where some karstic flow in the unsaturated zone is likely. This is most likely where there are stream sinks or river losses to the Chalk, and may also occur in a more limited way in association with dissolution pipes/dolines where there is thin cover, and also in areas of outcrop Chalk if there are vertical solutional fissures with no surface expression. Further assessment of surface karst features and consideration of water quality indicators of rapid flow at springs and abstractions would provide insights into unsaturated zone karst in East Anglia.

There is more widespread evidence for saturated zone karst. A small number of tracer tests from monitoring boreholes to abstraction boreholes or springs have demonstrated rapid groundwater flows of 14 to >3800 m/day over distances of 44 to 1650 m. Extensive networks of solutional fissures and conduits are also indicated by the many groundwater abstraction sites with high transmissivity (> 1000 m^2/day) which are distributed throughout East Anglia. There are also many springs, some of which are reported to be (or have been) large, including some with measured discharges of > 200 l/s.

Saturated zone karst networks may occur due to mixing corrosion or due to the development of current/past stream sink to spring connections. Whilst the exact locations and extent of the saturated zone solutional networks are difficult to determine, karstic solutional development in this area appears to occur more in river valleys than interfluves; and there is often a strong geological control, with flows focused on inception horizons (that in this area include the Totternhoe Stone, the Plenus Marls, the Chalk Rock and the Top Rock).

Although there is evidence for karst throughout East Anglia, there is more evidence for karst in the south and west of the area, and in river valleys and where superficial cover is thin. Some areas with particular evidence for karst include: the Beane and Upper Cam catchments, the Gipping valley, the Cambridge-Newmarket area, the Thetford area, and the Burn and Bure catchments in the north.

Karst is clearly an important aspect of the hydrogeology of East Anglia. Further work would be useful to improve datasets on dissolution pipes, dolines, stream sinks and springs which are generally very incomplete in this area; and further studies of these features would also be useful

to determine their characteristics and their hydrogeological role. Further tracer testing and further consideration of pumping test data in the context of karst would also be useful.

Introduction to the BGS Karst Report Series

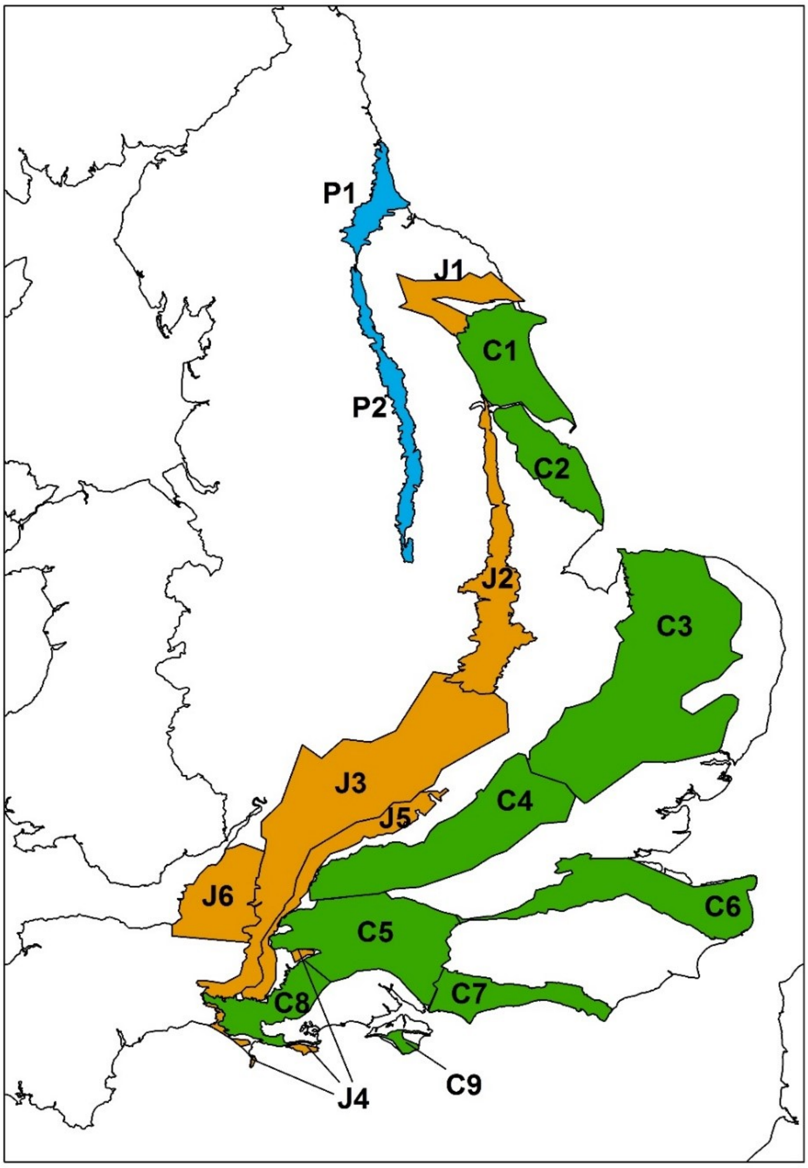
The BGS karst report series is focused on karst aquifers in England in which cave development is limited – the Chalk and the Jurassic and Permian limestones. The series originated from the NERC funded Knowledge Exchange fellowship “Karst knowledge exchange to improve protection of groundwater resources”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

The term “karst” applies to rocks that are soluble. In classical karst regions there are extensive caves; and there are large scale surface karst landforms such as dolines, shafts, river sinks, and springs. In the past the Chalk and the Jurassic and Permian limestones of England were not considered karstic because they have limited cave development, and because karst features are usually small and have not been well documented. However, permeability in these aquifers is determined by their soluble nature and groundwater flow is predominantly through small-scale karstic solutional features comprising small conduits ~ 5 to >30 cm diameter and solutionally enlarged fractures (fissures) of ~0.5 to >2 cm aperture. There are some short caves in all three aquifers; they all have dolines, stream sinks and large springs; and rapid flow can occur over long distances. Karst is therefore an important feature of these aquifers.

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

Karst data are compiled from the British Geological Survey databases on karst, springs, and transmissivity; peer reviewed papers and reports; geological mapping; and through knowledge exchange between 2015 and 2022 with the Environment Agency, universities, water companies and consultants. The data are not complete and further research and knowledge exchange is needed to obtain a fuller picture of karst development in these aquifers, and to investigate the detail of local catchments. The reports nonetheless provide an overview of the currently available evidence for karst and demonstrate that surface karst features are much more widespread in these aquifers than previously thought, and that rapid groundwater flow is common. Consideration of karst and rapid groundwater flow in these aquifers will improve understanding of how these aquifers function, and these reports 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 Wessex Chalk (Hampshire and Wiltshire)
C6) Karst in the Chalk of the North Downs
C7) Karst in the Chalk of the South Downs
C8) Karst in the Chalk of Dorset
C9) Karst in the Chalk of the Isle of Wight
J1) Karst in the Jurassic Limestone Corallian Group of Northern England
J2) Karst in the Jurassic limestones of Central England
J3) Karst in the Jurassic Great and Inferior Oolites of Southern England
J4) Karst in the Jurassic Portland and Purbeck limestones in Southern England
J5) Karst in the Jurassic Corallian Group limestones of Southern England.
J6) Karst in the Jurassic Blue Lias limestones of South-West England.
P1) Karst in the northern outcrop of the Permian limestones
P2) Karst in the southern outcrop of the Permian limestones

Introduction to Karst Data

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 and small holes in stream beds, to sink points located in karstic depressions of more than 10 m in depth and/or diameter. Some data sources report many/all individual sink points associated with a stream; whilst others report a single point for an individual stream irrespective of whether there are multiple sink points. The data presented here comprise all the sink point records that the studies report, but there are likely to be many more sink points in streambeds which have not yet been identified. Further information on the discharge and nature of the stream sinks is generally sparse, but where available, information from reports and papers are summarised.

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

Caves and smaller conduits

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

Smaller conduits are observed in quarry walls and natural cliff outcrops. Conduits (~5 to >30 cm in diameter) and larger solutional fissures (apertures of > 2 cm) are also 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 $l.s^{-1}$, have been identified. There are also some springs with no discharge data but which have been observed during field visits to be large (likely to be > 10 $l.s^{-1}$), or were used as monitoring outlets in tracer studies. 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 (Foley and Worthington, 2021; Maurice et al., 2021). Transmissivity data from the national aquifer properties manual (Allen et al., 1997; MacDonald et al., 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

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FIGURES

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1 Introduction

1.1 AREA/GEOLOGY

The C3 East Anglia Chalk area extends from the North Norfolk coast to just north of Harlow in Essex (Figure 1). When the project area boundary was defined it was considered unlikely that there would be karstic development in the far east of East Anglia where the Chalk is at considerable depth below overlying superficial deposits. However, some evidence of karst has emerged in these areas, and this is presented in the report, despite being outside the main project area.

The city of Norwich is present in the north-east of the area, and the city of Cambridge is towards the south-west. The area is low lying with elevations mostly less than 65 m AOD apart from some areas in the south of the area in Hertfordshire where relief is ~ 120 to 160 m AOD (Allen et al., 1997). In the north-east of the area, surface drainage is dominated by the River Yare and tributaries, including the Wensum and the Bure (Figure 2). The Yare drains eastward into the North Sea. In the central part of the area the principal rivers are the Wissey, the Little Ouse, the Lark and the Cam (Figure 2). These are all tributaries of the Great Ouse, which is just to the west of the C3 area and drains northwards into the Wash. The major rivers in the south-east are the Gipping and the Stour, which drain east towards the North Sea. A major groundwater divide is thought to follow the main south-west to north-east surface water divide along the crest of the Chalk escarpment (Allen et al., 1997).

The Cretaceous Chalk Group is underlain by the non-karstic Upper Cretaceous Gault Formation mudstones of the Selborne Group which crop out to the west. At the base of the Chalk the Hunstanton Chalk Formation (commonly known as the Red Chalk) is present, with the type locality at Hunstanton on the north Norfolk coast, where it is about 1 m thick (Owen, 1994; Hopson, 2005). The C3 Chalk area lies within the Transitional Province of the Chalk between the Northern and Southern Provinces with some characteristics of both (Hopson, 2005). Due to the extensive cover over much of this area, there is some uncertainty, but it is thought that the Transitional Province across most of the region has more stratigraphical similarities with the Southern Province (Hopson, 2005). The stratigraphy is outlined in Table 1, and more information can be found in Hopson (2005). Some important horizons for karstic development include the Totternhoe Stone in the Zig Zag Chalk Formation, the Plenus Marls and other marls in the lower parts of the Holywell Nodular Chalk Formation, marl seams within the New Pit Chalk Formation and the Lewes Nodular Chalk Formation, and the Chalk Rock and Top Rock hardgrounds in the Lewes Nodular Chalk Formation. Hardgrounds, flints, and marl horizons in Suffolk are described by Woods et al. (2012).

In the south-east of the area, the Chalk is overlain by the Paleogene-aged Lambeth Group and the London Clay Formation; and in the east it is overlain by the Neogene Crag Group (Figure 2; Table 1). These younger formations mostly consist of clay, silt and sand; with the Crag Group comprising more permeable larger grain sizes, and the London Clay Formation having the lowest permeability of these younger formations. The Crag Group is a minor aquifer used for water supply, and where the Paleogene strata are absent and the Crag Group overlies the Chalk directly the two aquifers may be hydraulically connected (Allen et al., 1997).

There are widespread superficial deposits (Figure 3), which mainly reflect the extensive glaciation of the area. These deposits predominantly comprise the Anglian glacial till which covers a large part of the Chalk and Paleogene outcrop (the blue areas in Figure 3). The till is less prevalent in the west of the area. Some areas of glaciofluvial and river terrace gravels occur across the region, with alluvium in the major valleys and along the north Norfolk coast. The river terrace deposits are locally extensive, especially in the south-west of the area, although the pre-Anglian river terrace deposits are partially buried by glacial till. Peat deposits occur in the low-lying Fens, especially to the west of Thetford. There are very small areas with blown sand, brickearth, lacustrine deposits and Clay with Flints.

The Chalk surface is not well defined because it is concealed below the glacial deposits throughout most of the area, but it is often irregular due to glacial erosion and deposition (Allen et al., 1997). There are also many distinctive “buried channels” – these are narrow deep valleys within the Chalk surface which are filled with glacial deposits (Allen et al., 1997; Kearsey et al., 2019).

The extensive glacial till deposits mean that there is considerably more surface drainage than observed in many areas of the Chalk in England, and dry valleys are much less common. However, many of the rivers draining the till outcrop become dry for much of the year where they traverse the Chalk, for example in the Upper Cam catchment (Farrant et al., 2022b).

Table 1. Basic stratigraphy in the C3 East Anglia Chalk area (from Hopson, 2005)

Group	Subgroup	Formation	Lithology	Thickness
Crag Group			Sand	0-70 m
Thames Group		London Clay Formation	Clay, silt and sand	0-150 m
Lambeth Group			Clay, silt and sand	0-39 m
Chalk Group	White Chalk Subgroup	Portsdown Chalk Formation	Chalk	62 m
		Culver Chalk Formation		65-75 m
		Newhaven Chalk Formation		45-75 m
		Seaford Chalk Formation		50-80 m
		Lewes Nodular Chalk Formation		35-60 m
		New Pit Chalk Formation		75-80 m
		Holywell Nodular Chalk Formation		10-15 m
	Grey Chalk Subgroup	Zig Zag Chalk Formation		35-50 m
		West Melbury Marly Chalk Formation		15-25 m
		Hunstanton Formation		~1 m
Selborne Group		Gault Formation	Mudstone	2-20 m

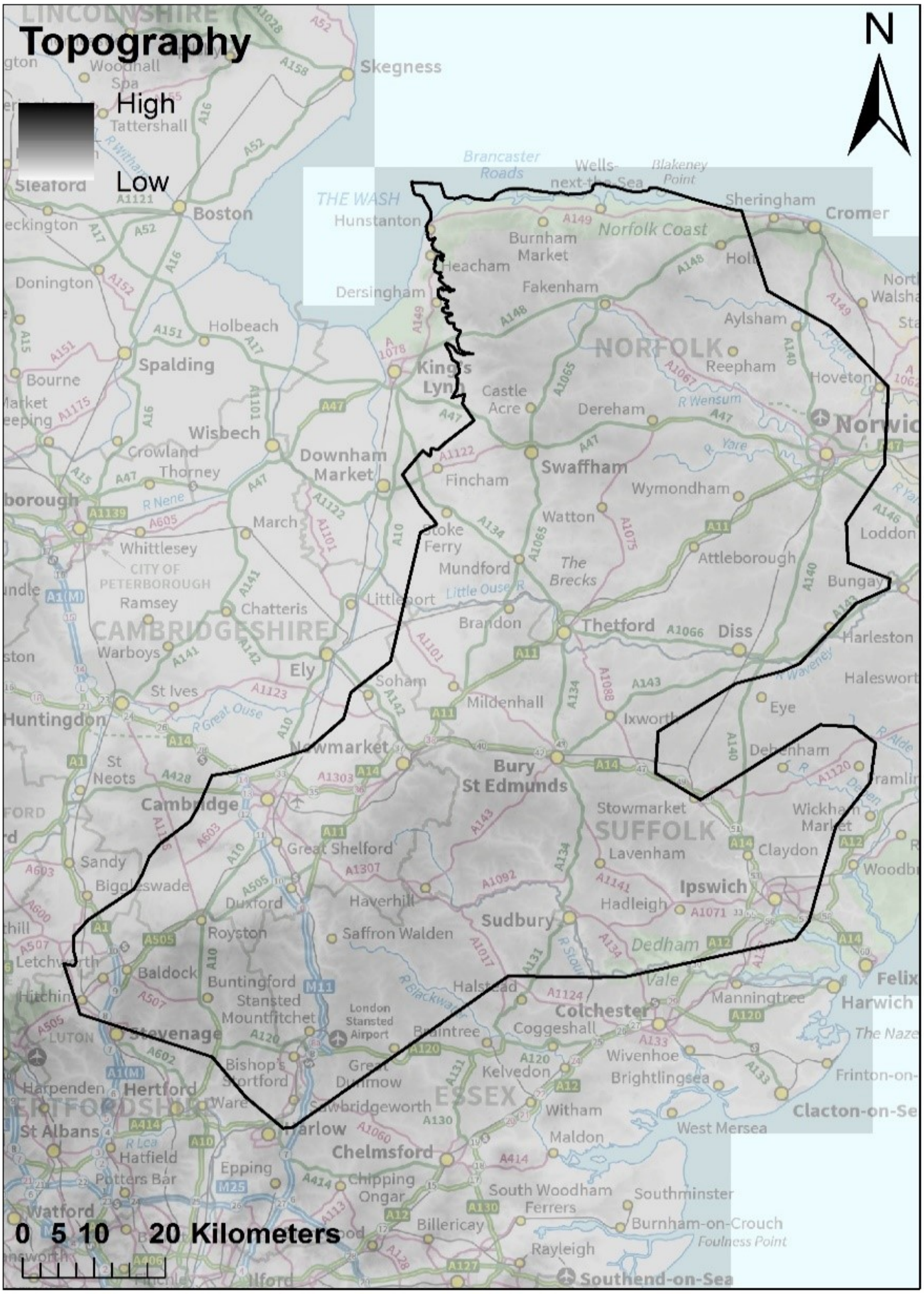

Figure 1. The C3 East Anglia Chalk area.

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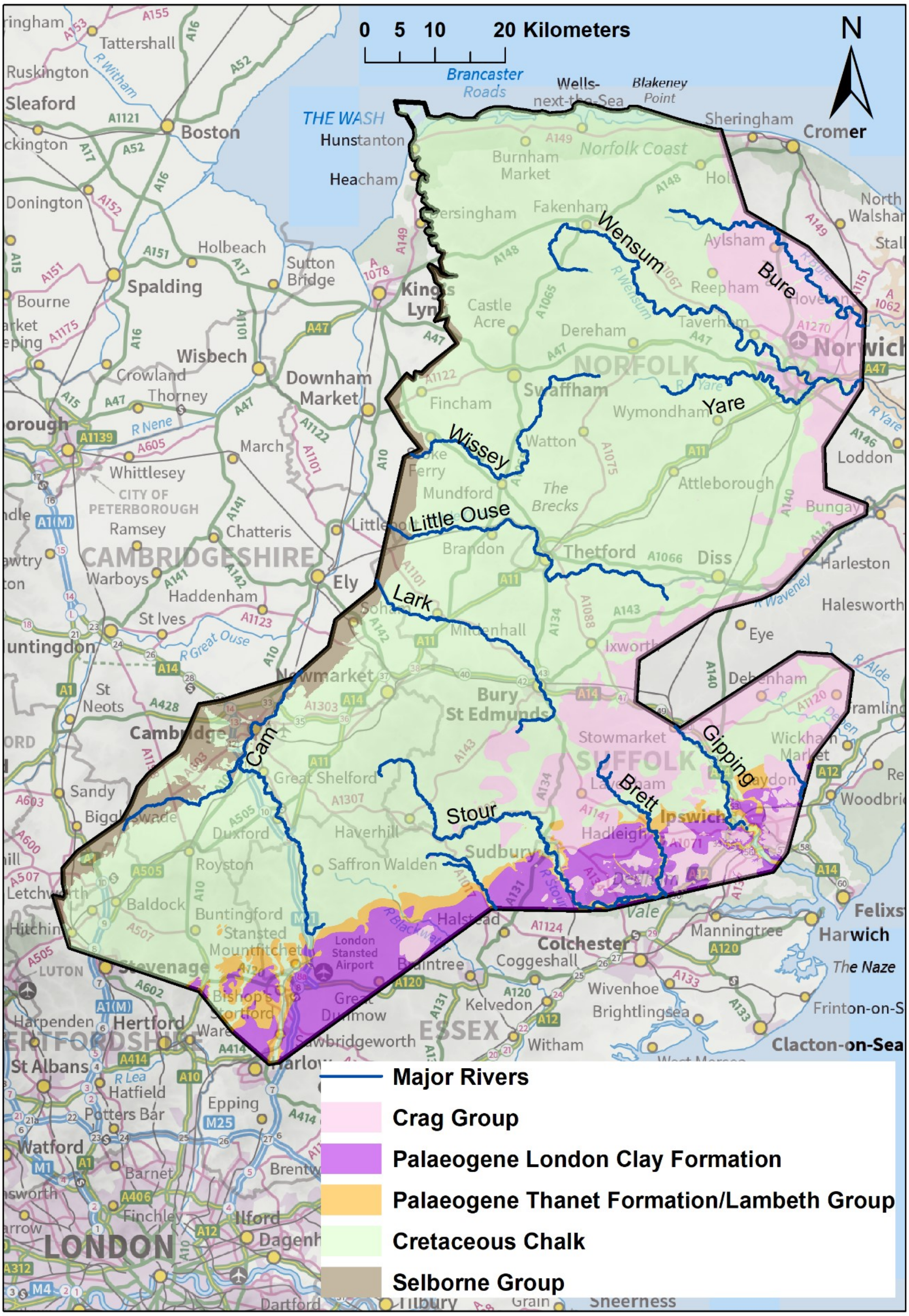

Figure 2. Bedrock geology and some major rivers

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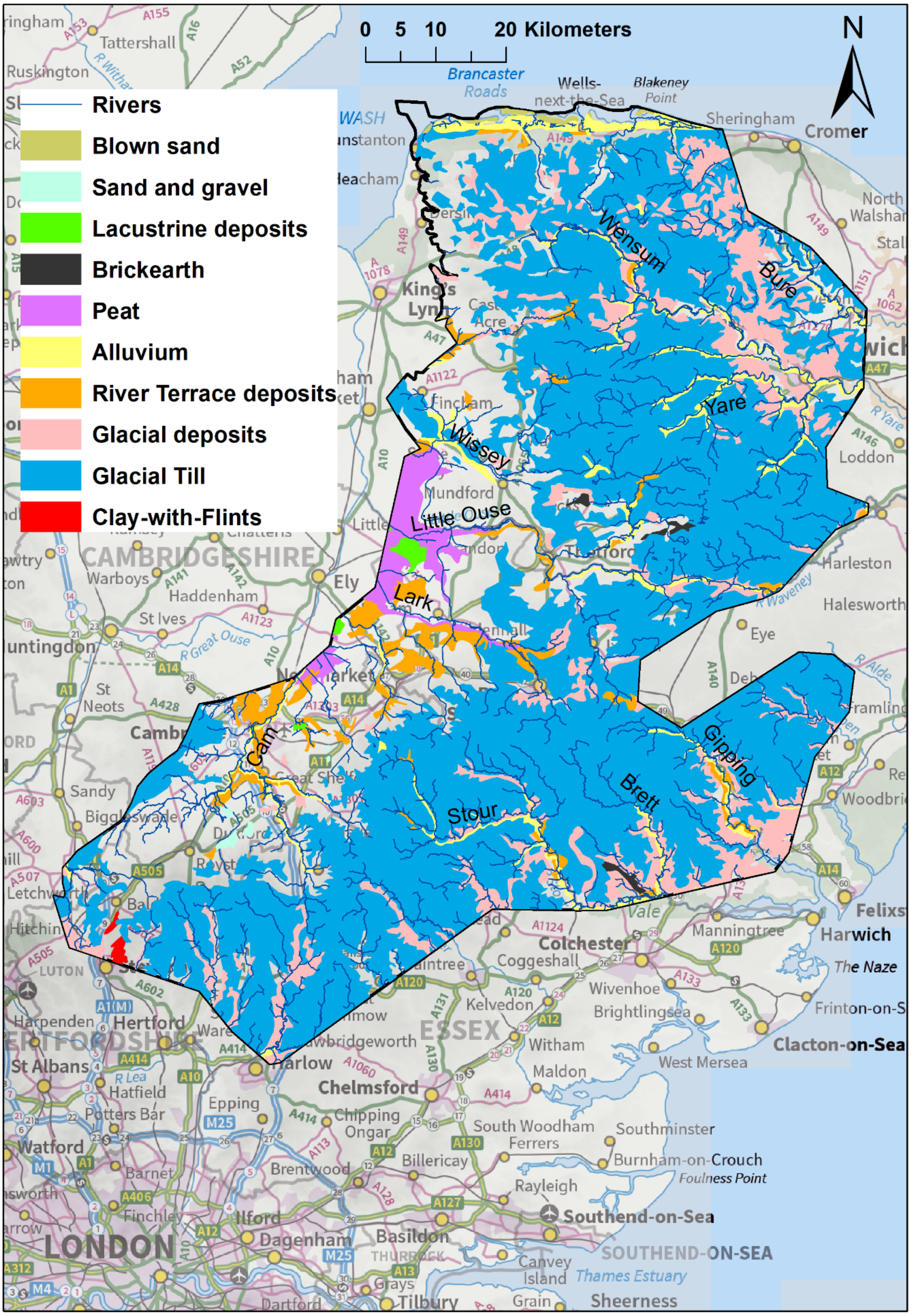

Figure 3. Superficial geology and rivers

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1.2 WATER PROVIDERS AND REGULATORS

Anglian Water is the major water provider in the C3 area. Cambridge Water and Affinity water provide water in the south-west of the area, and Essex & Suffolk Water provide water to a small part of the C3 area.

The C3 area mostly falls within the East Anglia Environment Agency (EA) area, with a small part in the south-west in the Hertfordshire and North London EA area (Figure 5).

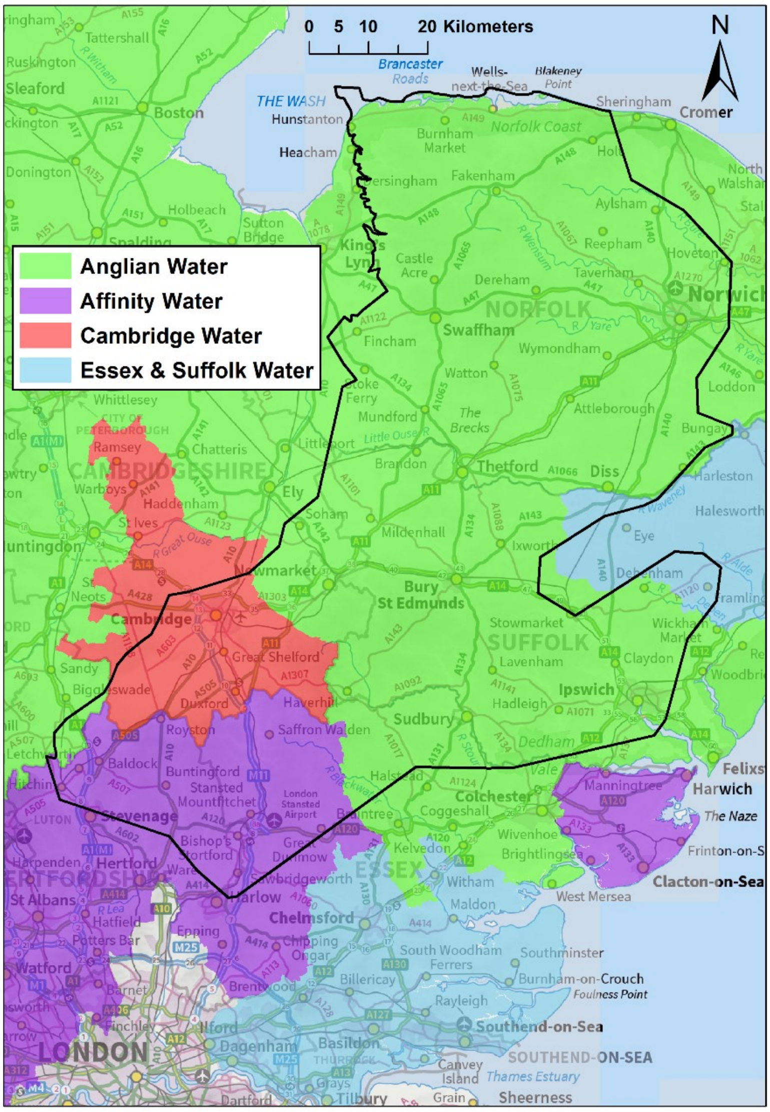

Figure 4. Water providers in the C3 East Anglia Chalk area.

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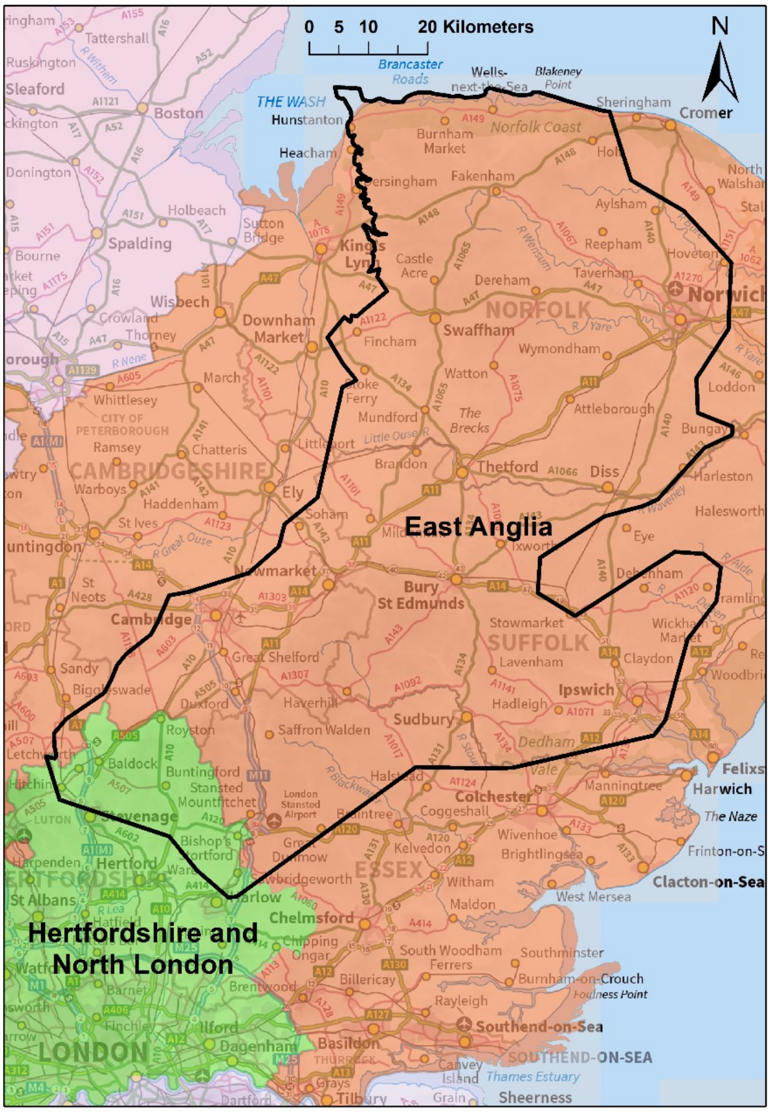

Figure 5. Environment Agency areas in the C3 East Anglia Chalk area.

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2 Karst geomorphology

2.1 CAVES AND CONDUITS

There is little evidence of cave development in the East Anglian Chalk. However, a small karst cave in the Chalk, together with some smaller karstic conduits and fissures can be observed at Hunstanton in Norfolk (Terry Reeve, personal communication, 2022; see Figure 6 for location and Figure 7 and Figure 8 for pictures). These conduits are developed in the beds immediately above the Hunstanton Red Chalk Formation which appear to be a karstic inception horizon with several solutional features present. There are sediment-filled cavities developed on marl bands in the lower New Pit Chalk in Kensworth quarry (not far to the west of the C3 area) that would be large enough to be classed as caves, although most of the cavities are smaller. No other caves have been reported in the C3 East Anglia area, although cave-sized conduits may exist in the subsurface, especially close to large springs. There have been no systematic surveys of caves, conduits and fissures along the East Anglian Chalk coastline, and such a survey might provide further information on conduit development in the Chalk in this area.

Information on conduit development from Chalk quarries and other inland exposures has not been systematically collated, but might also provide insights into the extent of conduit development. For example, Farrant et al. (2017) note that there is a chalk pit at Pinchpools near Stansted (TL 4920 2758) where sediment-filled solution cavities are observed along flint layers. This location is included on Figure 6. However, due to the extensive cover over much of the Chalk, and the lack of quarry and coastal sections, information on conduits and fissures from chalk exposures may be quite limited in East Anglia.

Boreholes provide a good window on subsurface conduit and fissure development, both above and below the water table. Images of borehole walls have revealed cavities within the Chalk in East Anglia (knowledge exchange meetings with water companies and the Environment Agency), but these data have not been collated to assess the frequency and controls on fissure/conduit development.

In a study of abstraction sites that included some sites in the south-west of the C3 area, Farrant et al. (2017) reported some solutional fissure development from borehole images, but there is little or no information on the nature/size of these features. Further east, in the Orwell estuary in the Ipswich area, a water-filled void 8 m deep was encountered in borehole TM14SE/381 (Mathers et al., 2007).

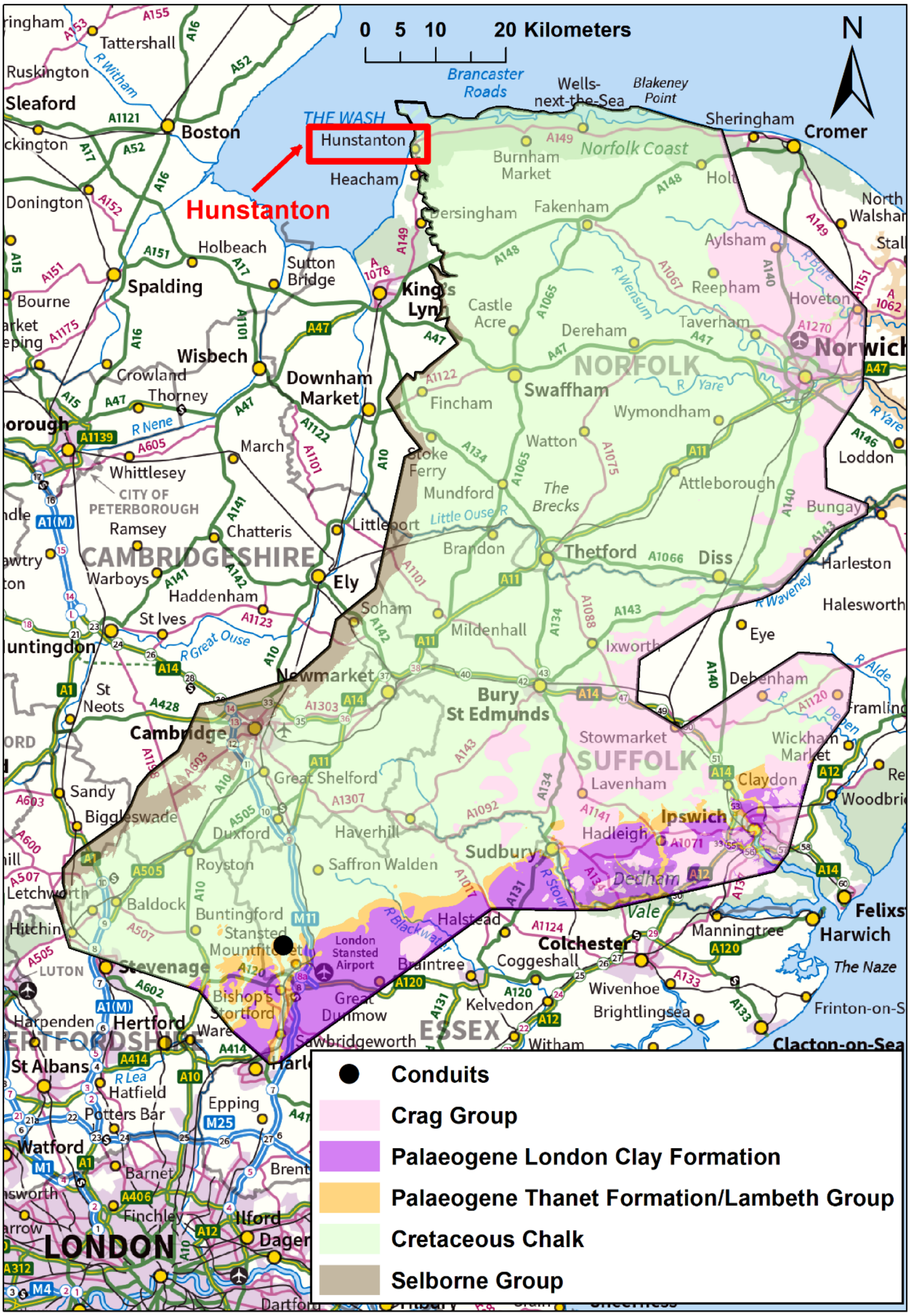

Figure 6. Location of Hunstanton where there are caves/conduits exposed in the Chalk cliffs and site near Stansted with conduits in quarry

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Figure 7. Small karst cave at Hunstanton

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Figure 8. Conduits developed above the Red Chalk Beds at Hunstanton.

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2.2 STREAM SINKS

The BGS karst database has not been completed in this area, but stream sinks have been known for more than a hundred years, with early descriptions of “swallow holes” in Whitaker (1921a,b; 1922). Recent work by BGS has documented stream sinks in several catchments in the C3 area through geological mapping studies in the Beane and Upper Cam catchments (Farrant et al., 2022a,b); and assessments of karst around Stansted, Chipping (and Offley just outside C3), where some places where water may sink into the Chalk were identified (Farrant et al., 2017). Figure 9 shows the locations of recorded stream sinks in the C3 area (with some records to the south-west in the C4 area also included for context). Some classic Chalk karst stream sinks occur at the Chalk-Paleogene margin. Many of the recorded stream sinks are associated with the boundary between the glacial till and the Chalk, and have formed because runoff from the low permeability deposits has dissolved the underlying Chalk at the geological boundary since the Anglian glaciation. Some stream sinks in the C3 area, and in particular those identified by Farrant et al. (2017), are likely to be relatively small-scale features compared to some of the well-developed chalk karst stream sinks observed to the west in the C4 area (Maurice et al., 2020). Stream sinks appear to be concentrated in the south-west of the C3 area, but the distribution in Figure 9 reflects the locations where studies have been undertaken, and there are likely to be many more small stream sinks associated with the boundary between the low permeability glacial till and the underlying Chalk. Studies of stream sinks in the area are described below, broadly from south to north:

Many stream sinks have been recorded around the Colliers Green Paleogene outlier and around the margin of the till outcrop in the River Beane catchment (Farrant et al., 2022a). These are in the very far south-west of the C3 area and the far north-east of the C4 karst (Figure 9). These were not discussed in the C4 karst report (Maurice et al., 2020), as the mapping was conducted after this report was completed, although stream sinks observed during geological mapping in the nearby Mimram catchment (Farrant et al., 2019) were included. The locations of the stream sinks from the Beane study (Farrant et al., 2022a) and the Farrant et al. (2019) Mimram study are shown in more detail in Figure 10. The stream sinks identified by Farrant et al. (2022a) around the Colliers Green Paleogene outlier between the Rib and Dane End rivers are classic chalk karst stream sinks which can take considerable flows following rainfall. During the 2020 mapping work in the Beane area, it was also apparent that many of the streams that originate on the glacial till sheet sink where they pass onto the Chalk (or in some cases into river terrace gravels over the Chalk). For example, in the Beane catchment and its tributaries (the Beane and the Old Bourne, the Dane End Tributary, Chelsing Tributary), the upper reaches were actively flowing (usually with small flows), but most of the middle reaches of the rivers were dry, with water emerging from groundwater springs lower down in the catchment. In very wet weather, rapid runoff from the till overwhelms these sinks and water can continue down valley through these middle reaches, but with a very flashy response of turbid runoff for a day or two (as observed during a wet period in Autumn 2020). Most of the time, in normal wet weather, water flowing off the till sinks. Many of these sinks do not have a discrete sink point, marked by a depression, rather the water sinks through the stream bed. The groundwater outlets for stream sinks in the Beane area are not known. It is possible that they discharge through local springs in the river valleys, some examples of which are discussed in Farrant et al. (2022a), and here in Section 2.4. Farrant et al. (2022a) also note that there are large springs at Chadwell and Amwell near Ware to the south of the C3 area which are connected to the Water End karst system, and suggest that it is not known whether the stream sinks in the Beane area might also be connected to these major karst springs.

It is also possible that some stream sinks have been artificially modified, blocked or diverted. Whitaker (1921a) describes at least two swallow holes on the Ardeley tributary of the Beane – one near St Johns Wood and one in the same field opposite Walkernbury, describing the upper one as a doline about “40 feet” in diameter with a small stream running into it, and noting that banks had been constructed to stop the water entering both features. The 1937-1961 1:25000 OS map (National library of Scotland side by side viewer) shows a small stream/drainage ditch just north of St Johns Wood which ends at [TL 30953 26011], a point where the LiDAR data indicate a large circular depression that appears to have been engineered, and may be the upper swallow hole mentioned by Whitaker (1921a). To the north of this, there is another small stream channel on the 1937-1961 OS map which ends at depressions [TL 30846 26730]. This may possibly be the second swallow hole described by Whitaker (1921a), and is very close to a stream sink identified by Farrant et al. (2022a). These sites can be seen on the National library of Scotland side by side viewer at:

https://maps.nls.uk/geo/explore/side-by-side/#zoom=15.0&lat=51.92129&lon=-0.09767&layers=10&right=LIDAR_DTM_2m.

River losses in this area are also reported by Sefton et al. (2019), who note that at certain times of year some sections of the rivers Beane, Rib, Ash, and Stort dry up completely; indicating recharge through the riverbed upstream of these points. Sefton et al. (2019) present figures to show whether, for the modal state, these rivers are dry or flowing or ponded at different distances upstream from the confluence with the River Lee, for each month of the year. The patterns are quite complex with sink points at different distances from the River Lee in different months, and more than one dry section along each river. The locations of these rivers are shown on Figure 10.

The Hertfordshire RIGS group (2003) document the Almshoe Bury Swallow Hole RIGS site [TL 207 246]. This site is in the Chalk immediately south-west of the C3 area, and is described as “a seasonal bourne leading to a large swallow hole”. Whitaker (1921a) also describes this stream sink, noting that it has considerable flow in wet weather. This stream sink is the record shown on the Langley Brook on Figure 10, from Farrant et al. (2022a). They report that the stream sinks in a well-defined blind valley several metres deep, and that the groundwater outlet for it is unknown, but possibilities might be the head of the Ippollitts Brook [TL 2001 2601] or the Nine springs south-east of Hitchin.

Farrant et al. (2017) report six locations where water may sink in the Chipping area in the headwaters of the Rib and Quin rivers and eight locations where this may occur in the Stansted area near the River Stort (Figure 9, Figure 10). These are very small-scale features and do not represent well-developed karst but may be sites where water sinks into solutional fissures in the Chalk. Farrant et al. (2017) also report three similar places where water may sink into the Chalk in the Offley area, just to the south-west of the C3 area (shown on Figure 9). A few kilometres to the south-east of the Offley sites, Whitaker (1921a) reports that there was a swallow hole below Frogmore to the east of Kings Walden, but that water was diverted away from it in about 1880.

Eight stream sinks in the Upper Cam and Upper Stort catchments are described by Farrant et al. (2022b) who report that in this area many of the streams running off the impermeable glacial till sink when they reach the Chalk, although in most cases they sink gradually through the streambed rather than in well-defined karst holes/depressions. Several streams were observed to have sink points during fieldwork in April and November 2021. In the upper Cam, Farrant et al. (2022b) describe two stream sinks to the east of Newport, and three in the Saffron Walden area. The GeoEssex website for the Uttlesford district (www.geoessex.org.uk/uttlesford/) also discusses the “Ashdown Road swallow hole” at Saffron Walden [TL 561 391] where the stream is reported to disappear underground at most times of year. Stream sinks have been known from the Saffron Walden area for a long time: Whitaker and Thresh (1916) report that there are few swallow holes in Essex but describe one in a small valley 1.5 miles “a little north of east from Saffron Walden Church”. This is likely to be one of the Upper Cam sites described by Farrant et al. (2022b). Whitaker and Thresh (1916) also describe a stream sink in a ditch neat Bilden End, Chrishall about half a mile west of Shisewick Hall (also discussed by Farrant et al., 2022b). In the Upper Stort, a substantial stream sink at Clavering was reported in the bed of the river Stort (Farrant et al., 2017; the GeoEssex website for the Uttlesford district). A two-metre wide solution hole in the chalk bedrock of the river was noted, but it appears to have been infilled with sediment (Farrant et al., 2022b). There are also sink points in the River Stort further downstream (Farrant et al., 2017; Farrant et al., 2022b). Chalk is exposed in the river bed at [TL 490 283] and [TL 489 276] and water may sink along this stretch (Farrant et al., 2017). Farrant et al. (2017) also discuss potential river losses from the downstream reaches of the River Stort near Sawbridgeworth, and also near Roydon which is just outside the C3 area.

In the south-east of the C3 area near Ipswich, there is some evidence of stream losses to the Chalk in the Gipping valley where superficial deposits are thin (Figure 9). On the east side of the Gipping valley, the Somersham tributary disappears underground and reappears at the B1113; whilst on the west side there are losses from tributaries at Coddenham and at Akenham near the Thanet Sand margin (Simon Linford-Wood, personal communication, 2016). Field observations of these water courses by Jackson and Rushton (1987) suggested that “on many occasions there were significant flows in their upper courses but they had disappeared or significantly reduced in their lower courses near to the River Gipping”. Jackson and Rushton (1987) discuss three different components of recharge in the Gipping chalk catchment, including “component B” which occurs at the margins of the glacial till where the Chalk has high transmissivity and results in large groundwater level fluctuations in the Chalk. Jackson and Rushton (1987) suggest that there are two parts to this recharge: firstly, from runoff and interflow in the glacial till, and secondly from lateral water movement in the sand and gravel deposits beneath the glacial till. They report that only some of this water is able to enter the aquifer due to limited infiltration capacity, with substantial surface flow. Nevertheless, they estimate the total recharge in the River Gipping catchment from “component B” for each month of 1981 and 1982 to be between 12 and 50 Ml/day (which would equate to about 140 to 580 l/s). This suggests substantial (and probably rapid), recharge along the Chalk-glacial till margin in this area which feeds into karstic solutional fissures, that are also indicated by high transmissivities in pumping tests (Section 4).

The remaining stream sink records shown on Figure 9 are not strictly natural stream sinks in that they are locations where soakaways have taken large flows with rapid infiltration suggesting solutional fissures in the chalk. The most southerly of these sites, is at Fulbourn to the east of Cambridge (Figure 9). Whitaker (1922) reports a description by Dr Copeman of the disposal of around 70,000 gallons per day of sewage near Fulbourn (equivalent to around 3-4 l/s of continuous flow), noting that the fact that such a large amount was disposed of without difficulty, suggests that the liquid must have travelled through fissures in the Chalk underlying the soil to contribute to “the immense reservoir that supplies the town of Cambridge”. Dr Copeman noted that water from cement lined cesspools overflowed into a “swallow hole in the extremely pervious Chalk, the bottom of which was only about 17 feet above the permanent water level” Dr Copeman went on to state “As the result of a test experiment carried out at my request, it was found practically impossible to fill this swallow hole with water….only about 150 gallons remaining after a couple hours notwithstanding that 12000 gallons had been pumped into the hole”.

The second site is at Swaffham (Figure 9). Whitaker (1921b) describes an 1849 report by W. Lee in which it is noted that wastewater used in Swaffham town was “poured into an old chalk pit on the eastern side of the road in the valley between Carol House and North Pickenham Warren”. The volumes involved are not reported, but the implication is that it was fairly substantial, and Swaffham is located around the boundary between the glacial till and the Chalk where some solutional development of the Chalk might be expected.

Large soakaways which take a lot of drainage have been observed in the River Burn area where there is also evidence of dissolution and large cavities in the ground (Simon Linford-Wood, personal communication, 2016). The River Burn is in the far north of the C3 area (Figure 9).

More generally, there remains considerable uncertainty about soakaways and SuDs (Sustainable Drainage Systems) providing drainage for unwanted runoff from roads, urban areas and fields. Old pits have been observed to take quite a lot of drainage water in wet weather during BGS fieldwork, but the contribution of soakaways and SuDs to point recharge to the Chalk has not been assessed for this report. Although these are not themselves karst features, it seems unlikely that the unmodified chalk fracture network would have the capacity to take large flows (unless there is a thick/extensive gravel aquifer above the Chalk which distributes the flow), and if they have high infiltration rates to the Chalk they must be feeding into some sort of karstic solutional network. The extent to which this occurs is unclear, and the threshold infiltration rate for unmodified fractures versus solutional fissures is not known. Data on the infiltration capacities of soakaways and SuDs are not available, but identifying those with high infiltration rates into the Chalk would be useful, as well as further work to investigate connectivity between such features and the saturated zone, perhaps using tracer testing.

In summary, the most significant karst stream sinks in the area are associated with the Chalk-Paleogene margin. There are are also a large number of stream sinks associated with the glacial till, but many of these are small and many are difficult to identify except when the conditions are right, if they are sinks within river beds, or small local sinks that are only active in wet periods. There have been no measurements of the amount of flow into these stream sinks, but based on visual observations it is likely that most of them have flows that would not exceed 1-2 l/s at the very most following prolonged rainfall. However, there may be quite a large number of small individual sink points around the Chalk-glacial till margin that collectively provide a substantial contribution to recharge. No recent field mapping has been undertaken in most of the C3 area, and it is likely that in addition to those shown on Figure 9, other similar stream sinks or losing reaches occur in the upper reaches of some of the Chalk catchments, particular those that demonstrate seasonal winterbourne behaviour.

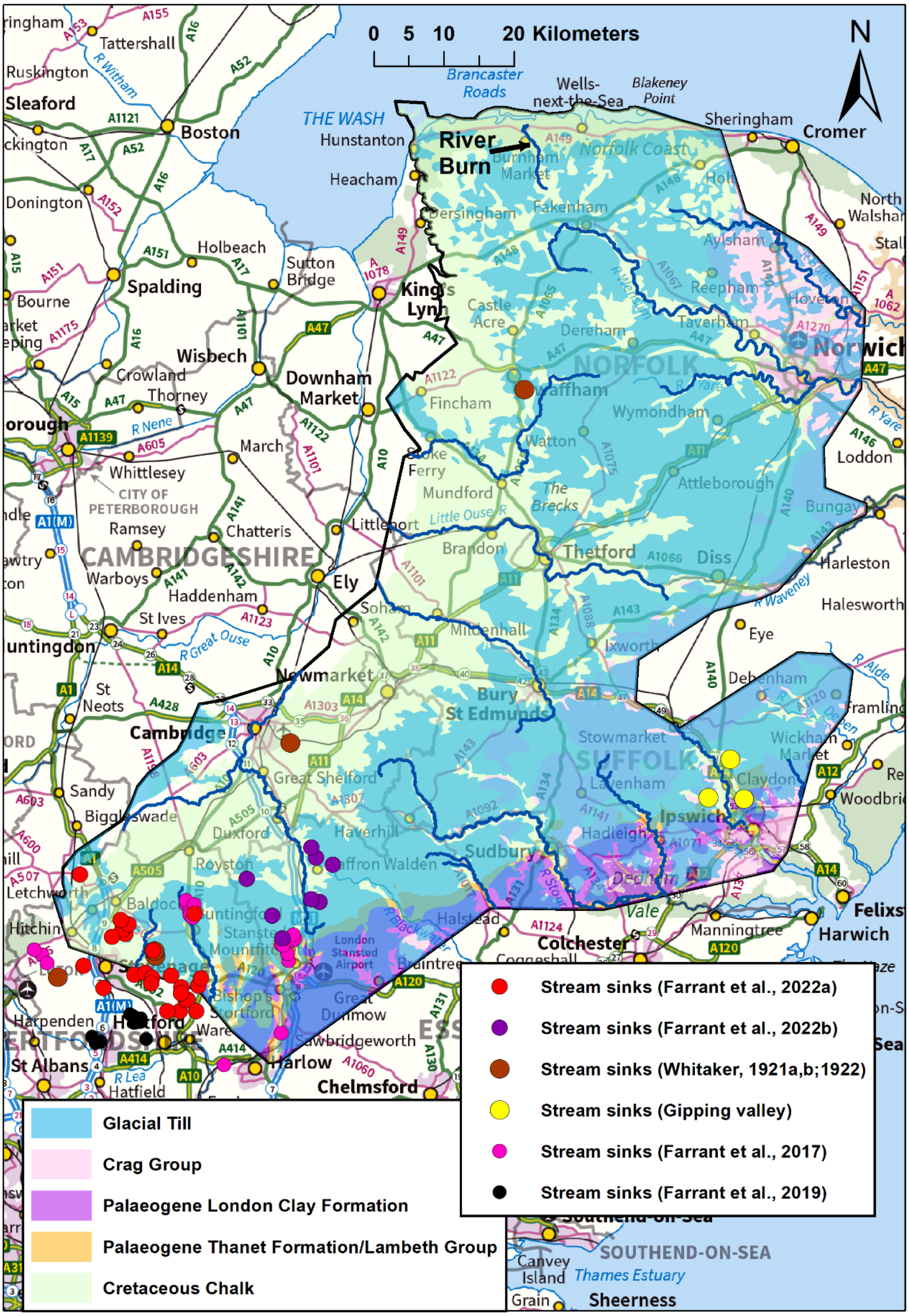

Figure 9. Stream sinks in the C3 area (and extending south-west into the C4 area)

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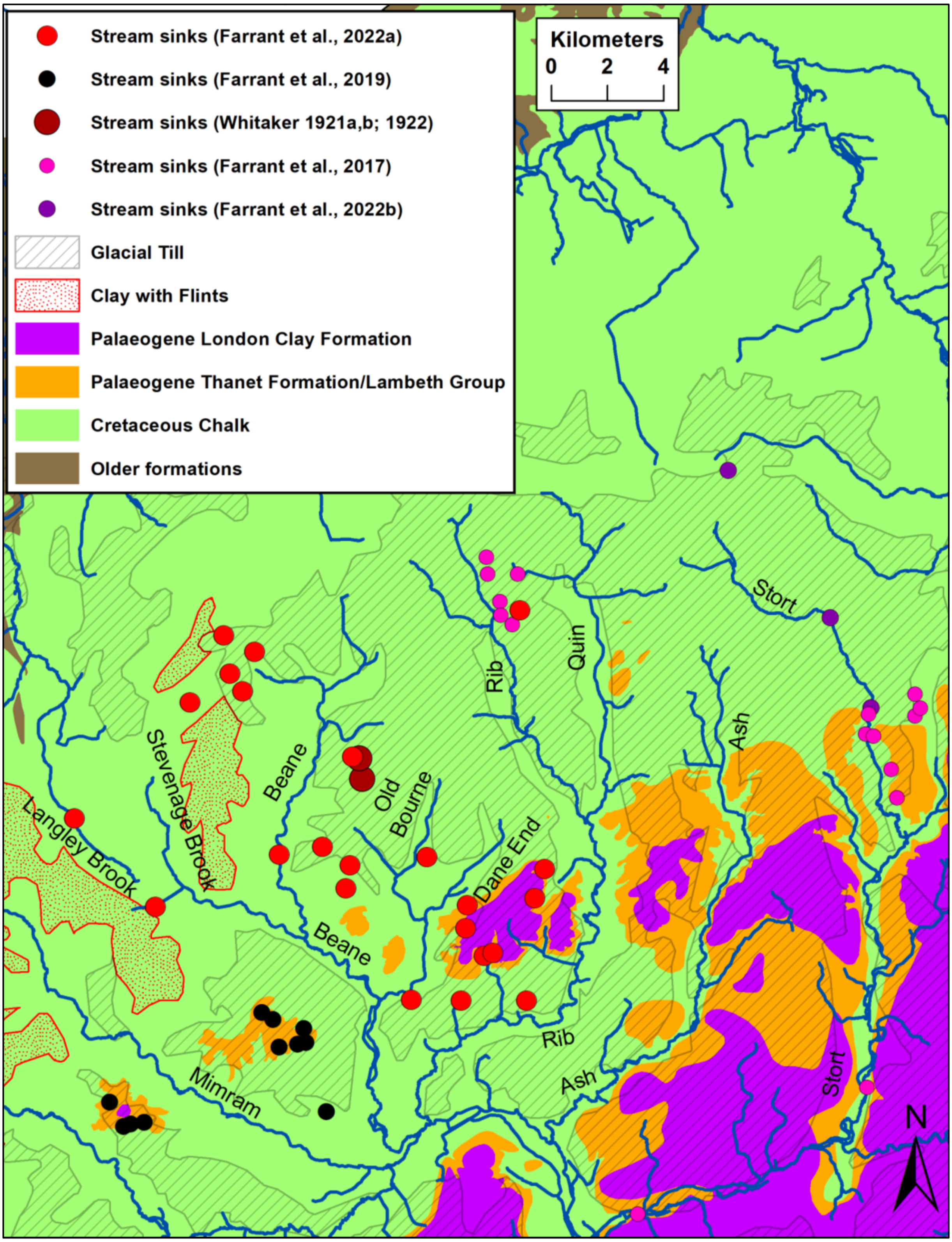

Figure 10. Stream sinks in the area of the Beane and Mimram catchments

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2.3 DOLINES AND DISSOLUTION PIPES

2.3.1 Introduction

There are extremely high densities of surface depressions in East Anglia, and their origin has been debated for some time. Prince (1964) provides a useful summary of four different origins: mineral workings, marl pits, karst processes and periglacial processes. Prince (1964) concludes that it is often difficult to determine the origin of surface depressions; a conclusion that is still true today. It is consequently difficult to assess how many karst dolines there are in East Anglia, and it is certainly the case that there are large numbers of surface depressions that are worked pits of anthropogenic origin, and that this area has been heavily impacted by glacial and periglacial processes. Dissolution pipes are a form of buried doline, and where they have been exposed there is little doubt over their karstic origin, although their past and present hydrogeological function is often less clear. Despite these difficulties, a literature review of surface depressions, dolines and dissolution pipes provides an indication of where karst is likely to be developed, and the distributions of features identified from this review is shown in Figure 11.

The BGS karst database has not been completed in East Anglia. However, there are records of dolines and dissolution pipes in the Natural Cavities database. This is a legacy dataset held by the British Geological Survey and Peter Brett Associates (now Stantec). It comprises data from a range of sources originally commissioned by the Department of the Environment and by Applied Geology Limited (1993). Although many sites are listed as “dolines” in this database, it not clear whether some (or indeed many) of these sites are in fact surface depressions of anthropogenic or periglacial origin. Figure 11 also includes locations of dolines and dissolution pipes identified from literature review. The dolines in this dataset are sites that are likely to be surface depressions of karstic origin, and comprise sites reported by Whitaker et al. (1921b), Atkinson (1981), Ward et al. (1998), Gibbard et al. (2012), West et al. (2014), and Farrant et al. (2017). The dissolution pipes in this dataset are from Boswell (1927), Burnaby (1950), and Farrant et al. (2022a,b). The other dataset on Figure 11 is from Norfolk Wildlife Trust (2008) who carried out an extensive survey of “pingos” in Norfolk. Pingos are surface depressions, sometimes on a mound or with a raised rim, that formed under periglacial conditions (Norfolk Wildlife Trust, 2008), but which can also look very similar to karst dolines where there is no mound or rim. Norfolk Wildlife Trust (2008) provide an appendix with grid references of 216 sites where surface depressions occur, and these are included on Figure 11. Although the focus in Norfolk Wildlife Trust (2008) is on the periglacial origins of these features, the many different origins of these surface depressions (including karst) are discussed. Many of these “pingos” are in areas where karst dolines are recorded in other studies/databases, and in some cases it may be difficult to be certain whether surface depressions are formed by periglacial or karst processes.

Both dolines and dissolution pipes are widely distributed throughout the C3 area. The distribution in Figure 11 reflects the locations where studies have been undertaken, rather than the natural distribution of karst features. It is very likely that there are other dolines and dissolution pipes that have not been recorded. In particular, there is likely to be a significant under representation of the number of dissolution pipes, as most do not have any surface expression. Surface depressions from LiDAR and old and modern Ordnance Survey (OS) maps were not collated for this study. It is likely that most of the large numbers of surface depressions that can be seen on LiDAR and on OS maps are anthropogenic in origin, but there may also be some dolines that are not shown on Figure 11. An early study of the density of solution features in the Chalk by Edmonds (1983) indicated densities of 5-10 per 100 square kilometres, suggesting that densities may be lower in East Anglia than in some other areas of the Chalk. However, data compiled here suggest that, at least locally, there may be higher densities of solution features than reported by Edmonds (1983). Despite the bias in distributions towards investigation sites, and the uncertainties in the origin of surface depressions, there is a general pattern of more karst dolines and solution pipes where there is thin superficial cover that can focus drainage (Farrant et al., 2017). In particular, dissolution pipes are likely to be extremely common, especially where river terrace gravels directly overlie the Chalk (Farrant et al., 2022a,b). Information on dolines and dissolution pipes is reviewed below for different parts of East Anglia.

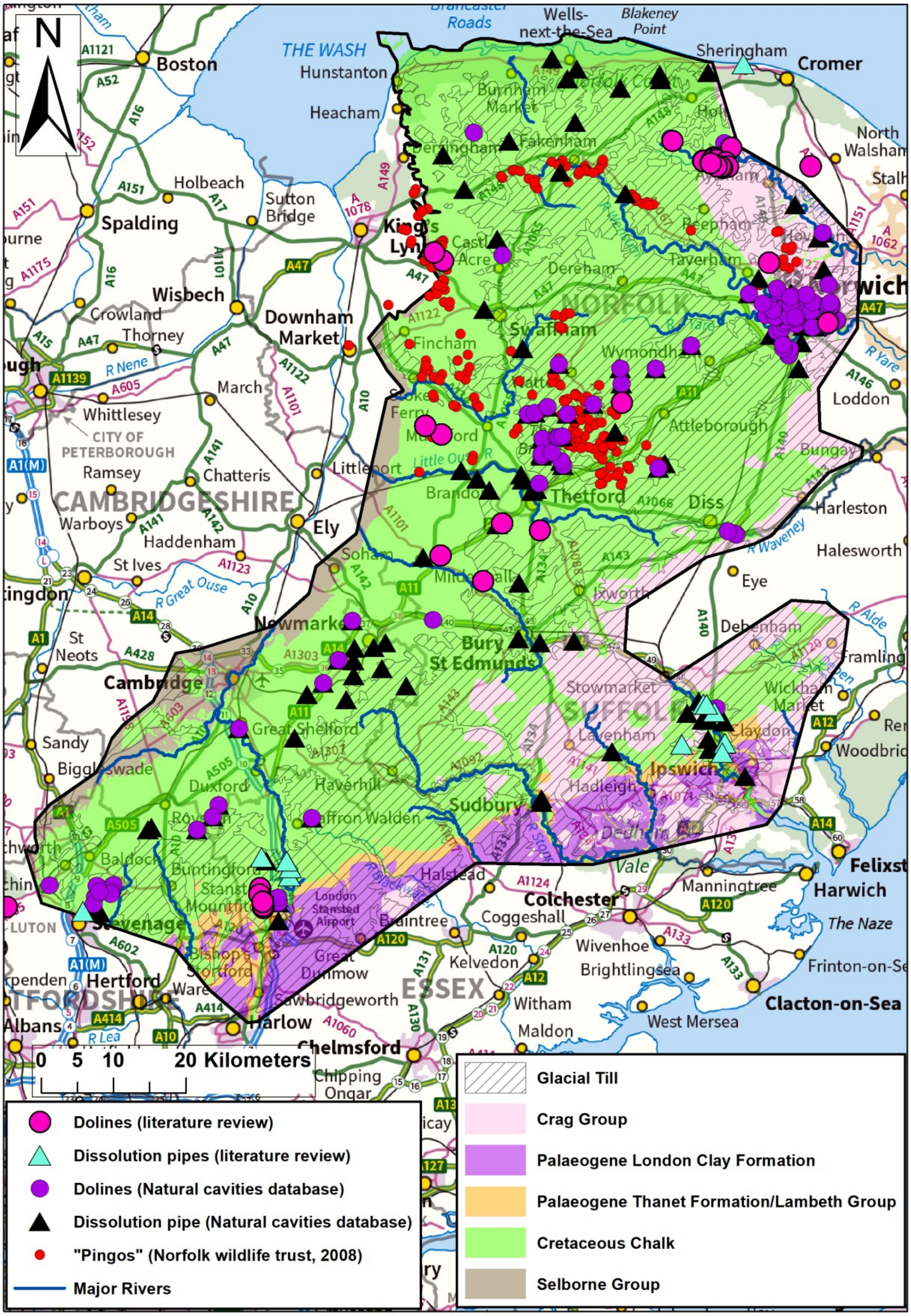

Figure 11. Dolines/surface depressions and dissolution pipes in East Anglia

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2.3.2 The South-west (Cam and Stort area)

A more detailed look at the south-west of the C3 area shows that dolines and dissolution pipes that have been recorded are located near the boundaries between the Chalk and overlying glacial till deposits, with some associated with the small outcrop of Clay-with-Flints (Figure 12). Figure 12 also includes the superficial thickness from the British Geological Survey BSTM (Basic Superficial Thickness Model). Whilst this model gives a rough approximation of the thickness of the superficial deposits, it should be used with caution as the data are interpolated from borehole records. Nevertheless, the BSTM data suggest that the karst features are where the overlying deposits are thin (Figure 12), which is the setting in which karst features are most likely to occur.

There are some BGS reports with records of dissolution pipes and dolines. Farrant et al. (2022a) report that the Hertfordshire RIGS group (2003) documented dissolution pipes in a temporary exposure in a road cutting in Stevenage at [TL 244 262], which is close to the south-west boundary of the C3 area. Farrant et al. (2017) discuss six surface depressions in the valley of the River Stort that may be karst dolines. Four of these are marked as sinkholes on BGS field slips in the upper Stort valley between Claverdon and Manuden and do not appear to take water. They suggest that these features may be suffosion dolines, or possibly degraded gravel pits. Farrant et al. (2017) also report some depressions in the Offley area at [TL 139 268], which is just outside the C3 area to the south-west. In a study of the Upper Cam area, Farrant et al. (2022b) report that small dissolution pipes were observed in the old chalk pit at Wicken Bonhunt at [TL 4917 3368], and also discuss the sites at Newport Chalk Pit, Hollow Road Quarry and Widdington that were studied by Baker (2018, 2019). Farrant et al. (2022b) reported that during the field mapping in the Upper Cam area, other than the dissolution pipes observed in the quarries and chalk pits, no definitive dolines were identified during the field survey; and suggested that most dolines in the chalk are quickly infilled or ploughed in, or form very gradually such that they do not form topographical surface features. They also suggest that many karst features may be pre-Anglian in age and buried beneath till.

The Newport Chalk Pit has one of the best exposures of dissolution pipes and has been discussed by Whitaker et al. (1878), Lake and Wilson (1990), Baker (2018, 2019), and Farrant et al. (2022b). Pictures of some dissolution pipes at the quarry from 1980 are shown in Figure 13 and Figure 14, and more recent pictures from Farrant et al, (2022b) are shown in Figure 15 and Figure 16. Some of the dissolution pipes that have been observed at this quarry seem to be truncated by Anglian glacial till suggesting that they formed before the Anglian glaciation (Baker, 2018). This has implications for modern day groundwater flow because it suggests a long history of subsurface solutional development.

Baker (2018) provided a map showing the distribution of some karst features in north-west Essex (Figure 17), and looked in detail at dissolution pipes in the area just south of Newport. Here, Baker (2018) describes in considerable detail, large dissolution pipes with dimensions of many metres at Hollow Road quarry Widdington, Shipton Bridge Farm, and Newport Chalk Pit, and suggests that they are formed by suffosion, subsidence and dropout mechanisms. Baker (2018) considers the different infill material within dissolution pipes and provides a discussion of how these paleokarst features may have evolved from 2.5 Ma when there may have been stream sinks associated with the Chalk-Paleogene margin, through subsequent major geological changes (including the Anglian glaciation) to the present, noting the impact of erosional and depositional processes on the paleokarst features that remain today. Taking these investigations further, with detailed examination of the infill material and structures, Baker (2019) suggests that many of the doline/dissolution pipe features in this area of north-west Essex may have originated in the early Middle Pleistocene (MIS 13). Baker (2018) discusses periods in the geological history of the area when karstification of the Chalk by groundwater flow is likely to have occurred. Whilst these features are themselves remnant paleokarst, they are an indicator of the importance of karst in the development of permeability in the Chalk of East Anglia, and there are also some active swallow holes present today in this area at Saffron Walden and Clavering (Figure 17, see also Section 2.2).

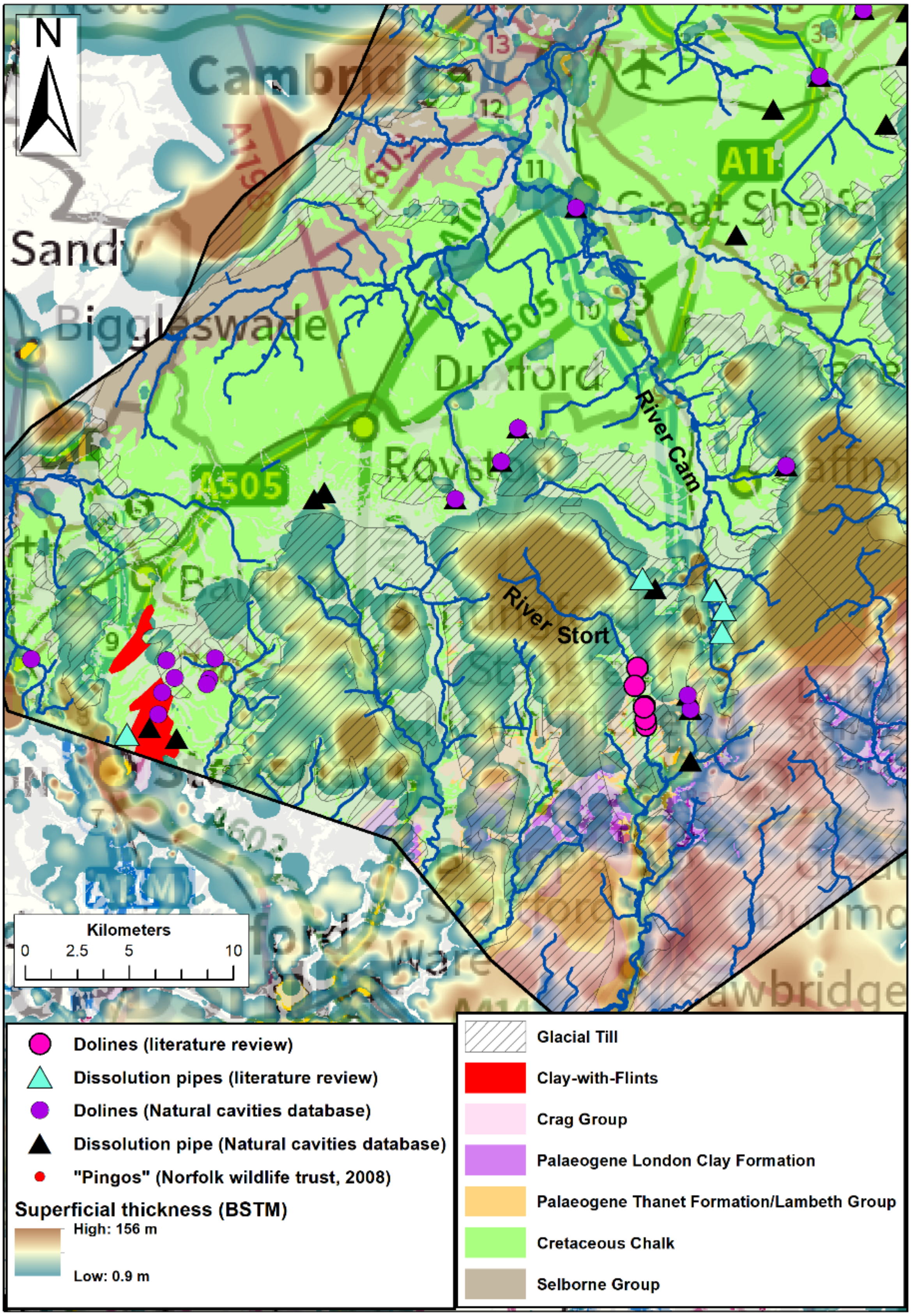

Figure 12. Dolines/surface depressions and dissolution pipes in the south-west of East Anglia

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Figure 13. Dissolution pipes at Newport Chalk pit in 1980

(Photographer C.J. Jeffery, BGS © UKRI). BGS photo archive P212618 (top left), P212616 (bottom left), P21619 (right). See hammer for scale on pictures on the top left and the right. Photos Available: [GeoScenic Home Page | British Geological Survey (bgs.ac.uk)]

Figure 14. Scraped surface (1980) showing dissolution pipe frequency at Newport Chalk pit (Photographer C.J. Jeffery, BGS © UKRI). BGS photo archive P212620. Photos Available: [GeoScenic Home Page | British Geological Survey (bgs.ac.uk)](https://www.bgs.ac.uk)

Figure 15. Dissolution pipes infilled with sand and Gravel, Newport Quarry. From Farrant et al. (2022b)

Figure 16. Dissolution pipes, Newport Quarry (from Farrant et al. 2022b)

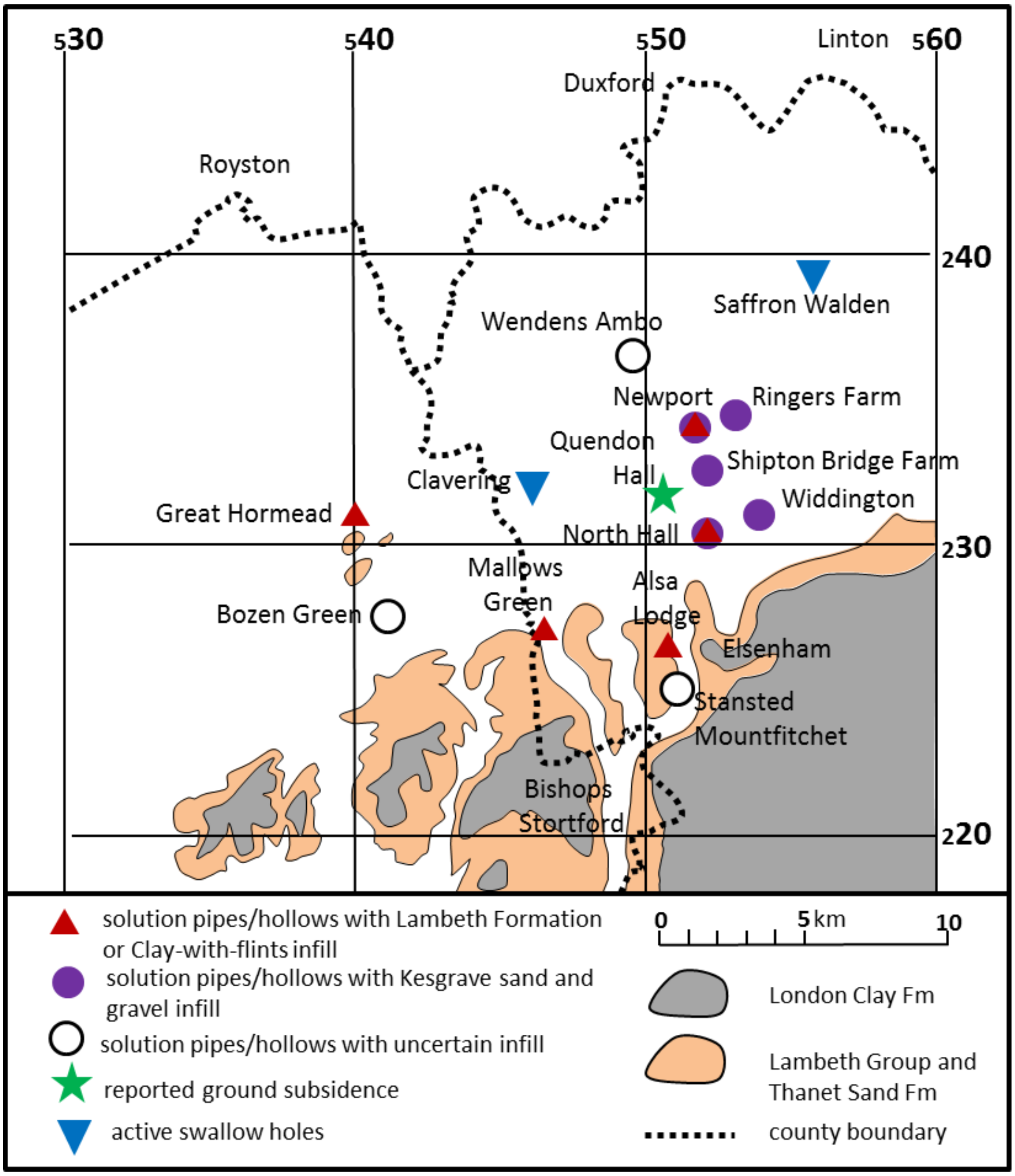

Figure 17. Chalk karst features in North-west Essex. Reproduced with permission from Colin Baker. See Baker (2018).

2.3.3 Ipswich area

In the Ipswich area, there are some records of dissolution pipes, and these are located in the valleys close to the Chalk outcrop where there is thin cover over the Chalk, with several identified in the Gipping valley (Figure 18).

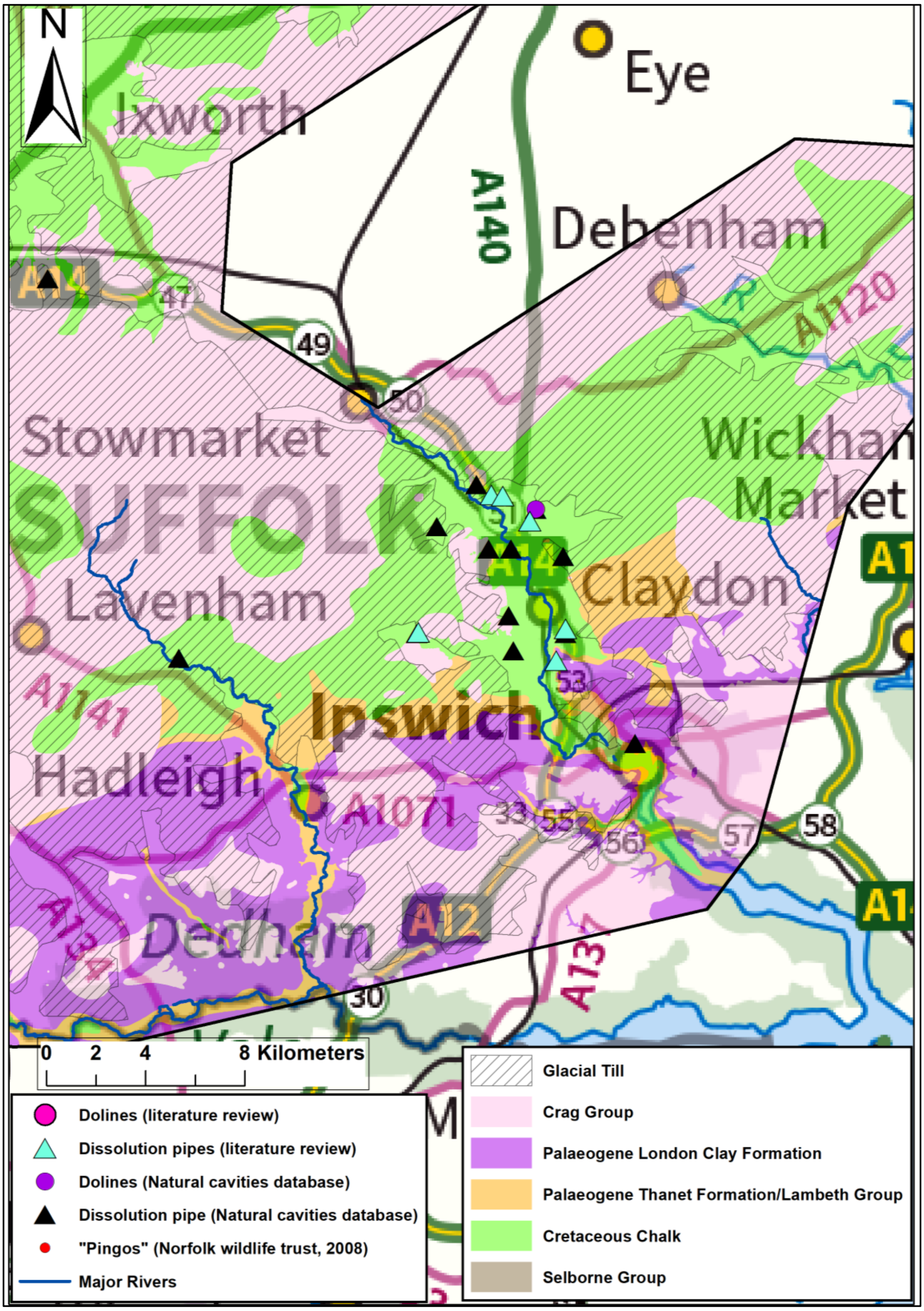

Figure 18. Dissolution pipes in the Ipswich area. Contains Ordnance Survey data © Crown copyright and database right 2023.

Deep cavities/pipes in the Chalk in the Ipswich area are reported by Boswell (1927), and these sites are included on Figure 18 as "Dissolution pipes (literature review)". Precise locations of these features are not reported by Boswell (1927) and the grid references used in the map and provided below are estimates based on OS maps and LiDAR. Boswell (1923) describes a “good pot hole 40 feet deep” at Offton Chalk pit [TM 07355 49341] and a “large pipe or pot hole 53 feet deep” at Claydon Chalk pit [TM 13303 49476]. He also suggests that there are solution pipes at Coe’s Chalk Pit near Bramford [TM 12928 48196], and that dissolution pipes were exposed in a road cutting at the north end of Shrublands Park near Coddenham [TM 11855 53819]. Boswell (1927) also describes “good examples of solution pipes” in the northerly of two chalk pits one mile ESE of Needham Market [TM 10314 54890], and “fine examples of swallow holes” in an old pit 0.5 miles ENE of Bosmere Hall [TM 10761 54844].

2.3.4 Thetford/Central area

There are many records of surface depressions in the Thetford area, and also some records of dissolution pipes (Figure 19). Many of these features appear to be near the boundaries between the Chalk and the overlying superficial deposits (which predominantly comprise glacial till). Figure 19 also shows the BSTM (Basic Superficial Thickness Model) which gives a rough approximation of the likely thickness of the superficial deposits. Most of the features are located where these deposits are thin, although there are a few on areas with thicker cover, which might suggest that they are less likely to be of karstic origin. There are many records of “pingos” from the Norfolk Wildlife Trust (2008). It is uncertain whether these are periglacial, karstic, or anthropogenic in origin, but many of them may be natural features and some of them may be karstic, especially where they are located near the boundary between the Chalk and the glacial till.

Waltham et al. (1997) note that there are particularly numerous dolines north and east of Thetford, in an area known as the Breckland. Jones and Lewis (1941) also report that there are about 50 “swallow holes” within “3 square miles of Fowlmere”. These features are developed entirely within the glacial drift, and normally contain small lakes. Many are conical depressions which are steep sided and up to 20 m across, although there are some shallower larger features (Waltham et al., 1997). These Breckland meres are some of the most distinctive karst features in the area (Jones and Lewis, 1941; Waltham et al., 1997). One of the best examples is the Devils Punchbowl [TL 87789 89182] which is 6 m deep and 150 m across and contains a lake which fluctuates in response to groundwater level changes, with hydraulic continuity between the Chalk and the overlying glacial deposits (Waltham et al., 1997). Waltham et al. (1997) suggest that the feature is a subsidence doline caused by subsurface solution of the Chalk and subsidence of the overlying glacial deposits, but also discuss the many different origins of surface depressions in Norfolk. Prince (1964) and West et al. (2014) also discuss the Breckland meres and suggest that they were formed by solutional activity. Other notable Breckland Meres include Fowlmere [TL 87904 89527], Langmere [TL 90627 88500] and Ringmere [TL 90966 87890] which have large water level fluctuations and are sometimes completely dry (Jones and Lewis, 1941). These three sites, together with the Devils Punchbowl, and some other Chalk fed Meres identified by Whitaker et al. (1921b) are the yellow circles marked on Figure 19 as “Breckland depressions”. Based on the volume of water and water level fluctuations at Fowlmere, Jones and Lewis (1941) estimated approximate flow rates of 3200 to 23100 cubic feet per day which would equate to 1 to 7.5 l/s (assuming that the flow rate was constant between the measuring intervals which varied from 19 to 210 days). The water levels in the Breckland meres do have a lag in their response to rainfall (Jones and Lewis, 1941; Waltham et al., 1997). The variations in the response to rainfall at sites under higher and lower water level conditions, and also between sites, during a period in the 1930s, are described by Jones and Lewis (1941). The overall conclusion was that the water level fluctuations are determined by the chalk water table. There may be some similarities between these features and the karst turloughs that occur in the Carboniferous limestones of Ireland (Skeffington et al., 2006; Naughton et al., 2012).

Whitaker (1921b) discusses the Meres north of Thetford noting that they generally only occur in places where the Chalk comes to the surface or where there is only a thin cover of sandy material. He suggests that many that are dry would have been water filled before the groundwater level in the Chalk was lowered by land drainage. Whitaker (1921b) reports that that those associated with the Chalk include the four mentioned above and also Mickle Mere [TL 90889 91914], Hill Mere [TL 90217 91889], Scot Mere (in Wretham Park, precise location unclear), Home Mere [TL 89322 89691], and Quiddenham Mere [TM 04081 87556], but suggests that some other meres associated with the glacial till are caused by the damming of streams and are not related to groundwater. Whitaker (1921b) suggests that many of the Meres occur due to subsidence, and also describes a dramatic subsidence event in August 1879 in the Rockland Parish where a deep (30 feet) shaft suddenly opened up with water rushing in. He suggested that the subsidence was caused by the dissolution of the underlying chalk. The precise grid reference for this site is uncertain, but it does seem to be in an area where there appear to be thick till deposits, which is surprising (Figure 19).

The karstic origin of closed depressions where the Chalk is directly overlain by the Anglian Lowestoft Formation till is also discussed by West et al. (2014). They suggest that there are some where the size, shape and infill material suggest that they are karstic dolines. West et al. (2014) studied an archaeological site at High Lodge, Mildenhall, Suffolk where there is a large closed depression which they concluded is most likely to be a karstic doline. West et al. (2014) also report that there are other similar depressions that are likely to be of karstic origin at Elveden, Suffolk, (Turner, 1973; Ashton et al., 2005); at East Farm, Barnham (Ashton et al., 1998); and Beeches Pit, West Stow, Suffolk (Preece et al., 2007). The precise grid references of these sites are unknown. However there are surface depressions in the vicinity of these places apparent on old OS maps and Lidar (see National library of Scotland side by side viewer at https://maps.nls.uk/geo/explore/side-by-side/), including some circular shaped depressions in addition to more irregular shaped pits. These places are included on Figure 19 as dolines from literature review, using grid references of circular depressions near the villages.

Gibbard et al (2012) investigated ice marginal sedimentation at Feltwell and Methwold Hythe, Norfolk using lithological analysis and GPR. Although the main focus is on the depositional environment of the ice-marginal deposits, they also note that there are “doline like hollows” near Feltwell quarry, and that at both the Feltwell Quarry and Methwold Hythe sites there is some evidence of collapse of the ice-marginal deposits into solution features in the Chalk. These sites are to the west of Mundford (Figure 19).

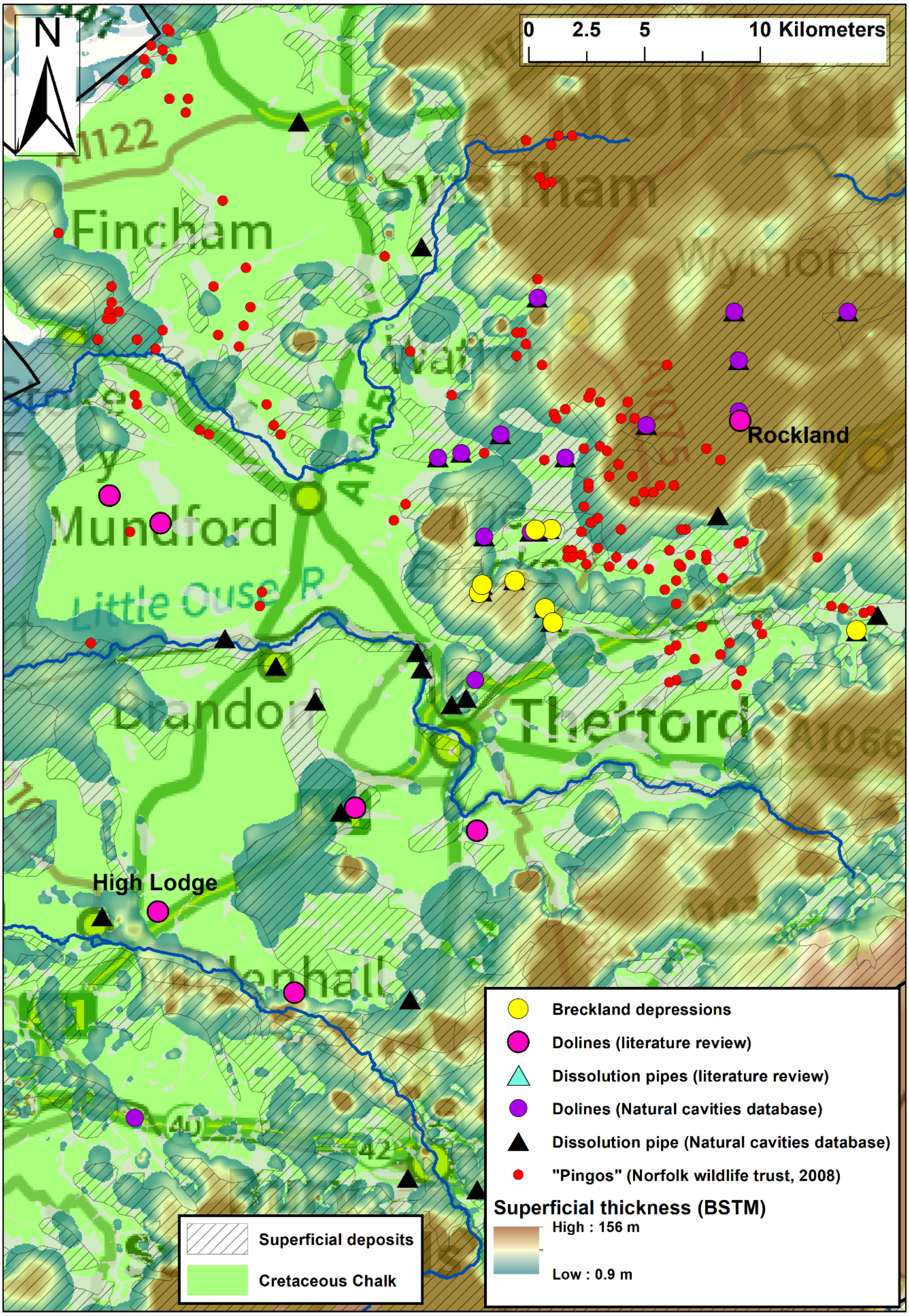

Figure 19. Surface depressions and dissolution pipes in the Thetford area.

2.3.5 Norwich and the North

The distribution of features in the northern part of East Anglia is shown in Figure 20, which includes some sites that are to the east of the original C3 project area. The distributions reflect areas where studies have been undertaken. There are many dolines recorded in the Natural Cavities database, especially in the area around Norwich where they appear to be associated with river valleys, and areas where superficial cover is thin (Figure 21). Some or many of these features may be surface depressions of anthropogenic or periglacial origin, rather than karst, especially where there is thick cover over the Chalk. This is also the case for the many “pingos” reported by the Norfolk Wildlife Trust (2008) that are shown on Figure 21. Nevertheless, there are some features which are likely to have a karstic origin, as indicated by the studies described below.

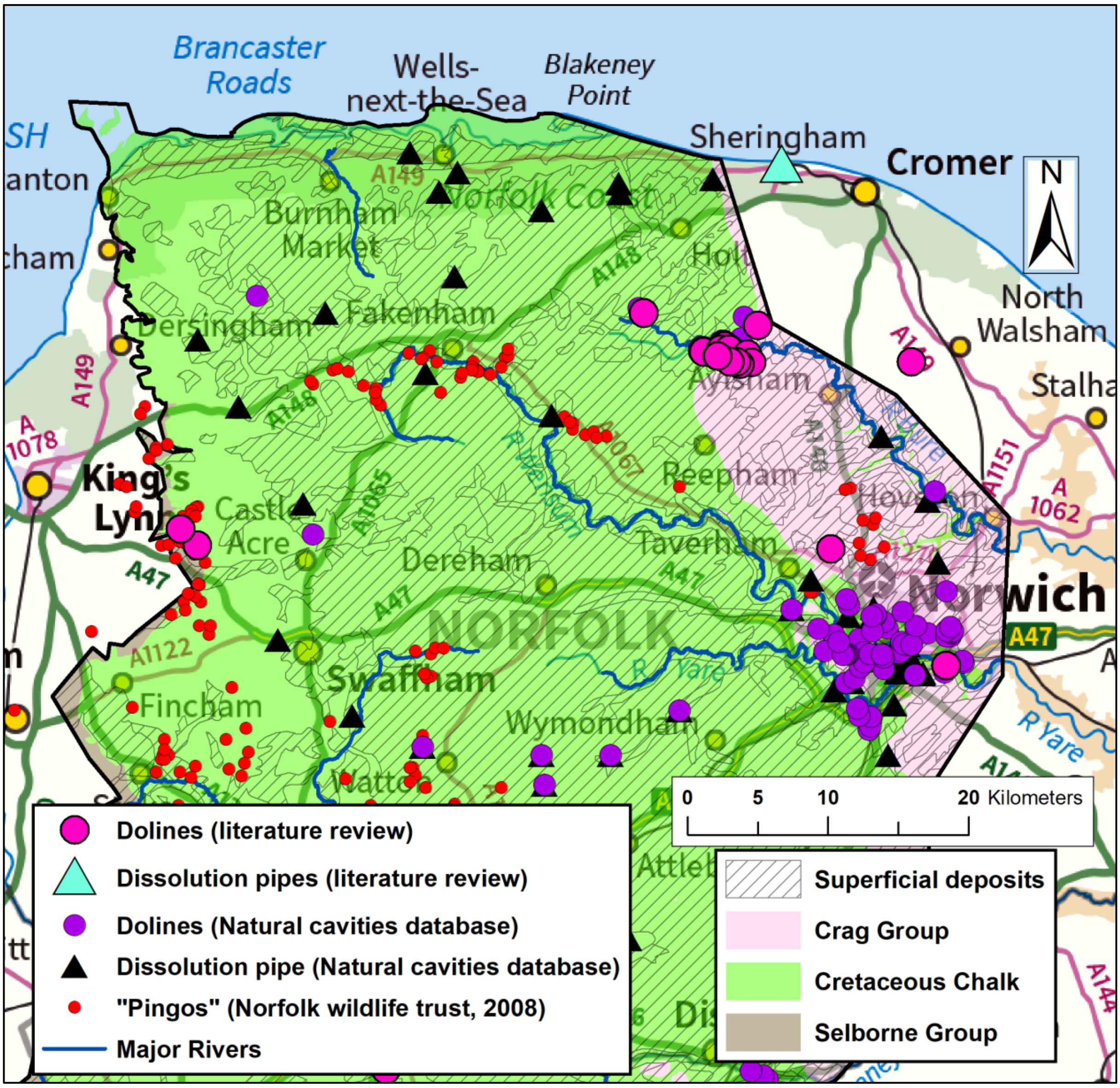

Figure 20. Surface depressions and dissolution pipes in the north of East Anglia

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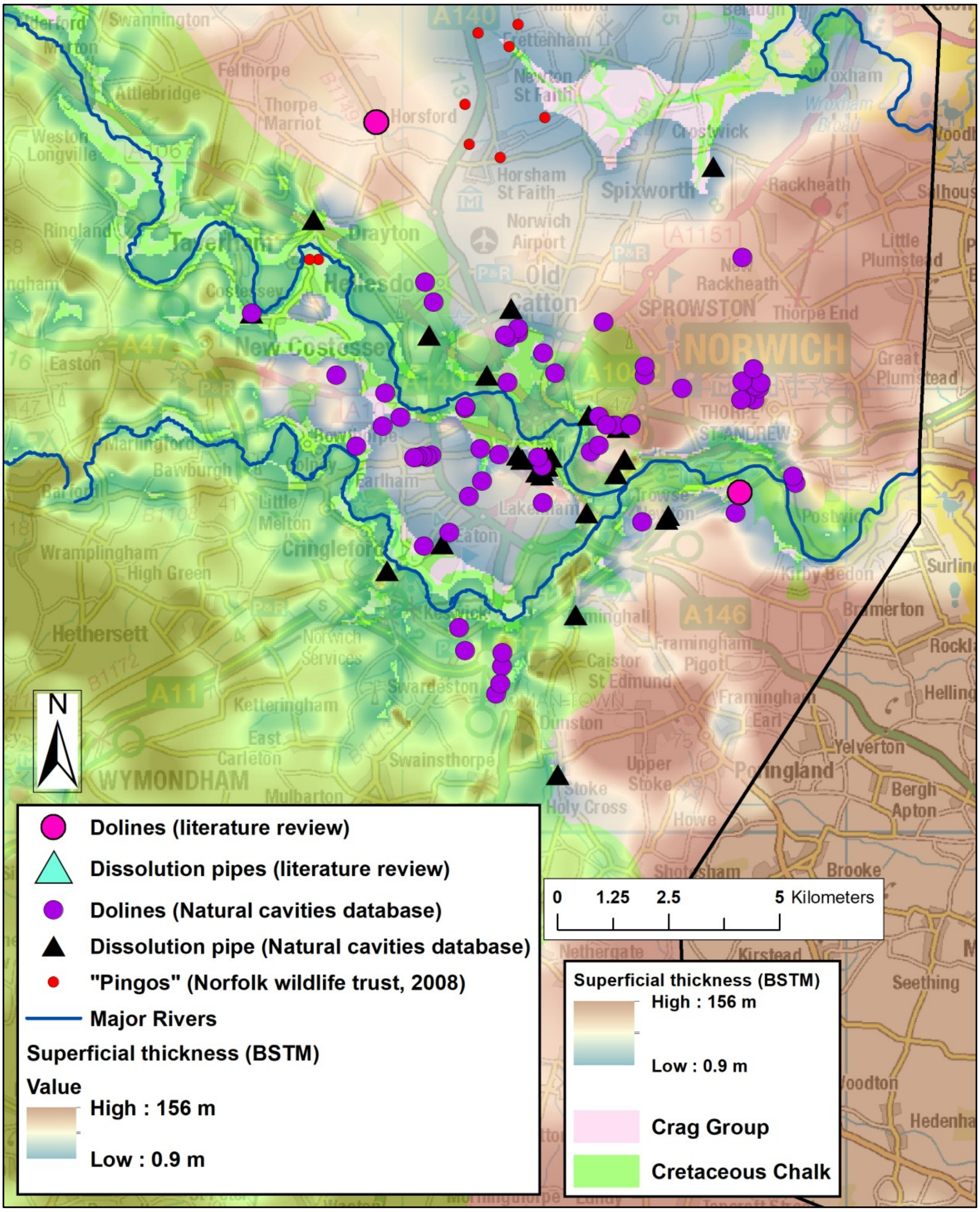

Figure 21. “Dolines” and dissolution pipes in the Norwich area

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Whitaker (1921b) describes some old reports of subsidence incidents. These include hollows in the ground at East Walton that increased after hot weather, and small subsidence meres in the area between Walton Common and Gayton Thorpe Common. These sites are in the west of the C3 area, to the east of Kings Lynn (Figure 20). In the east, Whitaker (1921b) also reports subsidence incidents in Mannington parish in 1717 in which trees sank suddenly into pits; a sudden subsidence at Horseford about four miles north-west of Norwich which followed a thunderstorm and resulted in a deep circular hole; sudden subsidence events in 1788 at Briston; sudden formation of circular hollows at Whitlingham caused by disposal of pumped sewage onto the land surface; and a sudden subsidence in the parish of Felmingham, in 1793. Whitaker

(1921b) notes that Woodward (1883) suggested that these subsidence's were caused by the dissolution of the underlying chalk in these areas.

Some of these sites reported by Whitaker (1921b) are in the valley of the River Bure, which is an area where Atkinson (1981) recorded the locations of 19 dolines. This was part of an investigation into a dramatic subsidence incident at Corpusti near Saxthorpe in which a house collapsed (Atkinson, 1981; Ward et al., 1998). It was thought that this subsidence may have been due to a pumping test in the Chalk 500 m away. This area is around the boundary between the Chalk and the overlying Crag deposits, although there are also other superficial deposits present.

There is documentation of interesting karst features exposed in the North Norfolk coastal cliffs near Sheringham (which is just to the east of the original C3 area; Figure 20). Burnaby (1950) provides a detailed description of the "Tubular Chalk stacks of Sheringham" which were observed at three localities. They are cylindrical features composed of a very hard cemented chalk which have a central cavity about 30 cm wide (Burnaby, 1950). They were exposed on the beach and were only about 0.5 to 1 m high, but appeared to have lost their upper sections from erosion by the sea suggesting that they were originally taller (Burnaby, 1950). They are associated with the boundary between the Chalk and overlying Crag deposits, and Burnaby (1950) suggests that these features are most likely to have originated as solution pipes. Burnaby (1950) also noted many small shallow depressions and channels within the surface of the Chalk below the Crag, providing further evidence of the dissolution of the Chalk in the Sheringham area. Similar very hard cemented calcretes were observed around the edge of the till outcrop in the Upper Cam catchment (Farrant et al., 2022b). These types of features have also been observed on the foreshore at Cuckmere Haven/Hope Gap in the South Downs area of the Chalk (Farrant et al., 2021a).

2.4 SPRINGS

There are many recorded springs in the C3 East Anglia Chalk area (Figure 22). The records shown on Figure 22 include those from the BGS springs database, with some additional springs from Hull (1995), Sims (1988), BGS memoirs (Whitaker, 1921a,b; Whitaker, 1922) and historic OS maps. There are many springs marked on old and modern Ordnance Survey maps and these have not been systematically reviewed and included in this data collation so it is likely that there are many more chalk springs. Springs were generally only included in Figure 22 if they are likely to be discharging Chalk groundwater, but it is not always possible to be certain of this as there are many springs emanating from the overlying and underlying strata, some of which may be in hydraulic continuity with the Chalk. There is generally no discharge data for springs, but some that have some measured discharge information are included in Table 2, and identified in Figure 22 as “large”. The discharges reported in Table 2 are generally from single or very few measurements and the actual range of flows at these springs is not known. It is also likely that the natural flows have decreased in response to the development of water resources, both prior to, and after, these measurements have been made. No time series data on spring discharges were identified for this report, and it is not known if any exist. Springs that have been used as tracer testing monitoring sites, and those that have descriptions in the old water supply memoirs (Whitaker 1921a; 1921b; 1922) suggesting that they are likely to have flows of more than 10 /s are also included as “large” springs on Figure 22, although the actual discharge of these sites is not known. Figure 22 also includes some significant springs discussed in Farrant et al. (2022b) in the Upper Cam catchment that are also likely to be large. The distribution of large springs on Figure 22 suggests that they are concentrated in the west and south of the area. Whilst this distribution may be biased by available information, more spring development might be expected in these areas where superficial cover is absent or thin.

Many springs are focussed along the base of the Chalk escarpment, often on spring lines either at the base of the Chalk, or on specific horizons in the lower part of the Chalk sequence, such as the Totternhoe Stone, or bands within the West Melbury Marly Chalk Formation (Whitaker, 1922). Some of these springs in the West Melbury Marly Chalk are quite large, such as Snailwell Springs (Kachi, 1987; Sims, 1988). Farrant et al (2017) report significant springs at Oughtonhead (just south-west of the C3 area) around the contact between the Zig Zag and Holywell Nodular Chalk formations and suggest the development of a fissure/conduit network in the lower part of the Holywell Nodular Chalk in this area. Some small springs occur around the margin of the Anglian till deposits.

In the south-west of the C3 area, springs in the Beane catchment are discussed by Farrant et al. (2022a) who describe several, mostly small springs, but suggest that the most significant springs might be those that are located in the Beane valley about 500 m upstream from Walkern Church. Here, a deep buried valley of glacial till may act as an impermeable barrier forcing groundwater to the surface at Walkern, before it sinks again to the south of the village (Farrant et al., 2022a). Farrant et al. (2022b) report the locations of seven significant springs in the area of the Upper Cam. They also note that the springs are generally located at the margins of a deep buried glacial channel, suggesting that the glacial silts in the channel may form a barrier to groundwater flow rather than a conduit. These springs are also discussed by Whitaker and Thresh (1916) who note that there are few Chalk springs in Essex, but give descriptions of some that do occur.

Whitaker (1922) reports that there are many springs emanating from the lower parts of the Chalk in Cambridgeshire, some from the Totternhoe Stone and some from the base of the Chalk. Whitaker (1922) also notes that the most well-known springs in Cambridgeshire are at Nine Wells and Cherry Hinton, and both discharge from the Totternhoe Stone. Springs east of Fulbourn also emerge from the Totternhoe Stone and are described as “one of the finest sets of springs in Cambridgeshire, known as Shardelowes Well”. There is a spring from the base of the Holywell Nodular Chalk Formation north-east of Warbraham farm (Whitaker, 1922). Whitaker (1922) also reports the largest spring supply taken in Cambridgeshire from the springs at Marham in Norfolk – these springs supplied several towns in Cambridgeshire and Norfolk.

There is considerable evidence of bourne behaviour in streams which are on the Chalk (or where thin permeable deposits overly the Chalk), with intermittent springs present some distance upstream of the perennial river head. This is something that occurs commonly in karst aquifers where the capacity of the solutional conduit and fissure system is exceeded and a higher, previously unsaturated network becomes active with water discharged from these ephemeral springs, often a considerable distance upstream. Bournes occur in many streams in Hertfordshire (Whitaker, 1921b; Sefton et al., 2019), for example in the Mimram, Beane, Quin and Ash catchments. Whitaker and Thresh (1916) suggest that in Essex it is likely that all the Chalk streams that flow into the Cam have bourne characteristics and provide some observations on this. In Cambridgeshire, Whitaker (1922) describes a bourne in the Fulbourn parish; and in Norfolk, bournes occur on the northerly tributary of the River Wissey, the Babingley river, the Wensum river, and the Burn (Whitaker, 1921b).

Table 2. Some large springs in the C3 East Anglia Chalk area.

Spring	Location	East	North	Discharge	Source
Shepreth Springs	Cambridge	540323	244693	230 l/s	Whitaker (1922)
Melbourn Springs		537603	244084	210 l/s	
Thriplow Springs		543948	246353	58 l/s	
Group between Thriplow and Whittlesford		545199	247304	110 l/s	
Nine Wells		546137	254151	> 100 l/s?	
Cherry Hinton		548539	256207	> 37 l/s	
Hunstanton	Norfolk	569207	342642	> 30 l/s	Whitaker (1921b)
Well Hall		572500	320313	32-76 l/s	
Sow’s Head		572497	320891	8-24 l/s	
Grimston Church		572077	321884	24 l/s	
Castle Acre Spring	Swaffham	582450	314930	500 l/s (combined flow of all springs)	Hull (1995)
Snailwell Springs	Newmarket	564200	267600	Tracer test site	Sims (1988)

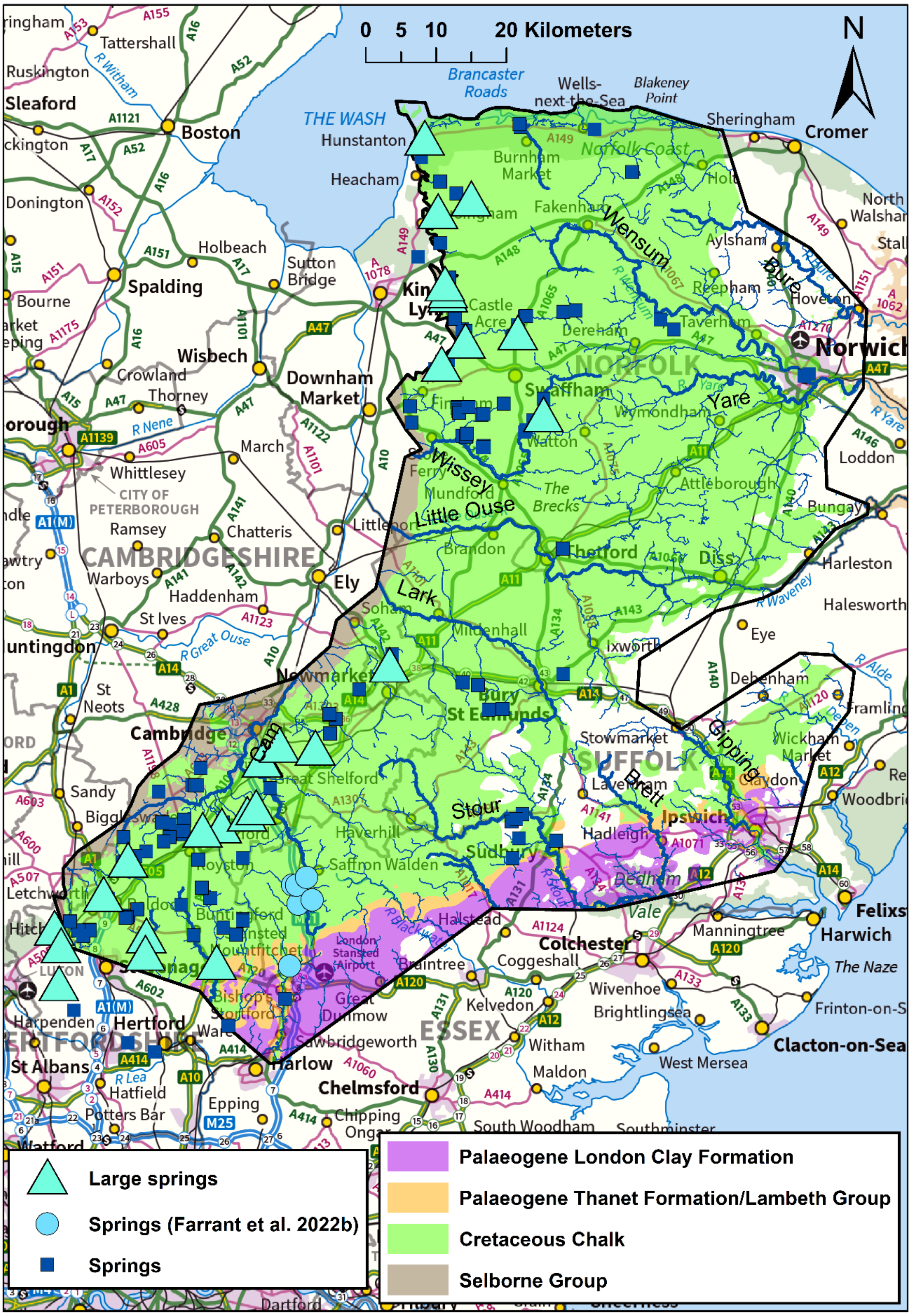

Figure 22. Chalk springs in the C3 East Anglia Chalk area.

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3 Tracer tests

3.1 POINT TO POINT TRACER TESTS

There have been no tracer tests conducted from stream sinks or dolines in East Anglia, and overall very few tracer tests have been undertaken (Figure 23). However, there have been four tracer test studies that have proven connections using boreholes as injection points (Kachi, 1987; Sims, 1988; Hull, 1995; Ward, 1989). These have identified ten groundwater flow pathways (Figure 23; Table 3). These tracer tests demonstrate rapid flow velocities of 14 to >3850 metres per day (based on time to first tracer arrival), over distances ranging from 44 to 1650 m. In most tests velocities exceeded 100 metres per day (Table 3). Where tracer recoveries are available they are variable, with very high recoveries (30 to 100 %) at many sites indicating low attenuation/dilution, and lower recoveries (0.05 and 1.2 %) at two other sites indicating high attenuation/dilution. These tests are described below.

In addition, very early tracer testing was undertaken at Fulbourn hospital, around 1906 to 1907. This is described by Whitaker (1922) on pages 17-20 and 36-40 which also include descriptions of other hydrogeological investigations and observations at this site. The tracer used was fluorescein dye, and a tracer test was first conducted from a borehole, but no tracer was observed at any of the monitoring sites. In 1907 a second test was conducted with fluorescein injected into a trench, which was constructed close to the borehole where tracer had previously been injected. Infiltration through the base of the trench was found to be rapid in an experiment in which 50,000 gallons per day (approx. 2.6 l/s) was pumped into the trench and easily absorbed. After 3 days of pumping water into it, fluorescein was added to both ends of the trench. No tracer was detected at the “south borehole six yards” from the trench, but it was detected at the “north borehole” in seven hours. Nine days after the start of the tracer test, chalk pits to the north-west were coloured for several days, and subsequently tracer was observed at a well at the Rosemary Branch public house “in the same direction” and in water at Leddon wells. No tracer was observed at the Fulbourn asylum well, another water supply well, or at Cherry Hinton springs. Whitaker (1922) reports that this experiment used only 500 grams of fluorescein, and a second experiment with “5 lbs” of fluorescein resulted in “evidence of definite colouration” at both the Fulbourn asylum well and the other water supply well. The precise locations of the injection and monitoring sites, distances, and timescales between injection and detection for these tests are unclear. Given that the detections were from visible colouration, it seems probable that flow was rapid and attenuation low. It was suggested that the tests demonstrated connections over “a considerable distance”. It is unclear how far this might be, but based on the descriptions in Whitaker (1922), it may be up to 1 to 2 km.

Kachi (1987) demonstrated five ‘borehole to borehole’ connections over distances ranging from 44 to 200 m in the Newmarket area. These were forced gradient radially converging tracer tests in which sodium fluorescein or Amino-G-acid tracer was injected into monitoring boreholes and detected in pumping abstraction boreholes. In three tests there were classic tracer breakthrough curves (BTCs) with sharp peaks in which the groundwater velocities based on the first arrival of tracer were rapid, ranging from 115 to >3840 m/day. These breakthrough curves had long tails indicating some attenuation via dispersion/diffusion processes along the flow paths. At a fourth site (New England) there was clear tracer detection but with scattered positives and no well-defined breakthrough curve, and at the fifth site (Eagle Lane) there were only sporadic positives and the test was somewhat inconclusive. In the three tests with classical breakthrough curves recoveries were high (43 to 71 %). At three of the sites, tracer was also detected in piezometers in a nested piezometer. The rapid tracer velocities indicate that there are karstic solutional networks of fissures and conduits, but other than at Cambridge Hill the velocities are lower than velocities of 1000s m/day which are observed in tests from stream sinks in the Chalk in other parts of England. This, combined with the tailing in the BTCs suggests that although some tracer is transported very rapidly through the network, there is also attenuation along the flow paths between the injection and monitoring boreholes via dispersion and diffusion into smaller voids.

In the tracer test in the Newmarket area by Sims (1988), fluorescein dye tracer was injected into a monitoring borehole, with sampling at two springs: Snailwell and Chippenham Fen. A previous single borehole dilution test in the monitoring borehole suggested that tracer took about 2-3 days to dilute from the horizon where the tracer was then injected in the catchment scale test. Although a charcoal bag was positive for fluorescence at Chippenham Fen, further analysis indicated that this was background fluorescence derived from organic matter, rather than injected tracer. In contrast, further analysis of positive water samples from Snailwell springs indicated that this was dye tracer not organic matter. The first arrival of tracer was 13.6 days after injection, indicating a velocity of 121 m/day over the 1650 m between the injection borehole and Snailwell springs. Tracer recovery was estimated at 1.2%, although Sims (1988) noted that the recovery was only estimated over a period of 2-3 days; and also indicated that the standard error was likely to be high due to fluctuating discharges and tracer concentrations.

Near Swaffham, tracer tests suggest another borehole to spring connection (Hull, 1995). In this test 4 kg of fluorescein and 4 litres of Rhodamine WT were injected into an observation borehole at a level of faster dilution indicated by a previous Single Borehole Dilution Test (SBDT). Dilution in this borehole was fairly slow (see below), and during the main test, ~ 0.1 to 0.2 % of tracer was still present in the injection borehole 28 days after injection. Low levels of tracer were detected in multiple peaks at Castle Acre springs, 1500 m away from the injection borehole. The velocity (based on first arrival of tracer) was 400 m/day and the estimated recovery was low (0.05%).

In the tracer tests undertaken by Sims (1988) and Hull (1995) the tracer concentrations were low, and clear tracer breakthrough curves were not obtained. In this situation it is difficult to distinguish positive tracer from fluctuations in background fluorescence. However, in both cases spectrofluorometry was used to distinguish injected dye from fluorescence due to organic contamination, therefore it seems highly likely that the tracer was detected, and that the connections are characterised by very high levels of attenuation via dispersion and diffusion and/or dilution of tracer with non-tracer laden water at the springs.

Ward (1989) conducted six radially converging tracer tests from observation boreholes to abstraction boreholes in the area north and east of Thetford. These tests were conducted in 1986 and are summarised in Ward et al. (1998). The abstraction boreholes had pumping rates of 38 to 58 l/s. Three ‘borehole to borehole’ connections were demonstrated at Snetterton, Dower House and South Farm over distances of 170 to 256 m (Ward, 1989; Ward et al., 1998; Atkinson, 2001, see Table 3). Groundwater velocities based on first arrival of tracer ranged from 149 to 341 m/day, with high recoveries of 30 to 100 %. The high groundwater velocities are indicative of solutionally-enhanced subsurface fissure networks, particularly alongside very low values for effective porosity ranging from 2.3×10^{-3} to 2.4×10^{-6} (Atkinson, 2001). There was tailing in the breakthrough curves indicating slower moving groundwater, and further analysis of the South Farm tracer test suggested that the breakthrough curve reflected double porosity diffusion alongside advection-dispersion under the radial flow conditions (Atkinson et al., 2000). No tracer was recovered in the three other tests (Ten Acre Plantation, Hockham Hall and Roudham), although in two of these tracer tests Ward (1989) noted that tracer was very slow to leave the injection boreholes. This suggests that the injection boreholes may not intercept the same fissure/conduit networks that supply the abstractions.

A tracer test was undertaken at Corpusti, near Saxthorpe in 1980 after a subsidence incident that resulted in the collapse of a house and was thought to be caused by a pumping test in the Chalk about 500 m away (Atkinson, 1981; Ward et al., 1998). Tracer was still present in the injection borehole seven months later, demonstrating that this injection site was too shallow and not connected to the main Chalk aquifer.

3.2 SINGLE BOREHOLE DILUTION TESTS.

Where there is rapid dilution of tracer in single borehole dilution tests (SBDTs), it is likely that boreholes intersect some solutional flow paths, and the tests can be useful for identifying flow horizons in boreholes (Maurice et al., 2011). Single borehole dilution tests (SBDTs) have been undertaken at several sites in East Anglia, although these were prior to the development of small downhole electrical conductivity logging probes that enable SBDTs to be easily conducted using saline tracers with detailed vertical profiles. This technology has enabled improved understanding of borehole flows, and demonstrated that in many boreholes, flows are dominated by vertical flow. In this situation the estimation of Darcy velocities and hydraulic conductivities from SBDT data is not valid because the assumption of homogeneous lateral flow across the borehole is not met, with flows determined by head differences between fissures intercepted in the borehole rather than the natural flows in the aquifer. Nevertheless older SBDT data still provide an indication of where flows are likely to be rapid, and the horizons at which flow occurs.

Kachi (1987) undertook SBDTs in eight boreholes in Cambridgeshire using dyes as the tracer. Summary details and interpretation of these tests are also provided in Ward et al. (1998). Interpretation of the SBDT data presented in Kachi (1987) is difficult because sampling was fairly infrequent, and vertical flow patterns were not determined. It appears that in some of the boreholes tracer dilution was quite slow, with tracer present several days or even weeks after injection. However, there are some horizons in some of the boreholes where dilution appears more rapid and some potential flow horizons were identified by Kachi (1987) and reported in Ward et al. (1998); and in some of the boreholes it does appear that most of the dilution occurred within a day suggesting that these boreholes intersect solutional fissures with more rapid flow in the aquifer. Kachi (1987) did attempt to develop a method to identify vertical flow by injecting variable concentrations of tracer at different depths in the borehole, but this was not successful, and the resulting profiles indicated very variable dilution rates at different depths (Ward et al., 1998). Darcy velocities and hydraulic conductivities were estimated by Kachi (1987), but it is likely that many of the boreholes have vertical flow. Nevertheless, the SBDTs presented by Kachi (1987) are useful as they show that there are both sites where dilution is slow indicating poor connectivity with karstic solutional networks, and sites where dilution is more rapid indicating more connectivity with such networks.

SBDTs using dye were also carried out by Sims (1988) in one observation borehole and one abstraction borehole in the Newmarket area. There are similar difficulties in data interpretation but there were zones that appeared to have faster and slower dilution, and zones where most of the tracer was diluted in 2-3 days. Dilution of tracer in an observation borehole in the Swaffham area by Hull (1995) was quite slow with some tracer still present 2 weeks after injection. Both Sims (1988) and Hull (1995) used the SBDT results to inform injection depths for larger scale tracer tests (see above). Two other single borehole dilution tests were carried out in the Swaffham area by Tim Atkinson in 1978 using Amino-G-acid (Ward et al., 1998). In both boreholes, zones of more rapid dilution were identified. SBDTs were also carried out in Norfolk in 1977 by Ian Spratley for a BSc dissertation under the supervision of Tim Atkinson. Ward et al. (1998) provide some details of eight of these tests, including calculated seepage velocities. However, it is unclear whether there is vertical flow in these boreholes and information on dilution times/zones of rapid dilution are not presented.

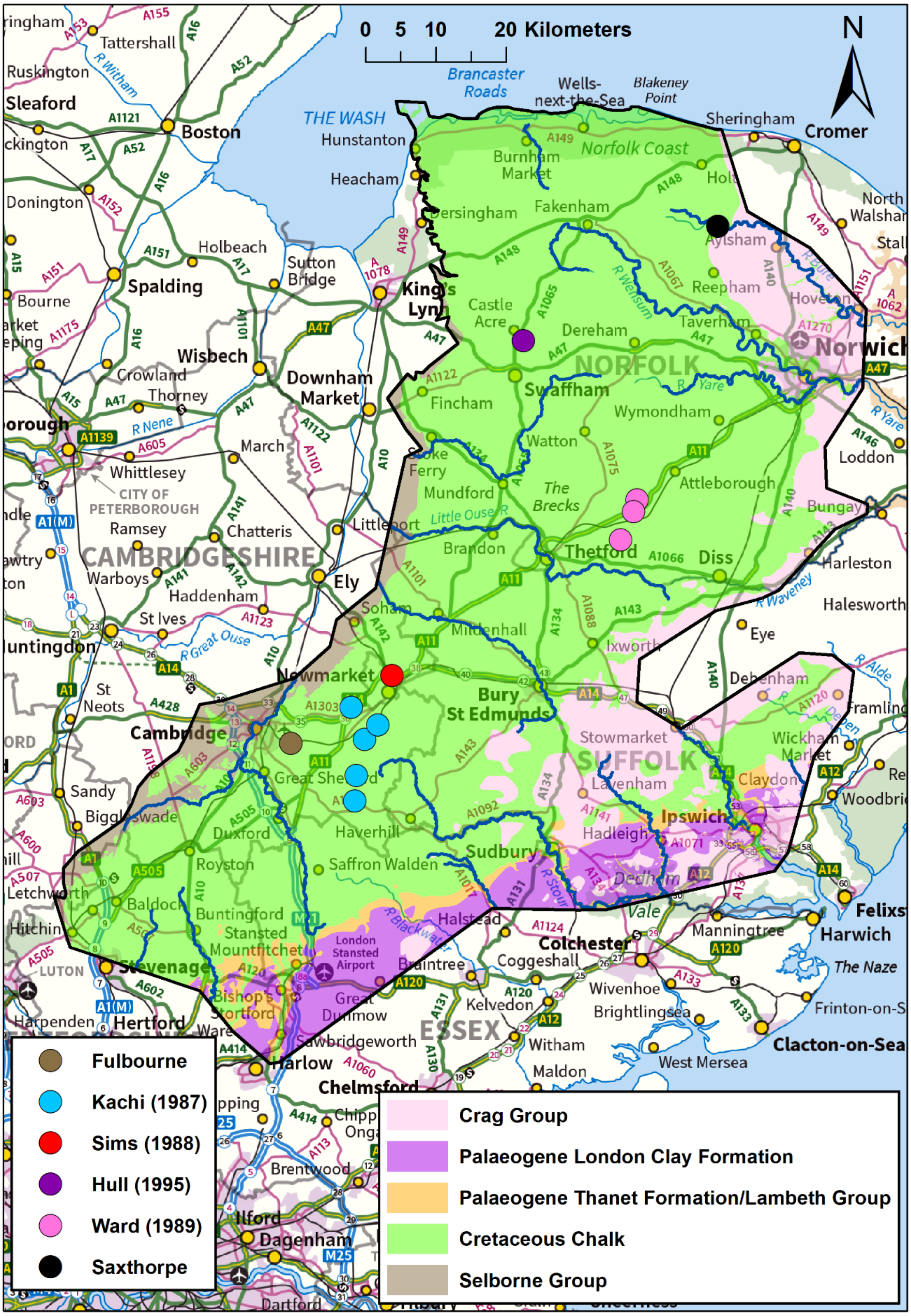

Figure 23. Point to point tracer tests conducted in the Chalk of East Anglia

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Table 3. Point to point tracer tests conducted in the Chalk of East Anglia, groundwater velocities based on time to first arrival of tracer.

(OBH = observation borehole, ABH = abstraction borehole, FL = fluorescein, AGA = Amin-G-acid, BTC = tracer breakthrough curve)

Area	Input	Output	Distance (m)	1st Arrival (hours)	Velocity (m/day)	Recovery (%)	Notes	Reference
Fulbourn	unknown	unknown	1000-2000?	unknown	Unknown	unknown	Dye visibly observed at several localities.	Whitaker (1922)
Newmarket	Horseheath OBH	TL 54/114 ABH	44	2.5	422	71	Classic BTC	Kachi (1987); Ward et al. (1997)
	Cambridge Hill OBH	TL 65/52 ABH	160	< 1	>3840	64	Classic BTC. Tracer also detected in 2 of 4 piezometers in nested piezometer site 126 m from injection site, only 3 sampling occasions	
	West Wratting OBH	TL 55/140 ABH	134	28	115	43	Classic BTC. Flow in Totternhoe Stone and Melbourn Rock. Tracer also in nested piezometers sampled on three occasions.	
	Eagle Lane OBH	TL 64/45 ABH	200	Unknown	32*	Unknown	Two tests, one FL one AGA. No clear BTCs, sporadic positives. Inconclusive test.	
	New England OBH	TL 56/132 ABH	178	Unknown	14*	Unknown	Definite detection but scattered positives. Tracer also detected in nested piezometers, with high concentrations in one piezometer and moderate in another.	
Newmarket	TL 66/93 OBH	Snailwell springs	1650	326	121	~1.2	Low levels of tracer, spectrofluorometry used to distinguish positives from background	Sims (1988)
Swaffham	Little Palgrove Hall Road OBH	Castle Acre Spring	1500	90	400	~0.05	Low levels of tracer, spectrofluorometry used to distinguish positives from background	Hull (1995)
Thetford	Snetterton Hall TL 99/1 OBH	Well 11A ABH	170	12	340	100	No tracer seen at nearby springs. Multiple peaks at ABH	Ward (1989); Ward et al. (1997)
	Dower House TL 98/6 OBH	Dower House Well 7A ABH	256	18	341	60	Two sets of multiple peaks in BTC	
	South Farm TL 98/7 OBH	South Farm Well 8A ABH	199	32	149	30	One main set of peaks in BTC	

*approximate, based on plots in Kachi (1987)

4 Other evidence of karst

Transmissivity data provide an indication of the extent of karstification in the Chalk (Foley and Worthington, 2021; Maurice et al., 2021). This is because the unmodified fracture network is estimated to have a transmissivity of about 20 m^2/day (Price, 1987) and extensive networks of solutional fissures and conduits are required to enable high transmissivities. There are many measurements of transmissivity in the East Anglia area from pumping test data in the BGS aquifer properties database (Figure 24). The datapoints on Figure 24 are the records that are attributed to the Chalk aquifer, and are not clipped to the C3 area. There are many sites that have very high transmissivities of greater than 1000 m^2/day and two where the transmissivity is more than 10,000 m^2/day. These high transmissivities are generally indicative of extensive fissure/conduit networks in the Chalk, although at some sites where highly permeable deposits overly the Chalk or there are buried valleys composed of high permeability material, it is possible that these may contribute to the high transmissivities (Allen et al., 1997). Pumping test data therefore need to be considered in detail at individual sites to assess whether they are indicative of karst. In some places in East Anglia connectivity with rivers may contribute to high transmissivity (Allen et al., 1997), and this may be indicative of karstic solutional flow paths connecting rivers with abstractions. There are also a large number of sites with transmissivity of less than 1000 m^2/day, indicating the high variability and heterogeneity of the Chalk, and Allen et al. (1997) report that there are lots of places in East Anglia with low transmissivity.

Figure 24 uses the best “locality” estimate of transmissivity from the national database. Details of this are explained in Allen et al. (1997), but in summary, there are many sites for which there are multiple estimates of transmissivity, either because pumping tests were carried out on different boreholes, or because multiple tests were carried out on the same borehole. For each test, the most appropriate value of Transmissivity was determined (based on factors such as the length of the test), and then a site value (incorporating all tests within 100 m) was determined by selecting the most reliable test result. The maximum and minimum Transmissivity values are also available, and there are 17 sites in East Anglia where the maximum value was > 10,000 m^2/day, and many where it was > 1000 m^2/day. Whilst the “locality” values may generally be the most useful, in considering karst, the maximum values may also be of some interest because some of the within site variation may be due to karstic heterogeneity. For example, Allen et al. (1997) note that at Brandon in Norfolk, two boreholes drilled close together had completely different yields. In other words, tests at multiple boreholes in which different parts of the fissure/conduit system are intersected may yield very different results, despite their close proximity; and therefore the maximum value may indicate where karst is important. The geographical patterns in transmissivity seen in Figure 24 are discussed in relation to the spatial distribution of karst in Section 5 below, together with other observations from Allen et al. (1997) on factors controlling transmissivity in East Anglia.

Other aspects of pumping test results are also indicative of karst, for example where there is highly anisotropic behaviour with high drawdown in one direction and none in another. Anisotropy in the Chalk in Norfolk is discussed by Toynton (1983), who shows that it can be predicted by considering fracture patterns. In another example, a pumping test at Havergate island on the east coast suggested both an intense local connection with Orford Ness and also connectivity with a site 10 km up the coast (Linford-Wood, 2012). Rapid responses of groundwater levels to pumping have been observed at some locations (Allen et al., 1997), which can also be indicative of karst if this occurs over long distances.

Allen et al (1997) also report quite a large number of sites where particularly high borehole yields have been obtained. One example is a site at Thetford in West Suffolk with a yield of 460 l/s for little drawdown and with no apparent contribution from the river (and a transmissivity of 10,000 m^2/day). Faulting or the presence of the Chalk Rock at 60-80 m depth were thought possible factors enabling the high yield. Another example is a borehole in the Cam valley with a yield of 12000 m^2/day (equivalent to ~140 l/s) for only 2.6 m of drawdown after 11 days (Allen et al., 1997). Other examples of high yields reported in Allen et al. (1997) include Marsh Road in Hertfordshire with a yield of 200 l/s (with a transmissivity of 1000 m^2/day) and Houghton St Giles in East Norfolk with a yield of ~ 80 l/s for 3.5 m of drawdown.

Water quality indicators of rapid flow have not been considered for this report, other than in a brief literature review. Farrant et al. (2017) report some water quality indicators of rapid flow at five abstraction sites in the area, with two other sites where rapid flow indicators were absent. Given the extensive superficial cover, and more limited karstic recharge than in other areas of the Chalk, it might be expected that there are fewer sites with water quality indicators of rapid flow. Nevertheless, such indicators may be present, especially where there are more surface karst features and where there is less thick low permeability cover which prevents rapid recharge. Further work is needed to investigate water quality indicators of rapid flow in East Anglia.

There is some evidence for karst in the River Burn catchment in north Norfolk (Simon Linford Wood, personal communication, 2016). Bourne behaviour occurs in the river, and high transmissivities, low storage, and significant fluctuations in groundwater level have been observed in the aquifer. There are also large soakaways that took lots of drainage and indications of solutional development of cavities. LiDAR data (available on the National Library of Scotland website: https://maps.nls.uk/geo/explore/side-by-side/) show high densities of surface depressions in the River Burn catchment area (not recorded on Figure 11 or Figure 20). Many of these have irregular shapes suggesting that they are anthropogenic pits, but there are also some circular shaped depressions, some of which may have a solutional origin. A pollutant was observed to travel quickly over a long distance in the River Burn area. Tracer testing in the Sculthorpe area by an MSc student under supervision from Tim Atkinson also suggested rapid flow in the River Burn catchment, but details are not presented in Ward et al. (1998).

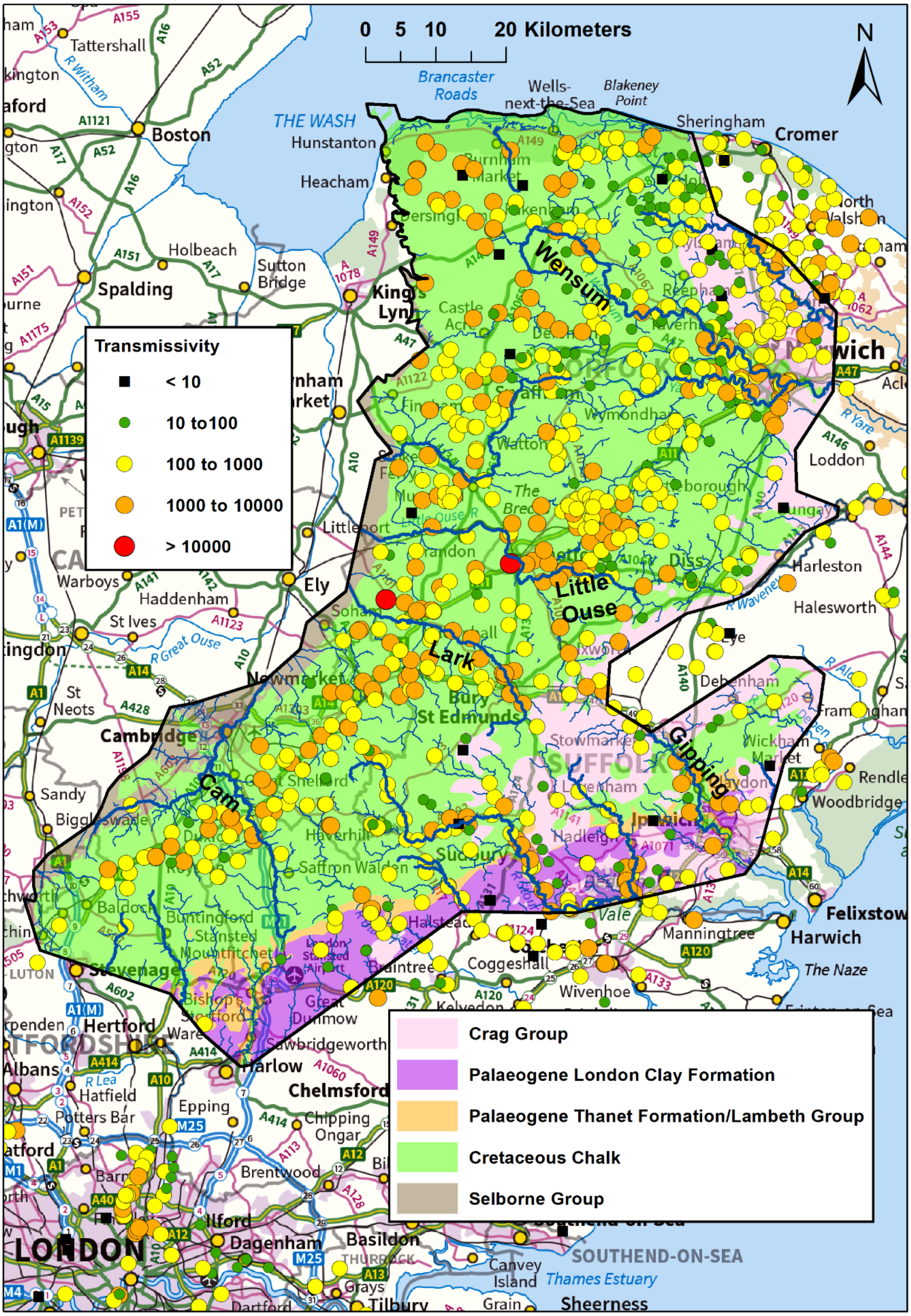

Figure 24. Transmissivity in the C3 East Anglia Chalk area, measured in m^2/day.

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5 Spatial distribution of karst

5.1 INTRODUCTION

East Anglia is not a place that most people would immediately associate with karst, and there have only been a few studies that are specifically on karst in this area. Nevertheless, bringing together the different strands of evidence in this report, there does appear to be considerable evidence that karst processes impact the Chalk in this area. Paleokarst features provide evidence of karstification prior to the Anglian glaciation. The spatial extent and depth of pre-Anglian karst development is unclear, as is the impact of the Anglian glaciation on this karst: glacial erosion may have eroded away karst features in the upper parts of the Chalk, and glaciation has also concealed karst which may still be present, but buried beneath the cover. There is certainly some good evidence for this – with high transmissivities, large springs, rapid flow, and cave/conduit development in the cliffs at Hunstanton. Post Anglian karst development also appears to be occurring, with many small stream sinks associated with the edge of the glacial till. Although much of the Chalk is covered, preventing karstic recharge, there are some classic chalk karst stream sinks associated with the boundary between the Chalk and the overlying Paleogene deposits where these are present. There are also many small stream sinks associated with the Chalk-till margin. It is possible that these may be quite transient - i.e. as the glacial till is eroded the stream sinks may be abandoned before they develop into more mature karst features. Nevertheless, this recharge may be feeding into older karst networks that pre-date the Anglian glaciation or into saturated zone networks formed by mixing corrosion (see below). There are clearly many uncertainties about when and how much karstic development has occurred, but this section presents some general observations of karst in the unsaturated and saturated zones (including a discussion on the general geological and topographical controls on karst); and an overview of the geographical distribution of karst.

5.2 UNSATURATED ZONE KARST

Karstic recharge is unlikely over large parts of East Anglia where there are thick deposits of glacial till overlying the Chalk. Indeed, there is little recharge at all beneath the till covered interfluves with estimates of less than 20 mm of recharge per year and possibly as low as 5 mm (Marks et al., 2004), and some very old groundwaters present beneath the thick cover (Lloyd et al., 1981). Recharge is thought to occur near the edge of the glacial till sheet where there is more fracturing of the till enabling recharge down to the underlying Chalk, and also where runoff from the low permeability till reaches the Chalk (Marks et al., 2004). In areas more than 1 km from the edge of the glacial till, CFC (chlorofluorocarbon) groundwater residence time indicators suggest low proportions (< 15 %) of modern water (Marks et al., 2004; Gooddy and Darling, 2009). On the other hand, sites near the till margin, or within the main river valleys, have a higher proportion of modern water (> 70%). These modern waters derived from recent decades are likely to include a component of very recent rapid recharge via karstic solutional features in the Chalk unsaturated zone. The proportion of rapid recharge through such features is uncertain and likely to have considerable spatial variation. Rapid recharge is most likely where surface karst stream sinks have developed in association with geological boundaries between the Chalk and lower permeability Paleogene or glacial till deposits (Section 2.2). They may also occur in association with karstic dissolution pipes/dolines which are more likely where there are thin superficial or Paleogene deposits overlying the Chalk (Section 2.3). Vertical solution fissures can also occur in the absence of any apparent surface karst features, including where the Chalk occurs at outcrop without any superficial cover (Farrant et al., 2021a,b; Maurice et al., 2021; Cullen-Gow et al., 2022a). There is not much Chalk exposed at outcrop in the East Anglia area, but where it does occur it is predominantly the Holywell Nodular and New Pit Chalk formations, which Cullen-Gow et al. (2022b) suggest may have a lower tendency for vertical solutional development than some other Chalk formations in other areas, although this is not certain. In most places the proportion of rapid recharge is likely to be small, but further work is needed to investigate this, which might include further investigations of stream sinks and losing rivers, and consideration of water quality indicators of rapid flow in springs and abstractions.

5.3 SATURATED ZONE KARST

The high transmissivities (Section 4), rapid flow indicated by tracer tests (Section 3), and the presence of many springs indicating focused discharge (Section 2.4), suggest that karstic solutional networks are common in the Chalk saturated zone in East Anglia. The types of voids that make up the karstic solutional networks in this area are not known. A small inactive chalk karst cave is exposed at one coastal site (Section 2.1), and if other caves have developed then they are likely to be concealed beneath the extensive superficial cover that occurs over most of the area. Nevertheless, it is uncertain how much cave development there has been in the East Anglia chalk, and many karstic networks may comprise fissures and small conduits. Further studies of coastal outcrops, inland outcrops, and borehole images could provide insights into how much conduit development there is in the Chalk in this area.

In the Chalk in general, karstic development in the saturated zone occurs along stream sink to spring pathways, or due to mixing corrosion which can occur in the saturated zone in isolation from surface karst features (Farrant et al., 2021b; Maurice et al., 2021). Although the presence of mature well developed stream sink to spring karst flow paths has not yet been proven by tracer testing in East Anglia, there are sinking streams and river losses in some areas (Section 2.2), which may feed into such saturated zone solutional networks. There is evidence of older karstification that pre-dates the Anglian glaciation (Section 2.3), which suggests that it is possible that saturated zone networks developed in the geological past along stream sink to spring connections. It is also likely that many saturated zone networks enabling high transmissivity (and perhaps focused spring discharges) are due to networks that have formed by mixing corrosion. This is a well-established mechanism of sub-water table karst development which occurs where saturated groundwaters with different PCO_2 concentrations mix, resulting in a reduction in the saturation index and enabling further carbonate dissolution (Bögli, 1964, Bögli, 1980). Many questions remain. It is difficult to establish which process is responsible for the saturated zone karstic development, and it is unclear how well connected the modern-day karstic recharge is to these networks. It also extremely difficult to identify the exact locations and extent of the saturated zone solutional networks. However, there are some general principles that have been established which provide some insights into where karstic fissure/conduit development is more likely to occur and these are outlined below:

The factors controlling the transmissivity distribution (and hence the karstic development of permeability in the saturated zone) in East Anglia are discussed in considerable detail by Allen et al. (1997). They report that in the North Essex area, most dissolution occurs in the 10 to 40 m below the top of the Chalk, and in the English Chalk more generally, it is usually the case that solutional development reduces with depth. As in other areas of the Chalk, fissures occur in the zone of water table fluctuation. For example, in boreholes at Bircham and in the Colney catchment, fissure flows are most common in the zone of water table fluctuation and within the top 20 m of the lowest water levels (Parker et al., 1987).

Unsurprisingly there is more evidence of karstic development in river valleys than on interfluve areas. This may be partly because springs, which are the natural outlets for karstic networks, feed the rivers; and because rivers have eroded the overlying deposits and are therefore places where chalk is often exposed, or there is only a thin superficial cover. This karstic development is reflected by generally higher transmissivities in river valleys than on interfluves in the East Anglia area (Allen et al., 1997). Allen et al. (1997) note that there are a few exceptions where boreholes away from valleys have intercepted fissure systems (e.g. boreholes south of Swaffham).

There is good evidence that solutional development is geologically controlled and related to particular karst inception horizons. Farrant et al. (2022b) suggest that in the Upper Cam catchment there may be discrete areas of small-scale conduit flow along particular horizons. They suggest that the Chalk Rock and Top Rock may be important karst horizons especially where they occur at more shallow depths in the area around Lindbury and Wendens Ambo; and that in areas further south, the marl seams in the Upper Lewes Nodular Chalk and the base of the Seaford Chalk may be important. Snailwell springs are located on the Melbourn Rock (Sims, 1988) suggesting that this may form an inception horizon in this area. Allen et al. (1997) also suggest that the Melbourn Rock and Totternhoe Stone are important horizons in Cambridgeshire. These types of geological inception horizons are important in determining the locations of springs (Section 2.4).

In contrast to other areas of the Chalk, Allen et al. (1997) reported that transmissivity is higher in the lower parts of the Chalk sequence than in the upper parts, and suggest that this may be due to the Totternhoe Stone and Melbourn Rock hardgrounds. It may also be due to the greater extent of the lower formations at outcrop and in areas of thin cover.

The solutional development of permeability can also relate to fracture orientations, and this was suggested in a study in Norfolk by Toynton (1983). A correlation was found between the angle of observed joints in the Chalk in Norfolk and the angle between the observation and pumped boreholes which gave high transmissivity values during pumping tests. The study concluded that the anisotropic nature of the Chalk in this area could be predicted by considering fracture patterns.

The relations between transmissivity and the locations of buried valleys appears to be quite complex, and several studies of this are described in Allen et al. (1997). There is some suggestion of higher transmissivity beneath buried channels in some places (Woodland, 1946; Great Ouse River Authority, 1970), but low transmissivity at other sites (e.g. Rushall in Norfolk, Foster and Robertson, 1977).

5.4 GEOGRAPHICAL DISTRIBUTION OF KARST

High transmissivity in the Chalk is generally indicative of karstic solutional networks, and the very large dataset on pumping tests in the East Anglia area provides a good indication of the geographical distribution of these networks. The first observation from Figure 24 is that high transmissivities appear ubiquitous, with values of over 1000 m^2/day observed throughout the entire East Anglia area from north to south and east to west, and include some high transmissivities in the eastern areas where there is a thick cover over much of the Chalk. The second observation is that many of the higher transmissivities are associated with river valleys (e.g. the Cam, the Gipping, the Lark, the Little Ouse and the Wensum).

The transmissivity patterns in East Anglia are described in detail in Allen et al. (1997). A map of yields (based on Woodland, 1946) is also presented and this shows the highest yields of more than 1640 m^3/day (equivalent to around 19 l/s) in the area between Cambridge and Thetford, the area between Ipswich and Felixstowe, and in other valleys, especially in the south of the area. Allen et al. (1997) suggest that mean transmissivity is higher in the area west of the groundwater divide (west Norfolk, west Suffolk, Cambridgeshire, and Hertfordshire) than to the east in east Norfolk and east Suffolk, noting that the higher transmissivities occur in areas that are mostly without low permeability cover because here there is greater solutional development of the Chalk.

Beyond these broader patterns in transmissivity, Allen et al. (1997) provide detail on the transmissivity distributions in different areas of East Anglia: Hertfordshire, Cambridgeshire, West Suffolk, West Norfolk, East Norfolk, East Suffolk and North Essex (see pages 86 to 97 in Allen et al. (1997)).

Considering the evidence for karst as a whole, whilst there is evidence for karst throughout the East Anglia area, there are some areas that appear to be more important for karst development. These include: (1) The south-west, in particular around the Beane and Upper Cam catchments, where there are stream sinks, large springs, bourne behaviour, dolines and dissolution pipes, and high transmissivities are commonly observed. (2) The area around Cambridge and Newmarket where there are large springs, and tracer tests have indicated rapid flow. (3) The Gipping valley near Ipswich where there is evidence of some karstic recharge, dissolution pipes occur, and some high transmissivities have been observed. (4) The Thetford area where very high yields and transmissivities have been observed and there is evidence of surface karst dolines. (5) The River Burn and the River Bure catchments in the north where there are several indicators of karst.

6 Summary

- There is a surprising amount of evidence for karst in the Chalk of East Anglia.
- A small karst cave has been documented on the north coast, and others may be present beneath the cover. It is unclear how much small-scale cave development has occurred.
- Many karst networks are likely to comprise fissures and conduits too small to enter. Assessment of coastal and inland outcrops and borehole images could be used to investigate conduit development.
- Paleokarst is widespread. There are many records of dissolution pipes, often large, and some that have been shown to pre-date the Anglian glaciation. The dataset is incomplete and there are likely to be many more where there is currently a relatively thin cover over the Chalk. It is also possible that there are deeper pre-Anglian glaciation karst features buried by the till if they were not eroded by glaciation.
- There are extremely high densities of surface depressions, and most of these have not been identified for this study. Whilst many are pits of anthropogenic origin, many are of natural periglacial or karstic origin, and there is good evidence that some are karst dolines.
- Stream sinks occur. The most significant are associated with the boundary between the Chalk and the overlying Paleogene, but there are also many associated with the boundary with the glacial till. There are no data on their discharge, but those associated with the till appear to be generally small features with only small flows following rainfall, although collectively they are likely to be important for recharge.
- Stream sink records are concentrated in the south-west where geological studies have been undertaken, and more may be present in other similar geological settings.
- Some streams on the Chalk (and where there is thin permeable cover) have losing sections and/or exhibit bourne behaviour.
- Many springs were identified for this study and there are many more marked on old and current Ordnance survey maps which were not collated.
- There is little information on spring discharge, and spring flows are likely to be greatly reduced since the development of groundwater resources, but some flows of more than 200 l/s have been measured. The springs that are likely to be large seem to be generally distributed in the west and south of East Anglia.
- A small number of tracer tests have been conducted in East Anglia. Rapid flow was demonstrated, with groundwater velocities based on first arrival of tracer ranging from 14 to > 3800 m/day over distances ranging from 44 to 1650 m. Tracer recoveries were highly variable, ranging from 0.05 to 100%, with generally higher recoveries in tests conducted over shorter distances.
- A very large pumping test dataset reveals highly variable transmissivities, but with high values (> 1000 m^2/day) at a large number of sites distributed throughout East Anglia, even beneath thick cover.
- Karst occurs in the unsaturated zone, although rapid recharge via karst is limited in many areas by thick low permeability superficial deposits.
- Karst appears common in the saturated zone, and fissure and conduit development may be due to mixing corrosion or past/present stream sink to spring karst development.
- Overall there is more evidence for karst in river valleys and areas in the south and west where the Chalk is exposed or the cover is thin.
- Areas with particular evidence for karst include: the Beane and Upper Cam catchments; the Gipping valley; the Cambridge-Newmarket area; the Thetford area; and the Burn and Bure catchments in the north.
- Karst is clearly an important aspect of hydrogeology in East Anglia and further work is needed to develop better datasets of karst features, and better general understanding of karst in this area (e.g. through tracer tests and further consideration of hydrogeological data).

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 karstic solutional 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.

Mixing corrosion: Dissolution of carbonate rocks due to the mixing of two saturated groundwaters with different concentrations of carbon dioxide resulting in an undersaturated solution enabling further dissolution.

Paleokarst: Karst developed in past geological periods that has been buried by younger rocks.

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

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

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

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

Swallow hole: Another term for stream sink, although it has been used in the past for dry dolines that do not contribute surface runoff to the aquifer. 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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