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The Cretaceous, Jurassic and Permian carbonate karst aquifers of England (UK)

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Abstract: Despite having limited cave development, the UK Permian, Jurassic and Cretaceous carbonates have standard karst features – caves, stream sinks, dolines, springs, dry valleys, and solutional networks of fissures and conduits extending multiple kilometres. This paper provides a new discussion and comparison of these karst aquifers, demonstrating that significant karst features are widespread. Tracer tests in the Chalk and Jurassic limestones demonstrate flows of thousands of metres per day from the surface to a spring or abstraction over many kilometres, comparable to results from karst aquifers with substantial cave systems, such as the UK Carboniferous limestones. They are less vulnerable in terms of having less cave development and a lower proportion of rapid point recharge, with greater attenuation via flow through smaller voids. However, the combination of long-distance transport via karstic networks and long-term storage of contaminants in smaller voids may make contaminant management particularly challenging. Karst development and the proportion of rapid recharge vary substantially at different spatial scales. Therefore, better groundwater conceptual models incorporating karst data at the local catchment scale, together with further investigations (tracer tests, borehole studies, water balance) are needed. Groundwater management and protection require the use of methods appropriate to the karstic nature of these aquifers.

Supplementary material: A table detailing indicators of karst in the 17 different areas of the Chalk, Jurassic and Permian limestones of England, and a map showing the locations of these areas are available at https://doi.org/10.6084/m9.figshare.c.8551882

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Karst occurs in all soluble rocks and produces particular geomorphological features and aquifer characteristics (Ford and Williams 2007). Karst aquifers are those in which permeability is enhanced by the solutional enlargement of primary fractures, stratigraphical discontinuities, and faults to form networks of solutional fissures and conduits (Ford and Williams 2007; Worthington and Ford 2009). The term 'conduit' is used here for solutional voids (often circular or elliptical in shape), which are termed 'caves' when large enough to enter. The term 'karst network' is used to describe subsurface solutional networks made up of some combination of fissures, conduits and caves. Karst aquifers have rapid groundwater flow, long distance pollutant transport, extreme heterogeneity, and high vulnerability to pollution (Kačaroğlu 1999; Gunn 2007). They are complex aquifers with triple porosity in which the three components (rock matrix, unmodified fractures, and solutional conduits/fissures) have substantially different flow velocities and storage properties (Worthington 1999).

Groundwater management and protection of karst aquifers is particularly challenging because karstic conduit networks are complex (Atkinson 1977; Perrin and Luetscher 2008; Gunn 2017), making catchment delineation difficult (Gunn 2007; Environment Agency 2019; Maurice and Ascott 2021; Maurice *et al.* 2023*a*). Adjacent springs can have different groundwater catchment areas (e.g. Atkinson 1977); flow paths can change dramatically under high and low groundwater level conditions (Ravbar 2013), groundwater flow can move across topographical catchments (Le Mesnil *et al.* 2020*a*, *b*), and there can be preferential flow in different parts of the geological sequence (Maurice and Guilford 2011; Marsili *et al.* 2023). Groundwater modelling is especially challenging in karst (Jeannin *et al.* 2021).

Karst is extensive in the UK and comprises carbonate, gypsum and salt (Fig. 1a), with the focus of this paper on the carbonate karst. Karst can occur on different scales reflected by the size of the surface and subsurface solutional features. The UK carbonate karst aquifers are particularly informative as they are developed in diverse lithologies and geomorphological settings and thus display a wide range of karst types (Atkinson and Smart 1981). The highly karstic Paleozoic Carboniferous-aged limestones form major cave systems and large-scale, well-developed karst features in England, Wales and Northern Ireland (Waltham *et al.* 1997). In contrast, the younger Permian, Jurassic and Cretaceous carbonates form karst aquifers in which caves are usually poorly developed, and surface karst features are smaller. Although karst in these aquifers has long been documented (e.g. Harold 1937), they are often not considered karstic in hydrogeological studies. This may be due to a lack of karst data and conceptual understanding.

Hydrogeological evidence for karst and data on karst features in the Cretaceous, Jurassic and Permian carbonate rocks in England were collated. The outcrops were divided into 17 areas, their distribution primarily based on geology, but also geomorphology and location. The Upper Cretaceous Chalk outcrop was divided into nine areas, the diverse Jurassic limestones into six areas, whilst the Permian dolomitic limestones were divided into the northern and southern part of the outcrop (Table 1, Fig. 1b). Karst reports, produced by the British Geological Survey, provide information for hydrogeologists and other interested parties on known stream sinks, dolines, caves/conduits, and springs, and include maps showing the distribution of karst features (Maurice *et al.* 2020, 2022*a*, *b*, *c*, 2023*b*, *c*, *d*, 2024*a*, *b*; Matthewson *et al.* 2021, 2022). They also present information on tracer tests, and other hydrogeological evidence of karst. Karst data were collated by desk study using information from geological maps and survey data, published reports, papers and other academic studies, and more informal 'grey' literature from the caving community, together with

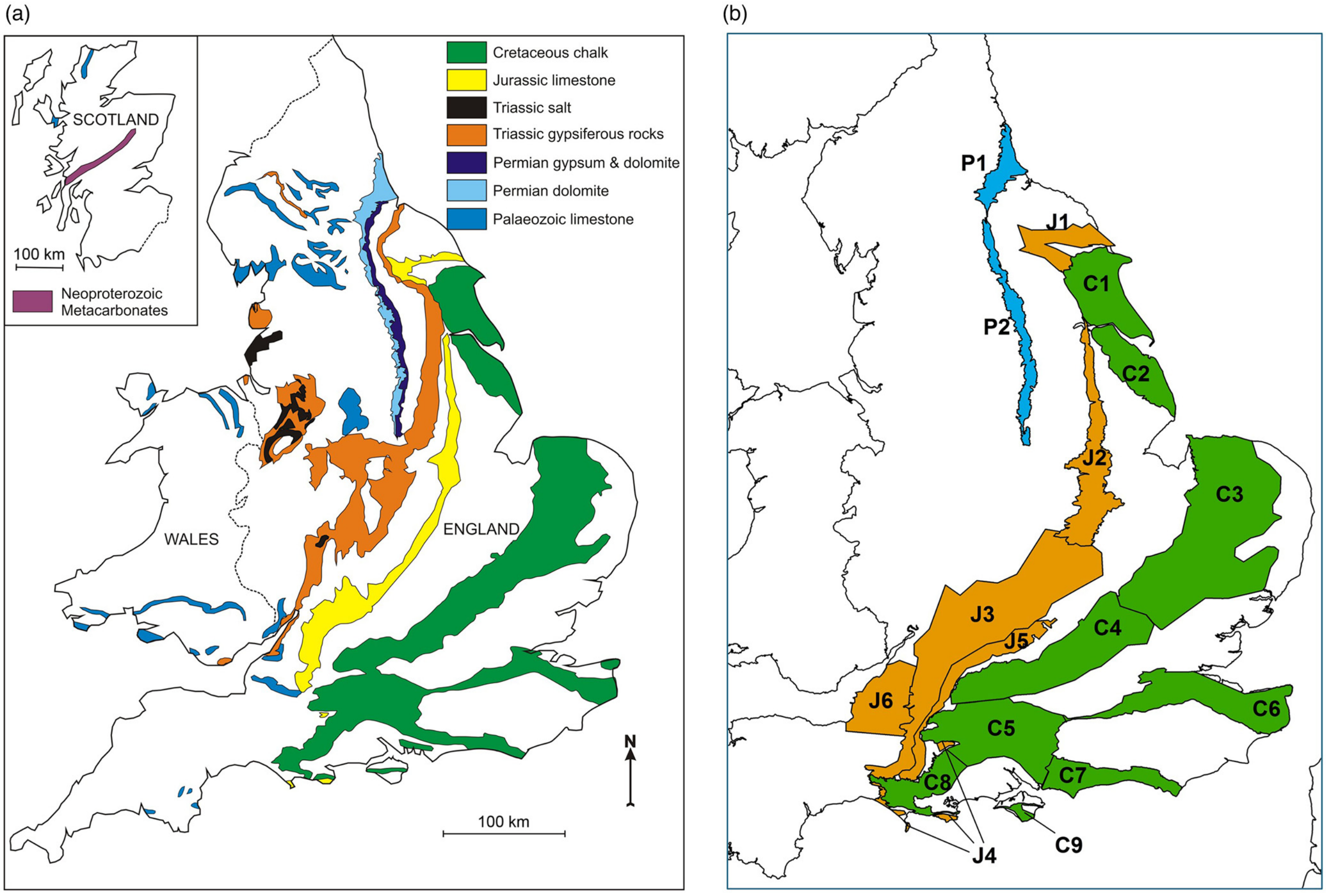

Fig. 1. (**a**) Distribution of karst in England, Scotland and Wales. (**b**) Karst areas for the Cretaceous Chalk (green), the Jurassic (orange) and Permian (blue) carbonates of England. Source: contains OS data © Crown copyright and database rights 2026.

information from water companies, regulators and other third parties through knowledge exchange. The distribution of data reflects where studies have been undertaken, therefore areas where karst features are absent may reflect a lack of field survey data or relevant hydrogeological studies, rather than actual lack of karst features. This paper summarizes the main findings from this work, providing an overview of the Chalk, Jurassic and Permian carbonate karst, compares them, and considers the implications for groundwater management and protection. The focus is on UK karst aquifers, but the principles are relevant to all karst aquifers, especially those with limited cave development.

Karst in the Upper Cretaceous Chalk aquifer

The English Chalk is perhaps the ‘type’ example of a karstic carbonate aquifer with limited cave development. Karst features and rapid karstic flow have long been documented (Richards and Brincker 1908; Harold 1937). Several studies discuss the evidence for Chalk karst in England (Edmonds 1983, 2008*a*; MacDonald *et al.* 1998; Maurice *et al.* 2006, 2023*a*; Farrant *et al.* 2023; Foley and Worthington 2023). Karst is also well documented in Chalk in France (El Janyani *et al.* 2014; Ballesteros *et al.* 2020), and in Northern Ireland where it is confined by Paleogene basalts and has much higher cementation (Barnes 1999). Here, the karst characteristics of the different areas of the English Chalk are outlined.

Chalk–Paleogene-dominated karst areas of southern England

In southern England, high densities of stream sinks are recorded where runoff from the overlying low permeability Paleogene Reading Formation clay sinks into the Chalk. This predominantly occurs in the C4 (Maurice *et al.* 2020), C5 (Maurice *et al.* 2023*b*), C6 (Mathewson *et al.* 2021), C7 (Maurice *et al.* 2022*b*), and C8 areas (see Fig. 1b for area locations). These areas therefore have a common karst setting and are considered together. Examples of high densities of stream sinks in the Chilterns to the NW of London (C4 area) are shown in Figure 2a. Most stream sinks are small, often ephemeral features but some provide substantial flows (>10 $\mathrm{l\,s^{-1}}$) to the aquifer. The largest stream sink complex at Water End in Hertfordshire [NGR 523097 204340] has inflows of up to 1000 $\mathrm{l\,s^{-1}}$ before overflowing (Walsh and Ockenden 1982). Streams feeding Chalk karst stream sinks often have flashy responses to rainfall (in part due to field drains) and following significant precipitation they collectively contribute substantially to aquifer recharge. Rapid recharge has also been observed through large and rapid borehole groundwater level responses to precipitation (Lee *et al.* 2006).

Short karst caves have occasionally been explored beneath stream sinks, but most have been exposed by coastal erosion, notably along the Sussex and Kent coasts (C6 and C7 areas). At 354 m, Beachy Head Cave [NGR 557807 095266] is the longest known Chalk cave in England (Farrant *et al.* 2021; Reeve 2021). Short caves have also been intersected in quarries and adits across the outcrop. Throughout the five areas solutional fissures and conduits are apparent in borehole image logs, quarries and outcrops (e.g. Fig. 2b). Many caves and smaller conduits/fissures are developed on stratigraphical discontinuities, in particular sheet flints, marl seams and hardgrounds (Farrant *et al.* 2021, 2023) and locally joints and faults. Together they form integrated stratigraphically guided conduit networks.

Dolines are locally present, especially associated with stream sinks and in areas with a thin, permeable cover. The greatest

Table 1. Karst areas in the Chalk, Jurassic and Permian aquifers of England

Area	Aquifer	Region	Report reference
C1	Upper Cretaceous Chalk Group	Yorkshire Wolds	In progress
C2	Upper Cretaceous Chalk Group	Lincolnshire Wolds	
C3	Upper Cretaceous Chalk Group	East Anglia	Maurice *et al.* (2023*c*)
C4	Upper Cretaceous Chalk Group	Chilterns, Berkshire & Marlborough Downs	Maurice *et al.* (2020)
C5	Upper Cretaceous Chalk Group	Wessex Basin (Hampshire)	Maurice *et al.* (2023*b*)
C6	Upper Cretaceous Chalk Group	North Downs	Mathewson *et al.* (2021)
C7	Upper Cretaceous Chalk Group	South Downs	Maurice *et al.* (2022*b*)
C8	Upper Cretaceous Chalk Group	Dorset	
C9	Upper Cretaceous Chalk Group	Isle of Wight	Maurice *et al.* (2022*c*)
J1	Upper Jurassic Corallian Group	North York Moors	Maurice *et al.* (2022*a*)
J2	Middle Jurassic Inferior Oolite Group	Central England (Lincolnshire)	Mathewson *et al.* (2022)
J3	Middle Jurassic Great & Inferior Oolite groups	Southern England (Cotswolds-Dorset)	Maurice *et al.* (2023*d*)
J4	Upper Jurassic Portland and Purbeck groups	Southern England	
J5	Upper Jurassic Corallian Group	Southern England	
J6	Lower Jurassic Lias Group*	SW England	
P1	Upper Permian Zechstein Group	Northern Permian outcrop	Maurice *et al.* (2024*a*)
P2	Upper Permian Zechstein Group	Southern Permian outcrop	Maurice *et al.* (2024*b*)

*The Lower Jurassic Lias Group outcrop within the general area shown on the map.

densities occur on the Dorset heathlands in the southwestern part of the Chalk outcrop (C8 area). Here large suffosion dolines occur usually associated with permeable sandy deposits overlying the Chalk; the largest being Culpeppers Dish [NGR 381410 092550] with a diameter of 86 m and a depth of 21 m (Sperling *et al.* 1977; Waltham *et al.* 1997). Other areas with significant concentrations of dolines include Burnham Beeches near Slough (Fig. 2a) and parts of Hertfordshire in the Chilterns (C4 area). However, most surface depressions on the Chalk are old chalk pits, dug for agricultural purposes to improve clay-rich acidic soils. Buried dolines, sometimes known as dissolution pipes, infilled with clay, sand and gravel are almost ubiquitous beneath the Clay-with-Flints and river terrace deposits. These can be up to ∼10 m deep and several metres across, but with no surface expression. In some areas, they coalesce to form very irregular rockhead prone to subsidence (Lamont-Black and Mortimore 1999).

These areas also have many large springs with flows of >100 l s^{-1}, indicating concentrated karstic flow. The largest are the Bedhampton and Havant springs (C7 area), with a discharge of more than 1000 l s^{-1}. They have been designated as among the globally Most Important Karst Aquifer Springs (MIKAS, https://mikasproject.org/mikas-list/, accessed 2025). Chalk streams often display winterbourne behaviour, with reactivation of ephemeral springs a long way upstream of perennial springs (Whitaker *et al.* 1910; Allen and Crane 2019). Streams can also have complex flow accretion profiles with dry sections downstream of sink points, and karst estavelles (Hopson *et al.* 2006; Allen and Crane 2019; see discussion in Maurice *et al.* 2023*b*).

Where tracer tests have been conducted from stream sinks, they have commonly demonstrated very rapid groundwater flows of thousands of metres per day over distances of thousands of metres to springs and borehole abstractions (e.g. Harold 1937; Atkinson and Smith 1974; Banks *et al.* 1995; Maurice *et al.* 2006; Matthews *et al.* 2024). No tracer tests have been conducted from karst features in Dorset (C8 area), but a tracer test from a borehole to a spring indicated a groundwater velocity of ∼100 m/day over ∼400 m (Alexander 1981; Macdonald *et al.* 1998). Recently, work on nitrate responses to precipitation in a Dorset catchment also suggested groundwater velocities of ∼100 m/day (Worthington 2024). Overall, these five Chalk areas (C4, C5, C6, C7 and C8) have strong evidence for karst.

The East Anglia karst

In the East Anglia C3 area (Maurice *et al.* 2023*c*), the Paleogene is present only in the southernmost part of the area, where high densities of stream sinks are present, and karst is similar to that described for the Chalk of southern England above. Much of the area is impacted by glaciation and the Chalk outcrop is largely covered by extensive low permeability till deposits which limit recharge where they are thick. Small diffuse stream sinks or streams with losing reaches commonly occur along the boundary between low permeability till deposits and the Chalk. These are typically less well developed than sinks at the edge of the Paleogene outcrop but significantly influence recharge. Under high discharge conditions, these immature sinks are often overwhelmed, and water continues via ephemeral overflow channels to the main rivers.

Despite the extensive till deposits, there is a surprising amount of evidence for karst in the C3 area. There are caves and conduits exposed in coastal cliffs, widespread palaeokarst, some dolines, and some spring flows >200 l s^{-1}. Pumping tests demonstrate high transmissivities (frequently >1000 m^2/day, occasionally >10 000 m^2/day); and tracer tests demonstrate rapid flows of 14 to > 3800 m/day over distances ranging from 44 to 1650 m, with tracer recoveries varying from 0.05 to 100% (Ward *et al.* 1998).

The Isle of Wight

The Isle of Wight (C9 area, Maurice *et al.* 2022*c*) has the least evidence of karst. Although the Paleogene is present, the steep dip and local topography is such that drainage from the Paleogene outcrop does not flow onto the Chalk. Therefore, the high densities of stream sinks seen along this geological boundary in other areas of southern England do not occur. Only two stream sinks occur on the Isle of Wight where, owing to the steep dip, drainage from the topographically higher Lower Cretaceous strata flows onto the Chalk. There are some signs of karstic processes in some of the coastal caves, but marine erosion is likely to be the main factor responsible for their large dimensions. There are a few dolines and dissolution pipes, small conduits have been observed in quarries and borehole records, and a pumping test transmissivity of >1000 m^2/day has been observed. These suggest some subsurface conduit networks are likely to be present.

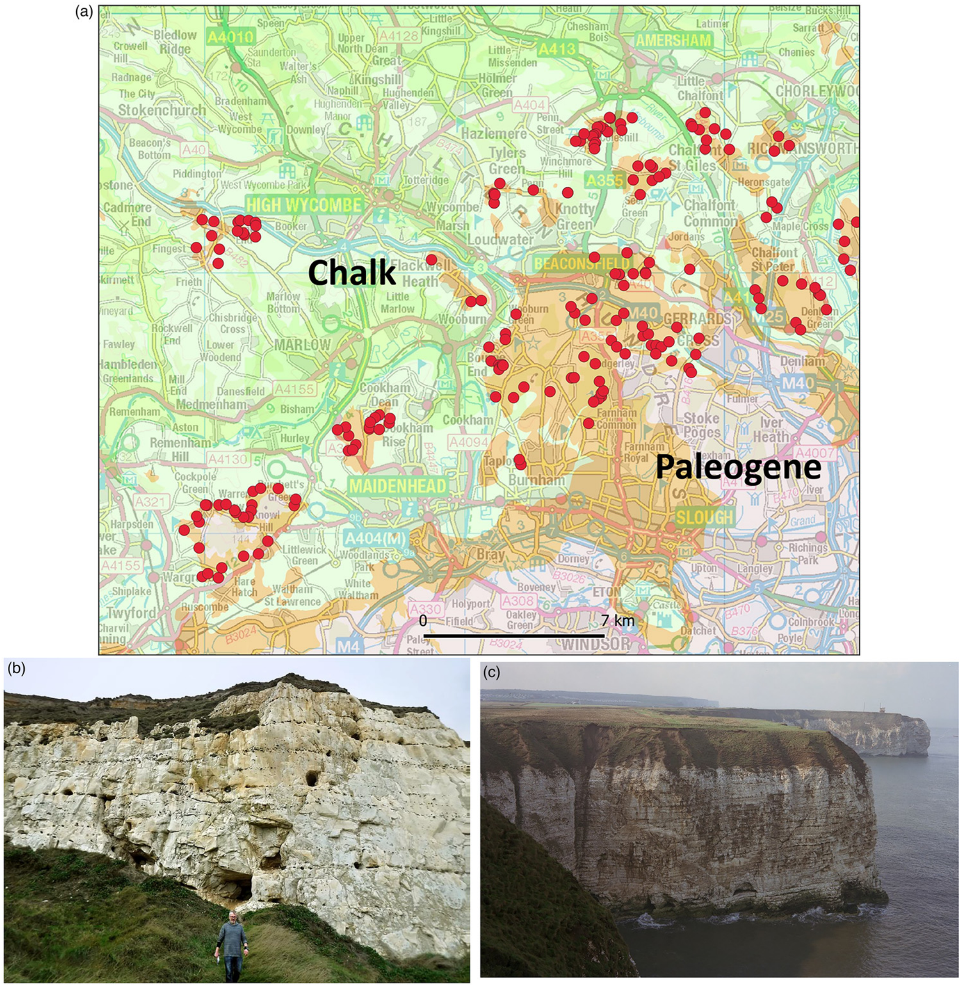

Fig. 2. Karst in the Chalk: (**a**) High density of stream sinks (red circles) along the Chalk–Paleogene contact in the Chiltern Hills, southern England. (**b**) Karst conduits in the Chalk, associated with inception horizons and a fault (Newhaven, South Downs, C7 area, southern England). (**c**) Caves, fissures and dissolution pipes in the Chalk at Flamborough Head, Yorkshire, northern England. Source: (a) contains BGS Geology 50 K data © UKRI 2025. Contains OS data © Crown copyright and database rights 2026. OS AC0000824781. (b) BGS © UKRI 2020. (c) BGS image P006786 © UKRI 1976.

The northern England Chalk karst

In northern England (C1 Yorkshire and C2 Lincolnshire) the geological setting is different due to glaciation and the absence of Paleogene deposits. Consequently, the classic Chalk–Paleogene margin stream sinks are absent, with only occasional stream sinks present where rivers cross the Chalk outcrop or where there is localized runoff from till deposits. Nevertheless, there is considerable evidence for extensive karst networks. For example, pumping tests demonstrate extremely high transmissivities in Yorkshire, sometimes >10 000 m^2/day (Allen *et al.* 1997; and see further discussion in Farrant *et al.* 2016). Tracer tests from boreholes in Yorkshire have proven rapid groundwater flows of hundreds of metres per day over several kilometres (Ward and Williams 1997) and thousands of metres per day over several hundred metres (Skilton and Wheeler 1989), and unsaturated zone tracer tests have demonstrated rapid bypass recharge over vertical distances of 12–38 m (Allshorn *et al.* 2007). In Lincolnshire, a tracer test from a soakaway to a borehole 3.2 km away demonstrated flows of ∼1000 m/day (Robertson *et al.* 1966). Caves and conduits are commonly exposed in Yorkshire coastal cliffs. Whilst the larger caves are due to marine erosion, smaller stratigraphically-guided cave sized relict conduits are visible (Fig. 2c). The cliffs also expose substantial karst dissolution pipes (Fig. 2c).

Chalk karst summary

The Chalk is a karst aquifer with some small-scale cave development, point recharge via stream sinks and riverbeds, rapid groundwater flow, and subsurface karst networks transporting groundwater and contaminants over many kilometres and in sometimes unexpected directions. Geological inception horizons (hardgrounds, flints and marl seams) exert a major influence on the locations of fissure/conduit flow paths (Allen *et al.* 1997; Farrant *et al.* 2021, 2023). Whilst the Chalk is highly vulnerable due to its karstic nature, high matrix porosity and fracture density result in more storage and contaminant attenuation than many karst aquifers (Maurice *et al.* 2023*a*). This is indicated by the typically high baseflows of Chalk-fed rivers (Marsh *et al.* 2000).

The proportion of point recharge and rapid groundwater flow is smaller than in karst aquifers with larger-scale cave development. This was illustrated in a comparative study of 15 karst springs across Europe (Maréchal *et al.* 2021). The UK Bedhampton and Havant Chalk springs (located in Hampshire, in the C7 karst area) have very strong indicators of karst in terms of rapid flow and connectivity to stream sinks; with tracer tests demonstrating flows of ∼2–12 km/day over distances of up to 5.8 km, and high tracer recoveries of up to 70% (Atkinson and Smith 1974; Price 1979). High levels of coliforms and turbidity at the springs following rainfall are comparable to the more classical limestone karst springs from other countries (Maréchal *et al.* 2021). However, most classifications based on spring flow characteristics indicate a lower level of karstification at Bedhampton and Havant than at the other European springs (Maréchal *et al.* 2021). The widely used Mangin (1975) method puts the Bedhampton and Havant springs in the least karstic category, and the discharge has a substantially lower coefficient of variation (0.24 compared to ∼0.8–1 for most of the limestone springs, Maréchal *et al.* 2021). This suggests that although rapid karstic flow occurs to the springs, they are also fed from a large volume of groundwater with a much longer residence time.

Jurassic karst aquifers

The Jurassic outcrop in England is lithologically diverse, with interbedded limestones and mudstones in the Lias Group (Blue Lias Formation), oolitic limestones in the Middle Jurassic Inferior and Great Oolite group (including the Lincolnshire Limestone Formation), and limestones in the Upper Jurassic Corallian, Portland and Purbeck groups. Fracture density and porosity vary significantly, with many of the oolitic limestones having significant matrix porosity. This diversity results in considerable hydrogeological variability.

The northern England Corallian karst

Karst is most extensive in the Upper Jurassic Coralline Oolite Formation in northern England (Report J1, Maurice *et al.* 2022*a*). Rivers crossing the Jurassic limestone outcrop sink (Fig. 3a), with some sinks taking flows of hundreds of litres per second, notably on the River Dove, Hutton Beck, and River Derwent (Foley 2006; Dale and Thomas 2015). These feed large springs (sometimes >700 l s^{-1}), with rapid flow responses and turbidity following precipitation. Significant caves include the 4 km long Excalibur Pot [NGR 471050 487810] karst system (Fig. 3b, c) which takes water from Hutton Beck, and the 436 m long Kirkdale Cave (Dale and Thomas 2015) [NGR 467800 485500]. Tracer velocities estimated from two tests between the Hutton Beck sinks and the spring were 4.5 and 12 km/day (Waters-Marsh 1984; York Caving Club 2014). Further east, in the Derwent valley, tracer tests between sinks and abstraction boreholes and springs also indicated very rapid flows of up to 13 km/day, and over distances of up to 7 km (Foley *et al.* 2012).

The Lincolnshire Jurassic karst

In the Lincolnshire area (Report J2, Mathewson *et al.* 2022), karst is principally developed in the Lincolnshire Limestone Formation (Inferior Oolite Group), with some karst in the Great Oolite Group. There are no known caves, but there is much evidence for karst, notably in the Witham, West Glen and East Glen catchments (Fig. 4a, b) where tracer testing and karst mapping has been conducted (Booker 1977). Solutional conduits with scallops indicating past karstic flows can be observed in quarries (Fig. 4c, d). LiDAR data and field surveys indicate locally high densities of dolines and stream sinks, particularly around the margins of low permeability till deposits (Booker 1977). Some stream sinks have significant flows, e.g. the Easton Wood stream sink [NGR 496800 325900] (Fig. 4e), which can take up to 300 l s^{-1} (Atkinson and Farrant 2015). Several large springs are present (hundreds of litres per second), notably the major artesian spring at Bourne [NGR 509500 324900]. Here, tracer testing revealed very rapid groundwater flows of up to 10 km/day and over distances of up to 11.9 km, spanning different topographical

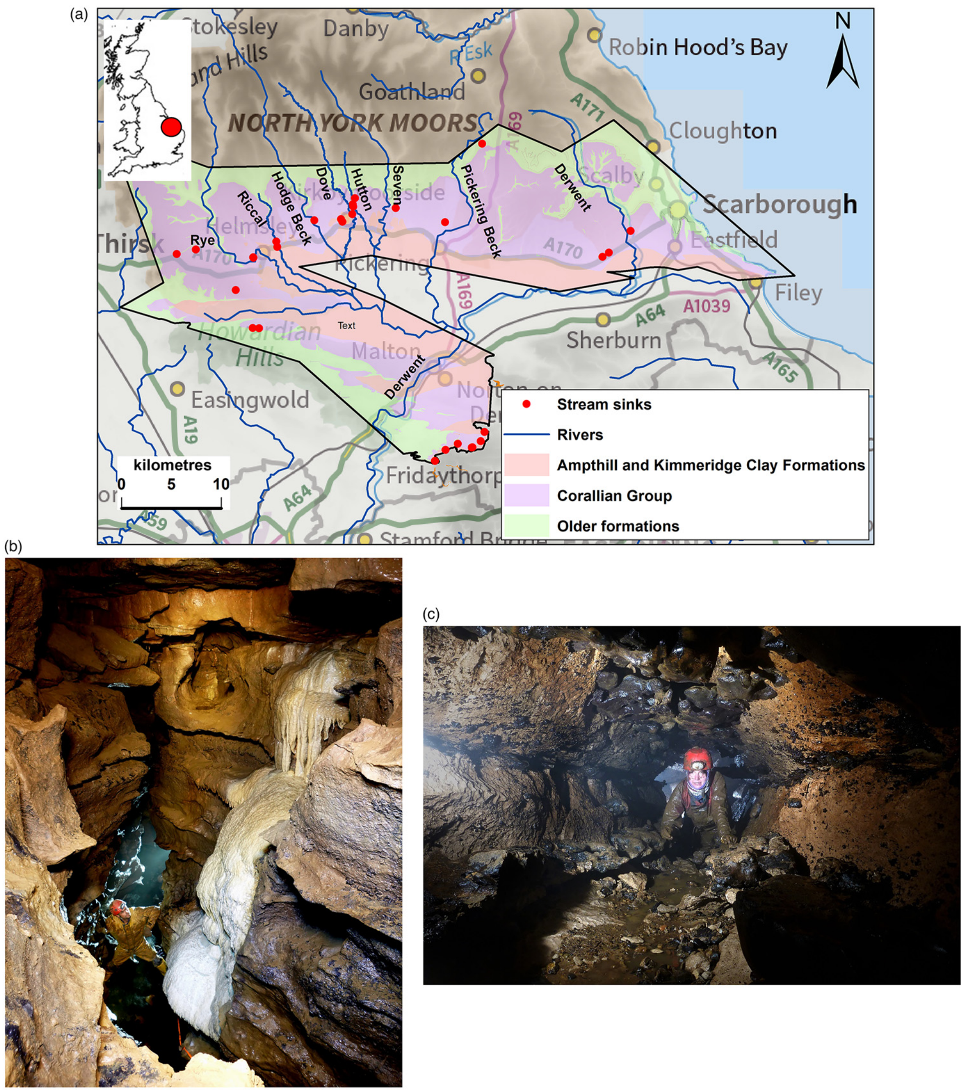

Fig. 3. Karst in the J1 area, Yorkshire, northern England: (**a**) Stream and river sinks (from Maurice *et al.* 2022*a*). (**b**) Flowstone formations in a vadose stream canyon, developed within Upper Jurassic Corallian Group limestones, Excalibur Pot, Hutten Beck. (**c**) 'Chert alley', part of the same karst system. Source: (a) Contains BGS Geology 50 K data © UKRI 2025. Contains OS data © Crown copyright and database rights 2026. OS AC0000824781. (b) Photo by John Dale. (c) Photo by Gary Douthwaite.

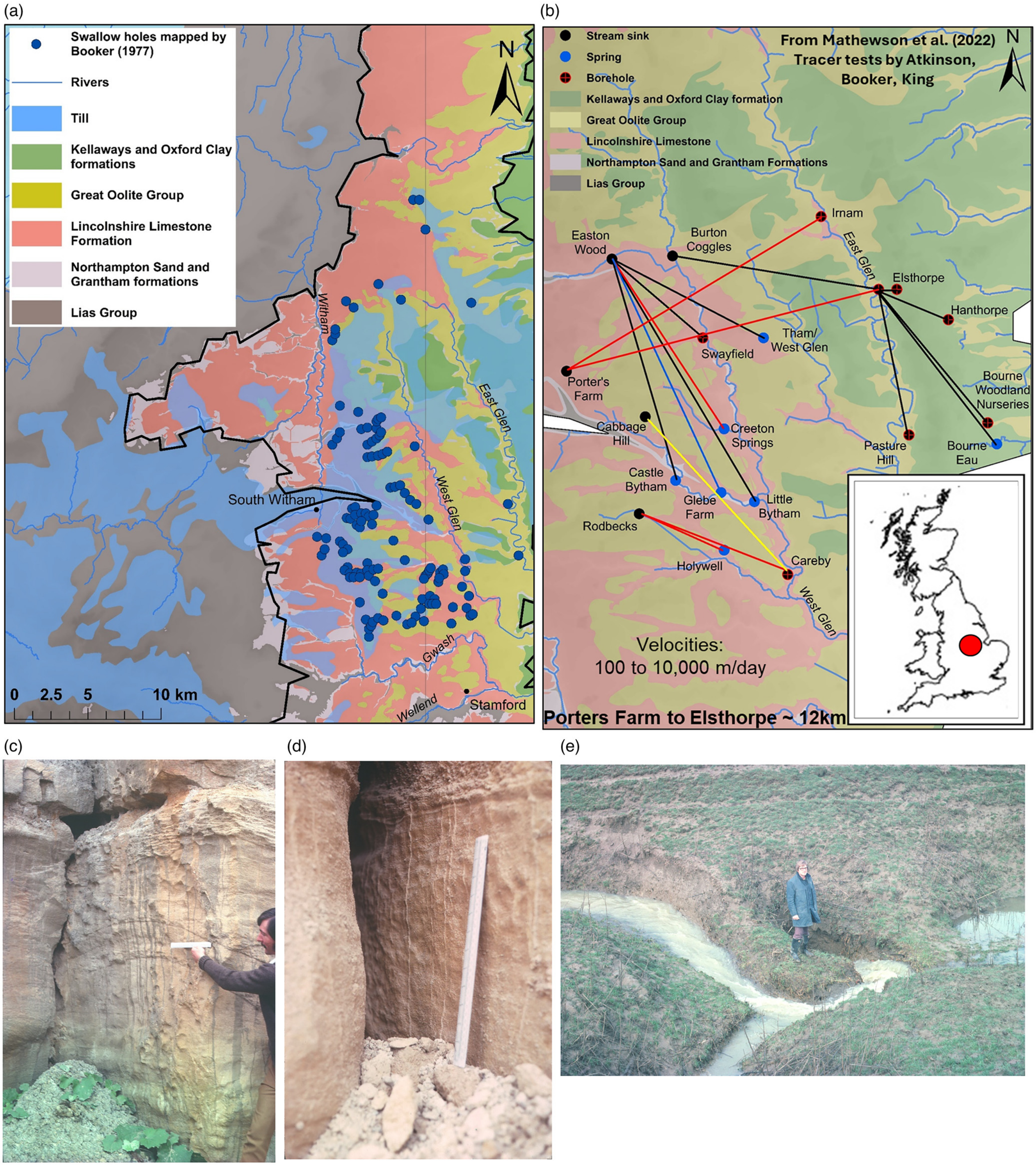

Fig. 4. Karst features in the J2 Lincolnshire area of central England. (**a**) High densities of 'Swallow holes' mapped by Booker (1977), which included both stream sinks and surface depressions. (**b**) Tracer test connections showing complex conduit networks with divergent and convergent flow based on tests conducted by Ian Booker, Emma King, and Tim Atkinson. Inset shows approximate location of the J2 karst area. (**c**, **d**) Solutional fissures/conduits at Medwells Quarry, Clipsham with scallops indicating past turbulent water flow. (**e**) Easton Wood stream sink, Lincolnshire, 1977. Source: from Mathewson *et al.* (2022). Photos by Tim Atkinson. Contains BGS Geology 50 K data © UKRI 2025. Contains OS data © Crown copyright and database rights 2026. OS AC0000824781.

catchments (Fig. 4b). Tracer recoveries of up to 98.6% were recorded (Booker 1977; King 1994; Atkinson and Farrant 2015), but in some tests recoveries were low and, in most tests, there was substantial breakthrough curve tailing (sometimes for up to 100 or 200 days), indicating attenuation in the aquifer via dispersion and diffusion. The rapid tracer velocities and frequent high transmissivities (>1000 m^2/day, and in some places over >10 000 m^2/day) suggest well-developed and complex karstic conduit networks, with divergent and convergent flows. Along the eastern outcrop margin, artesian flows occur within the confined aquifer, including Bourne springs and the 'wild bores' at Aslackby with flows of ~40 l s^{-1} (Barton and Perkins 1994).

Southern England Oolitic limestone karst

Karst features are also developed in the limestones of the Great and Inferior Oolite groups of the Cotswold Hills, extending south of Bath into Somerset and Dorset (Report J3, Maurice *et al.* 2023*d*). Here, karst feature distributions are greatly influenced by the variable lithology, with low permeability mudstones interspersed with well fractured oolitic and bioclastic limestones with significant matrix porosity. Whilst few dissolutional caves are known, stream sinks, dolines and large springs are locally common. Stream and river sink records are shown in Figure 5a. Some of the rivers, have substantial losses where they cross onto the limestones, sometimes via discrete 'swallow holes', and are also fed by large springs (some >100 l s^{-1}) which discharge at the base of the limestone aquifers and/or are associated with faults (Bricker *et al.* 2014). Many rivers display classic karstic winterbourne behaviour, with the seasonal head migrating suddenly up or downstream over distances of hundreds or thousands of metres. Moreover, the aquifer is characterized by rapid responses to rainfall, and responses to pumping over distances of many kilometres (Rushton *et al.* 1992; Allen *et al.* 1997; Bricker *et al.* 2014).

Tracer tests provide additional evidence of karstic groundwater flow. Twenty-nine separate connections, mostly from stream sinks, have been demonstrated (Fig. 5b), with very rapid flows of up to 10 km/day (based on first arrival of tracer), and over distances of up to 5 km (Smart 1977). Tracer recoveries range from 5 to 95%, and tracer continued to be discharged for long periods, indicating attenuation and slower tracer transport. For example, tracer was discharged at one site for 51 days (Smart 1977). Boreholes with high yields of ~100–300 l s^{-1} are also indicative of well-developed solutional networks (Rushton *et al.* 1992). Although pumping tests indicate some transmissivities >1000 m^2/day, many boreholes have lower transmissivity which is thought to be due to the low saturated thickness of the aquifer (Allen *et al.* 1997).

The longest known karst cave in the (J3) region is the 145 m long Cloford Quarry Cave [NGR 371680 144530], which is formed along the unconformity between the classically karstic Carboniferous Clifton Down Limestone Formation and the Inferior Oolite Group (Drew and Smith 1972). This cave formed by water rising from the Carboniferous limestones up into the Inferior Oolite where it dispersed into a network of smaller conduits. The other known cave is the 46 m long Walditch Cave [NGR 348543 092159] near Bridport (Fig. 5c), again in the Inferior Oolite Group (Poole 1988). Most conduit development appears to be on a smaller scale, as seen in rock exposures which commonly dissect solutional fissures and conduits. This is probably due to the high fracture density allowing many flow paths to be enlarged to a small degree rather than a small number of large cave networks, with the high matrix porosity creating a classic triple porosity aquifer (matrix, fracture and conduit).

The Portland and Purbeck Group karst

More extensive caves are known in the Portland and Purbeck Group limestones (J4 area, Fig. 1b), especially on the Isle of Portland (Ford and Hooper 1964; Churcher *et al.* 1970; Cooper *et al.* 1995; O'Connor and Graham 2017). Maps and photographs are available on the Portland Caving website (https://sites.google.com/view/the-caves-of-portland/home, accessed October 2025). Many of these are mass-movement caves but relict phreatic conduit systems are also present, including Sandy Hole [NGR 367990 071245] with over a kilometre of relict phreatic passage. Inland, about 30 stream sinks, some springs and several small caves have been documented in the Portland and Purbeck Group limestones in the Vale of Wardour near Salisbury (Sparrow 1975, 1977; Bristow 1995; Clark and Waters 2002; Hopson *et al.* 2006).

Other southern England Jurassic karst

Karst is known from the Corallian Group limestones of southern England (J5 area, Fig. 1b). There are stream sinks at the boundary between the low permeability Kimmeridge Clay Formation and the Stanford Formation of the Corallian Group around Cumnor Hill to the west of Oxford (Laverty 1983).

In the Bristol–Bath–Mendip Hills area, small caves, stream sinks and large springs are associated with limestones in the Blue Lias Formation and the Langport Member ('White Lias'), in particular associated with the littoral facies around the Mendip Hills (the J6 area, Fig. 1b). There is one notable cave, Welsh's Green Swallet near Wells [NGR 355052 147688] which is 412 m long and 35 m deep (Mendip Cave Registry, https://www.mcra.org.uk/registry/sitedetails.php?id=267, accessed October 2025). There are also stream sinks associated with the boundary of the Charmouth Mudstone Formation and the underlying Langport Member/Blue Lias Formation limestones. Many stream sinks occur along this contact between the Mendip Hills and Bath.

Summary

Overall, the Jurassic karst aquifers of England all have localized point recharge via stream sinks, rapid groundwater flow, and large springs. The degree and style of karst development is strongly influenced by the lithology and fracture density, which dictates the degree of fracture porosity, and the number of potential stratigraphical karst inception horizons.

Permian karst aquifers

Permian rocks crop out in a narrow band in northern England (Fig. 1b) and comprise interbedded evaporites (gypsum/anhydrite), and dolostones/dolomitic limestones (Cadeby and Brotherton formations, formerly known as the Magnesian Limestone) of the Zechstein Group. The evaporite karst is well documented with substantial sinkhole development and severe engineering hazards (Cooper 1998, 2020; Farrant and Cooper 2008). By contrast, hydrogeological information on karst in the carbonate Permian dolomite aquifers (henceforth termed 'Permian carbonates') is less well documented. Nevertheless, karst caves have been reported in the speleological literature (Gibson *et al.* 1976), and the carbonates are karstic (Murphy and Lowe 2021). Karst is documented in two reports covering the northern (P1) and southern (P2) outcrops (Fig. 1b; Maurice *et al.* 2024*a*, *b*). Although there is evidence for karst in both areas, there is more information for the southern part of the outcrop (Fig. 6a).

The distribution of karst features in the Permian carbonates is influenced by two geological factors: (1) the presence of evaporites which are interdigitated with the carbonates causing collapse of the limestones into underlying gypsum karst, as well as hydrogeological connectivity between the gypsum and carbonate aquifers, and (2) the superficial deposit thickness and composition, which vary greatly. Thicker low permeability superficial deposits limit modern day karstic recharge, whilst extensive glacial and fluvioglacial deposits can obscure karst features developed prior to glaciation.

All the known caves in Permian carbonates are dry and represent relict karstic development. The greatest concentration of caves is in the Creswell Crags gorge, with Robin Hood's Cave being the longest at 290 m [NGR 453410 374190]. These are unambiguously karstic caves with obvious dissolutional passages several metres across (Fig. 6b, c), demonstrating that substantial cave-sized conduit

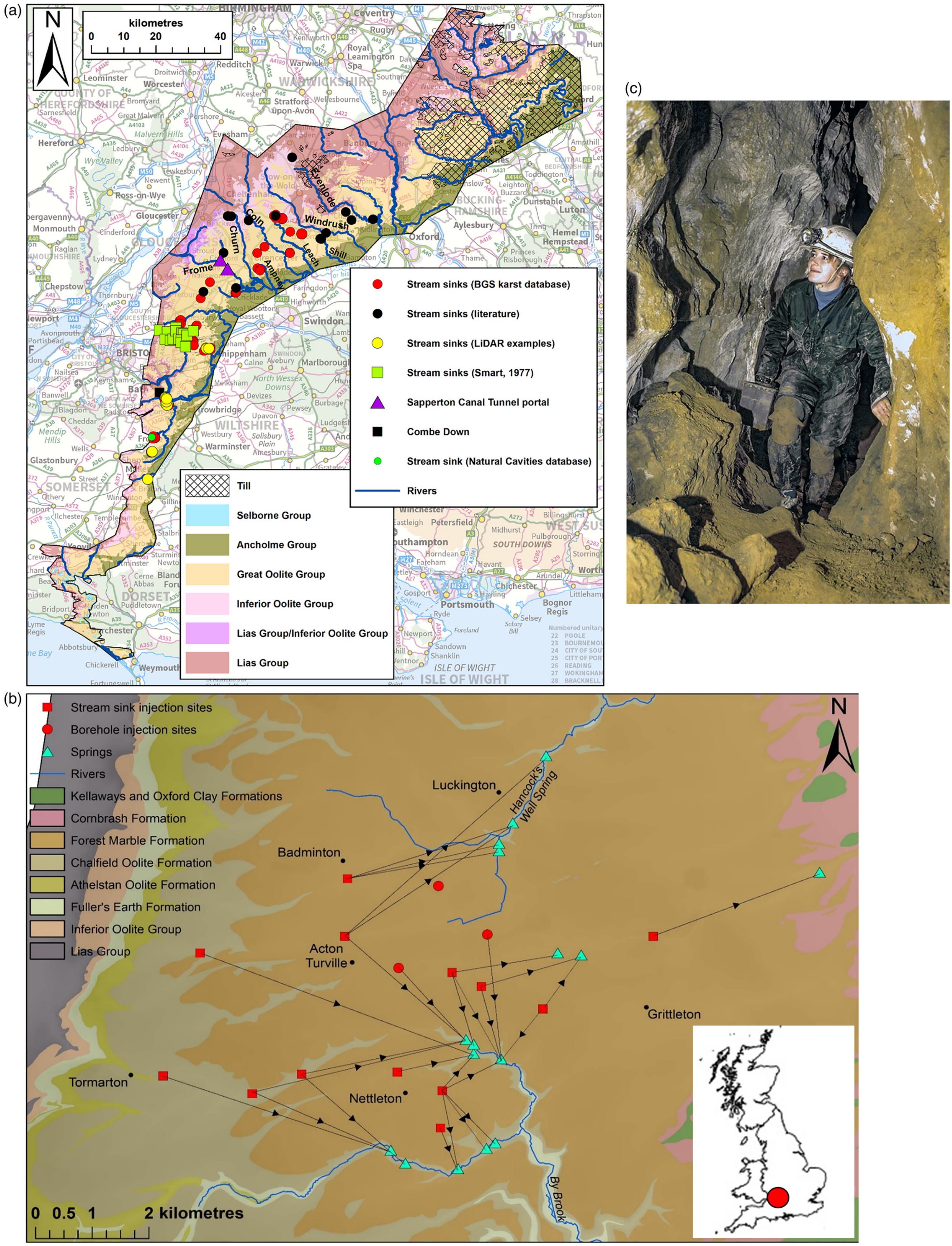

Fig. 5. Karst in the J3 area of southern England. (**a**) Stream and river sinks. (**b**) Tracer connections demonstrated by Smart (1977) in the Cotswold Hills north of Bath. Inset shows approximate location of the J3 area. (**c**) Walditch Cave in the Inferior Oolite Group of southern England. Source: from Maurice *et al.* (2023*d*); photo by Peter Glanvill. Contains BGS Geology 50 K data © UKRI 2025. Contains OS data © Crown copyright and database rights 2026. OS AC0000824781.

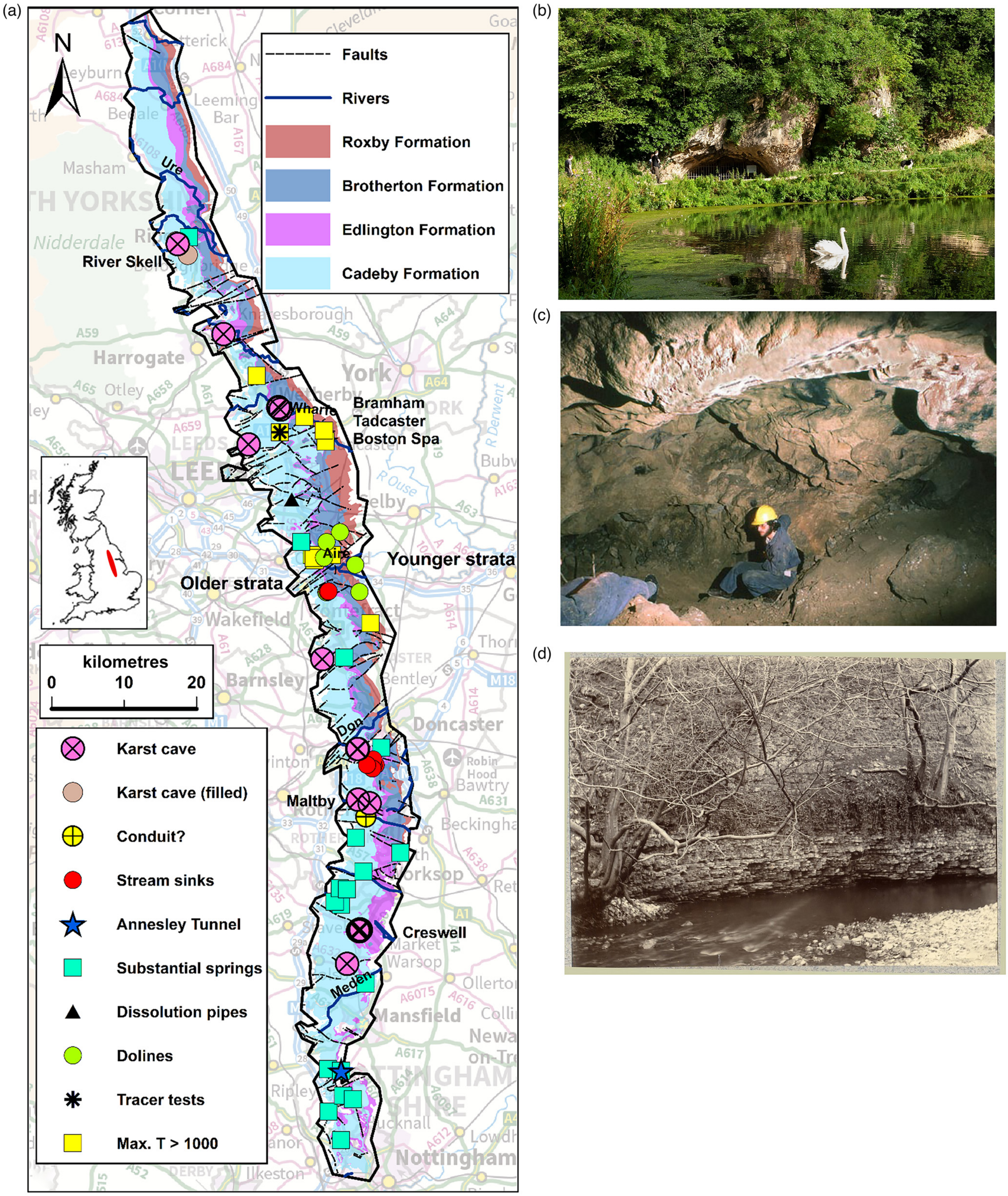

Fig. 6. (**a**) Compilation of karst features and indicators in the carbonates of the P2 area. (**b**) Carbonate karst cave entrance in the Cresswell Gorge. (**c**) Karst phreatic passage in Herne Hill cave. (**d**) Large karst sink into the Cadeby Formation on the River Skell near Ripon. Source: (a) from Maurice *et al.* (2024*b*). Contains BGS Geology 50 K data © UKRI 2025. Contains OS data © Crown copyright and database rights 2026. OS AC0000824781. (b) Geophotos, photo by Tony Waltham. (c) Photo by Pete Ryder. (d) BGS image P236561.

development can occur in the Permian carbonates. It is therefore possible that short hydrologically active conduits of comparable size occur within the aquifer. Some mass-movement 'gull' caves occur where steep sided valleys cross the outcrop, for example at Pleasley Vale [NGR 452000 364900]. Some of these can be hard to distinguish from dissolutional caves.

Stream sinks are locally present, notably in the P2 southern outcrop area along the River Skell (Murphy and Lowe 2021; Fig. 6d), and in Wadworth Woods near Doncaster (Higgins 2018); and in the P1 northern Permian limestone outcrop area along the River Skerne and its tributaries SE of Durham (Burgess 1970; Cairney and Hamill 1977; JBA 2017; Palumbo-Roe *et al.* 2019).

Some of these stream sinks take substantial flows: for example, in dry weather the entire River Skell sinks into its bed [NGR 428470 469132], and the Woodham Burn tributary of the Skerne was reported to lose 50 l s^{-1} (Burgess 1970). Geological settings conducive to stream sink development may include areas of runoff on low permeability superficial deposits or from interbedded mudstones within the Zechstein Group that sink upon reaching the karstic strata.

There is little information on purely carbonate dolines and dissolution pipes. There are reports of a few dolines east of Leeds in the Cadeby Formation below the gypsiferous strata (Murphy 2000, 2003) including dissolution pipes in a quarry at Micklefield [NGR 444130 433671] (Kendall and Wroot 1924). Most known dolines occur in strata above the gypsum-rich Edlington Formation due to dissolution of underlying gypsum, although the solubility of the carbonates may also be a contributing factor (Cooper 1998). Collapse and subsidence related to the gypsum has hydrogeological implications because there is hydrological connectivity between the strata influencing water flow and quality (Cooper *et al.* 2013). Although there are many springs recorded in the Permian carbonates, there is little information on their discharge, and it is unclear whether/where there are large karstic discharge points. Larger springs are likely to include contributions from the gypsum. There are a small number of springs with reported discharges of a few tens of litres per second. A survey of 138 springs on the Permian outcrop in the East Midlands in 1977 (Cradock-Hartop and Steel 1979) showed that most had small flows, with only four with flows of >5 l s^{-1} and the largest with a flow of 72 l s^{-1}. In the north of the outcrop, much of the carbonate outflow may occur through submarine springs that discharge under the North Sea (Younger 1995).

There is further hydrogeological evidence for karst in the Permian carbonates. In the southern P2 outcrop area, rapid groundwater velocities of 13 to 242 m/day were estimated from slug tests at the Leeds University Farm (Medici *et al.* 2019*a*), and modelling the wider area suggested very rapid flows of 9000 m/day (Medici *et al.* 2019*b*). Medici *et al.* (2019*b*) recommend that the low effective porosities (2.8×10^{-4}) determined from borehole hydrogeophysical field studies (and supported by visual evidence of karst from quarry scanline surveys) should be used for modelling the UK Permian limestone aquifer. They suggest that this will enable more reliable estimates of contaminant transport velocities and aquifer vulnerability, which are underestimated with higher effective porosities that do not reflect the karstic nature of the aquifer.

Other evidence of karst comes from an artificial recharge infiltration experiment at a quarry in an excavation 100 m × 50 m × 10 m deep at Thrislington in the northern P1 area [NGR 432150 532580]. An infiltration rate of 12–17 l s^{-1} was easily achieved and demonstrated rapid flow through an unsaturated zone of 30–35 m to a nearby monitoring borehole (Wardrop *et al.* 2012). Additionally, some major inflows have been encountered during tunnel construction. For example, flows >100 l s^{-1} at Annersley (north of Nottingham) in the P2 southern outcrop area (Lamplugh *et al.* 1914), and during construction of the Roker sewer tunnel (near Sunderland in the P1 northern outcrop area) where there were inflows of 8 l s^{-1} despite extensive mitigations to prevent water ingress (Davis and Horswill 2002). Some boreholes have high yield/high transmissivity (Allen *et al.* 1997), also suggesting karstic flows.

Overall, there is substantial evidence that the Permian carbonate aquifers contain karstic networks of conduits and fissures, but the hydrogeology is particularly complex as it is strongly influenced by the gypsum karst, and variability in superficial cover.

Discussion

Comparison of karst aquifers

The evidence presented demonstrates that the Chalk, Jurassic and Permian carbonates contain all the classical karst features; but how do they compare to each other, and to the well-known karst of the Carboniferous limestones which occur in England, Wales, and Northern Ireland and have extensive cave development (Waltham *et al.* 1997)? There are many different ways to classify karst aquifers and assess the degree of karstification (Hakoun *et al.* 2020; Maréchal *et al.* 2021). In the past, it was proposed that UK karstification increases from Cretaceous- (Chalk), to Permian-, to Jurassic-, to Carboniferous-aged carbonates (Atkinson and Smart 1981). Whilst this is broadly reflected by the more recent work, it depends on the spatial scale, and on which karst factor is considered.

Considering the scale of karstification at the country scale, one striking observation is the similarity in groundwater velocities that can be obtained from tracer tests conducted in the different carbonate aquifers (Table 2). Tracer velocities in the Carboniferous limestones are well known to be very rapid, commonly exceeding 1000 m/day (e.g. Atkinson *et al.* 1973; Atkinson 1977; Smart *et al.* 1991; Maurice and Guilford 2011). Whilst there are no data for the Permian, there have been many tracer tests with groundwater velocities exceeding 1000 m/day (exceptionally > 10 000 m/day) over distances of several kilometres (sometimes > 10 km) in the Chalk (e.g. Harold 1937; Banks *et al.* 1995; Maurice *et al.* 2006; Matthews *et al.* 2024) and the Jurassic limestones (e.g. Booker 1977; Smart 1977; King 1994; Foley *et al.* 2012; Atkinson and Farrant 2015).

Karst networks in all these aquifers can develop over scales of kilometres, but the proportion of rapid groundwater flow is likely to differ, which is reflected by the differences in caves and stream sinks (Table 2). The Carboniferous limestones are clearly the most karstic in terms of cave development with many caves >1 km in length.

Table 2. Broad outcrop-scale comparisons between UK carbonate aquifers

Parameter	Aquifer	Scale of karst development
Groundwater velocities (tracer tests)	Carboniferous limestones	>1000 m/day over distances of 1 to >10 km
	Jurassic limestones	>1000 m/day over distances of 1 to >10 km
	Chalk	>1000 m/day over distances of 1 to >10 km
	Permian limestones	? (no data)
Cave development (length)	Carboniferous limestones	Frequent > 1 km
	Jurassic limestones	Occasional > 1 km
	Chalk	Occasional > 100 m; none known > 1000 m
	Permian limestones	Occasional > 100 m; none known > 1000 m
Stream sinks (flows)	Carboniferous limestones	Frequent > 100 l s^{-1}
	Jurassic limestones	Sometimes > 100 l s^{-1}
	Chalk	Occasionally > 100 l s^{-1}
	Permian limestones	Smaller (none known > 100 l s^{-1})

Large stream/river sinks recharging hundreds (sometimes thousands) of litres per second are also common. Although there may be some areas where subsurface conduit development is more limited (Gunn 2015), particularly in areas dominated by autogenic recharge, in general, there is a much higher proportion of rapid point recharge in the Carboniferous limestones compared to the younger carbonates. The possible exception is the Jurassic Corallian Group limestones in the North York Moors (J1 area), where there is more cave development and rapid point recharge.

As in all karst, the UK karst aquifers have triple porosity comprising a rock matrix, an unmodified fracture network, and a solutional conduit/fissure component. One notable difference between the UK karst aquifers is the bedrock matrix porosity which is much higher in the younger carbonates than the Carboniferous limestones (Allen *et al.* 1997). This has important implications for storage of groundwater and for contaminants that can enter the matrix via diffusion (Barker and Foster 1981).

The higher degree of cave development and the larger amount of point recharge via stream/river sinks in the Carboniferous limestones suggest that they are more vulnerable to pollution in terms of the potential for rapid transfer of pollutants from the surface, and for rapid contaminant transport through the aquifer to discharge points. The Chalk, Jurassic and Permian carbonates are less vulnerable in these respects, but with higher potential for contaminant attenuation through dispersion and diffusion, contamination may be more likely to persist for long periods (as observed in the Chalk Hertfordshire bromate plume, Cook *et al.* 2012). The combination of long-distance (scale of multiple kilometres) contaminant transport via karstic networks, and long-term storage of contaminants in the smaller voids may make contaminant management more challenging in these types of karst aquifer.

Whilst there are a few large relict caves >100 m long in the Permian carbonates, and some local stream sink development, much of the carbonate karst appears to be related to the interdigitated gypsum karst. At the national scale, and considering caves and stream sinks, the Carboniferous-aged limestones are clearly the most karstic, and the Jurassic limestones more karstic than the Chalk and Permian limestones which are themselves hard to differentiate (Table 2).

However, considering karst at a regional scale, there is a lot of variation (Fig. 7, Table 3, with further details provided in Supplementary Material). For example, in the Chalk, there are areas with few stream sinks and areas with well-developed stream sinks. Across England, karst in the Jurassic limestones is highly variable, reflecting the different lithologies and geomorphological settings. For example, there are areas with extensive cave development (e.g. J1 in the north, and J4 in the south), and areas with none (the Lincolnshire area J2, and the Corallian limestone of southern England, J5 area). In the Chalk, there are some areas which appear more comparable to the Jurassic limestones (e.g. C4, C6, C7). In other areas there are no or fewer known caves and stream sinks, and recharge is mostly diffuse (the northern and eastern Chalk outcrop of areas C1, C2, and C3). Nevertheless, high transmissivities and /or rapid flows demonstrated by tracer tests in these areas indicate that the subsurface karstic networks are still well developed. At this regional scale, there appears to be more variation within the Jurassic limestones and within the Chalk, than between them (Fig. 7). This variability is also apparent locally within the areas investigated.

Consideration of caves and stream sinks is useful from a hydrogeological perspective: cave development is an indicator of the size of solutional voids, and where extensive cave systems occur, a substantial amount of groundwater flow is through these. This results in faster transport and less contaminant attenuation than in aquifers with little cave development, as well as lower aquifer storage leading to increased susceptibility to droughts and floods. Stream/river sinks can occur with and without extensive cave networks and are useful indicators of the proportion of rapid point recharge to the aquifer and provide evidence of the development of solutional networks of conduits and fissures beneath them, even in the absence of caves. However, in local scale studies it is important to consider a wide range of water quality, hydrogeological and geomorphological karst indicators because each catchment has different combinations of karst indicators present and absent. This can be seen in Figure 7 which shows that the regional patterns in cave development differ from those for stream sinks; for example, there are some areas with large stream sinks ($>100\ \mathrm{l\,s^{-1}}$) but little cave development (e.g. the C4 and J3 areas in Southern England). Other factors show different patterns (Table 3). For

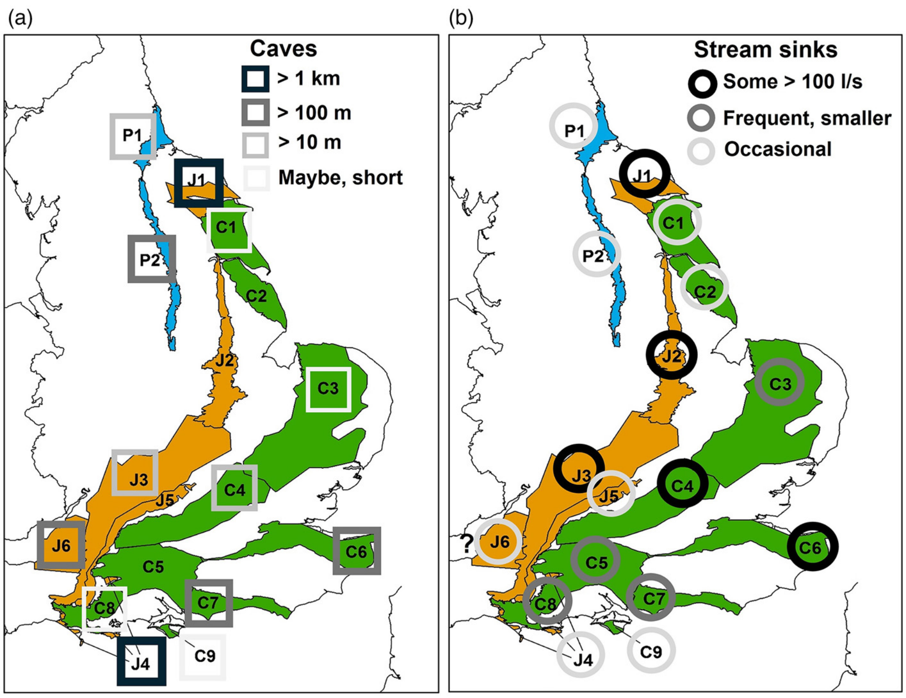

Fig. 7. Spatial variability in the extent of (**a**) maximum known length of cave systems and (**b**) stream sink development in the Chalk and Jurassic and Permian limestones of England. Source: contains OS data © Crown copyright and database rights 2026.

Table 3. Summary of some of the evidence for karst in different areas of the Chalk, Jurassic and Permian carbonates of England

Area	Known karst caves	Known caves > 100 m long	Known caves > 1000 m long	Stream sinks	Stream sinks $> 100\ l\ s^{-1}$	Stream sinks $> 1000\ l\ s^{-1}$	Dolines	Dissolution pipes (buried dolines)	Tracer velocity > 100 m/day	Tracer velocity > 1000 m/day	Tracer velocity > 10 000 m/day	T > $1000\ m^2/day$	T > $10\ 000\ m^2/day$	Springs and/or abstractions $> 100\ l\ s^{-1}$
C1	?	No	No	Rare	No	No	Rare	Rare	Yes	Yes	No	Yes	Yes	Yes
C2	No	No	No	Rare	No	No	Rare	Rare	Yes	Yes	No	Yes	No	Likely
C3	?	No	No	Yes	Unlikely	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
C4	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
C5	No	No	No	Yes	Unknown	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes
C6	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes
C7	Yes	Yes	No	Yes	Unknown	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
C8	?	No	No	Yes	Unknown	No	Yes	Yes	Yes	No$^{\sim}$	No	Yes	Yes	Yes
C9	?	No	No	Rare	No	No	Yes	Rare	No tests	No tests	No tests	Yes	No	No
J1	Yes	Yes	Yes	Yes	Yes	Unknown	Rare	Rare	Yes	Yes	Yes	Yes	Yes	Yes
J2	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
J3	Rare	No*	No	Yes	Yes	No	Yes	Unknown	Yes	Yes	Unknown	Yes	Yes	Yes
J4	Yes	Yes	Yes	Yes	Unknown	Unknown	Yes	Unknown	No tests	No tests	No tests	No$^{\sim}$	No$^{\sim}$	Unknown
J5	No	No	No	Yes	Unknown	Unlikely	Yes	Yes	No tests	No tests	No tests	No data	No data	Unknown
J6	Rare	Yes	No	Yes	Unknown	Unknown	Yes	Yes	No tests	No tests	No tests	No data	No data	Likely
P1	Yes	No	No	Yes	Unlikely	No	Rare^	Rare	No tests	No tests	No tests	Yes	No	Unlikely^
P2	Yes	Yes	No	Yes	Unlikely	No	Rare^	Rare	No tests	No tests	No tests	Yes	No	Unlikely^

T, transmissivity; ?, possible very short karst caves in coastal cliffs; *apart from one cave partly in Carboniferous limestones; ^other than associated with gypsum; $^{\sim}$very little data.

example, in the C8 Dorset Chalk area where there is little/no cave development, there is extensive doline development, and dolines provide an important indicator of karst in this area. By contrast, in the J1 Corallian limestone area where caves and stream sinks are very extensively developed, there appears to be little doline/dissolution pipe development.

It can be concluded that karst features are usually larger and more common in the UK Carboniferous-aged limestones than in the younger Permian, Jurassic and Cretaceous karst aquifers. However, the data suggest that karst features are widespread in these younger carbonate rocks. Whilst cave development may be limited, dolines, stream sinks, dry valleys and indicators of rapid groundwater flow can be common. Although cave development is an important indicator of rapid recharge and subsurface karstic networks, other factors show conduit networks and rapid flow are often present even where caves are absent. In all the carbonate karst aquifers there is considerable variation at regional and local levels, demonstrating the importance of detailed catchment scale karst investigations to determine local hydrogeology.

The importance of karst for groundwater management

It is well established that permeability of the Chalk, Jurassic and Permian carbonates is determined by dissolutionally enlarged fractures (Allen *et al.* 1997). However, in the past they have usually not been considered as karst aquifers. The data presented above demonstrate conclusively that these aquifers are karstic, with karst networks developed over many kilometres. They should be routinely described as karst aquifers, with karst principles used in aquifer characterization and catchment conceptual models. This is because an understanding of karst is relevant to all areas of hydrogeology including: (1) identifying pollution sources; (2) Groundwater Source Protection Zones; (3) sustainable groundwater abstraction; (4) groundwater flooding; and (5) geothermal groundwater.

(1) *Identifying pollution sources:* The transport and attenuation of pollutants through these aquifers depends on the spatial distribution and connectivity of the karstic conduit networks, which are guided by stratigraphical karst inception horizons and geological structure (Farrant *et al.* 2021, 2023), and the history of speleogenesis and karst geomorphological processes within the catchment. Groundwater catchments have highly erratic spatial distributions, leading to challenges in correctly identifying pollution sources or in assessing potential environmental impacts of new developments on groundwater resources and groundwater dependent ecosystems.

(2) *Groundwater Source Protection Zones:* In the UK, Source Protection Zones (SPZs) are a major tool in groundwater protection. The area within which saturated zone flow reaches an abstraction point within 50 days (or a minimum of 50 m if the 50-day travel time is less than 50 m) defines SPZ1, which has the highest level of protection. The area with a 400-day travel time is SPZ 2, and SPZ 3 comprises the remainder of the abstraction catchment (Environment Agency 2019). These zones are generally defined using EPM (equivalent porous medium) groundwater models (Environment Agency 2019). In karst, the locations of these zones depends on where the karstic solutional networks are located and SPZs cannot be accurately delineated using EPM models (Gunn 2007). Therefore, karst specific methods can be used as an alternative to modelling for SPZ delineation for karst sources (Environment Agency 2019). Karst results in groundwater flow from some areas far from abstractions to reach them within 50 days (Fig. 8).

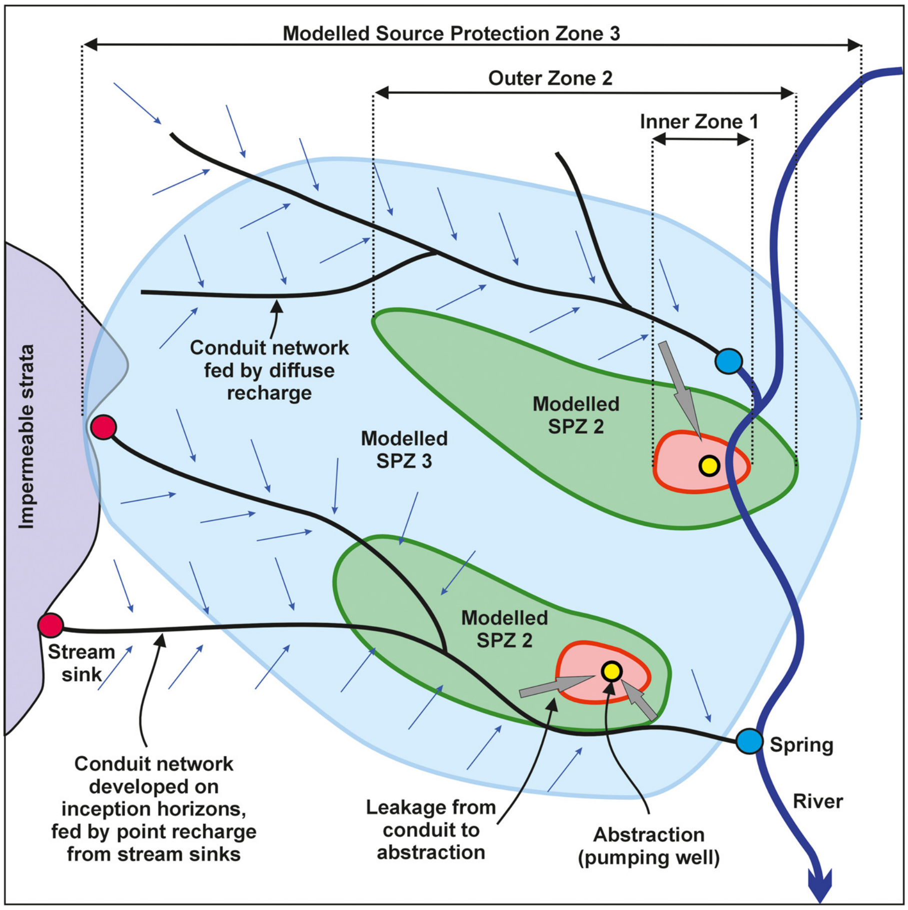

Fig. 8. Conceptualization of the contrast between modelled SPZs, and karstic conduit flowpaths with rapid flows. Building on the standard SPZ conceptualization presented in Environment Agency (2019).

Conversely, there may be areas within a modelled SPZ 1 where groundwater flow is not well connected to a conduit network and is very slow. To identify these zones requires having a good conceptual understanding of karst development, which can occur both with and without active karst stream sinks (Gunn 2007).

(3) *Sustainable groundwater abstraction:* Groundwater abstractions reduce river flows (where they abstract water that would otherwise have discharged to rivers, which is the case in most settings other than where groundwater would have discharged to submarine springs), and they may impact groundwater dependent ecosystems (Owen 1991; Bickerton *et al.* 1993; Wetherell 2023). Abstraction can alter conduit networks, drawing flow away from springs (Matthews 2024). Stratigraphical compartmentalization of an aquifer can help protect surface streams from abstraction at depth if the conduit networks are not well connected to the surface streams (Karapanos *et al.* 2021; Taylor *et al.* 2024). Assessing the impacts of abstraction therefore requires a good understanding of the karstic networks and where the water would have gone under natural conditions.

(4) *Groundwater flooding:* Groundwater flooding in karst aquifers occurs when usually unsaturated conduit networks become active as groundwater levels rise and discharge via springs at higher elevations. In contrast to groundwater flooding in porous aquifers where the water table gradually discharges at higher levels, in karst, this can suddenly occur at locations several kilometres away from the perennial springs (e.g. Hughes *et al.* 2011; Xanke *et al.* 2024) and therefore understanding the controls on the locations of the karst conduits is helpful in understanding and predicting where groundwater flooding will occur. Rapid recharge can trigger the re-activation of unsaturated karst networks, and this has been observed in boreholes which have large groundwater level responses (Lee *et al.* 2006). Incorporating karst conceptualization of conduit flowpath locations and recharge processes should lead to better models of groundwater flooding and enable more effective mitigation strategies.

(5) *Geothermal groundwater:* Karst aquifers provide important geothermal resources in which karstic permeability development is a critical factor (Krumbholz *et al.* 2024).

Karst approaches to groundwater management and protection

Despite the lower proportion of rapid flow and higher potential for contaminant attenuation, the Permian, Jurassic and Cretaceous karst aquifers are highly vulnerable to pollution at or near the ground surface: Point recharge via stream sinks, riverbeds, dolines, and solutional fissures with no surface expression can facilitate rapid contaminant transport into the subsurface. Conduit networks can allow rapid flows of ~1–10 km/day from the surface to a spring or abstraction over distances of many kilometres, sometimes >10 km. Karst results in networks of voids, developed over multiple kilometres, that enable pollutant transport across topographical catchments, and in unexpected directions. Furthermore, determining the locations of these flowpaths is difficult because of the lack of obvious caves that can be mapped, and difficulties in tracer testing in these more attenuating and diluting karst aquifers, where high tracer losses can occur (Maurice *et al.* 2012; Matthews 2024). Nevertheless, the new data and understanding of karst in these aquifers could be used to improve conceptual models to inform groundwater modelling and catchment management. Insights into the locations of the karstic networks that ultimately control permeability and contaminant transport can be gained, and some of the management challenges can be addressed by using karst specific methods and consideration of the geology. Four areas of karst approaches to hydrogeology are discussed here:

(1) *Consideration of surface karst:* Springs are the natural outlets in karst aquifers and are therefore key to catchment conceptual and numerical models. Their location provides information on the outlet of the karstic conduit network and the geological influences on conduit development. Their size (prior to impacts from anthropogenic abstractions) provides an indication of the likely spatial extent of the catchment. Their current discharge is an important component of water balance estimates, whilst water quality and flow variability also provide information on the nature and likely spatial extent of the conduit network. Recording spring locations and discharges is a key part of any groundwater investigation, including concealed groundwater discharges that may be dispersed into alluvial gravel deposits. The latter may be identified through river flow accretion monitoring and/or using geological and karst principles to identify the location of the karst inception horizons and conduits that are likely to be guiding groundwater discharges. Stream sinks are also key factors for conceptual and numerical models, providing information on the locations, nature and amount of point recharge. Water quality of stream sink waters provides key information on contaminant sources. The current work has identified the locations of many large springs and stream sinks, and this new information can be incorporated into regional- and catchment-scale conceptual models. It has also shown that there are some important gaps in UK national karst datasets, particularly in relation to spring and stream sink discharge and their water quality. It is recommended that more detailed desk and field-based investigations of springs and stream sinks are carried out, which should lead to better conceptualization to aid aquifer modelling and management.

(2) *Geology and karst concepts:* Geology (lithology, stratigraphy and geological structure) is a major influence on the spatial distribution of conduit networks (Perrin and Luetscher 2008; Jeannin *et al.* 2013; Farrant *et al.* 2021, 2023). A good understanding of the stratigraphical and structural features guiding conduit developed is critical in hydrogeological investigations of karst aquifers, whilst the interplay with topography is key in determining the aquifer boundary conditions, including the location of stream sinks and springs. This is particularly important in low dip settings like the English Chalk where subtle variations in the degree and direction of dip can radically alter the location of inception horizons and thus potential spring locations. Stream sinks predominantly occur at boundaries between impermeable rocks or sediments and the soluble karst rock, as streams/rivers flowing over impermeable strata sink upon reaching the karst aquifer.

There are two main mechanisms that result in solutional development of primary fractures (joints and faults) and stratigraphical discontinuities (Dreybrodt 1996; Dreybrodt *et al.* 2005; Ford and Williams 2007), which should both be considered in catchment conceptual models. The first is the development of karstic flowpaths fed by point recharge, either via sinking streams or concentrated autogenic recharge through cover strata or superficial deposits. Water entering the aquifer dissolves out certain flow pathways. As the flow rate is strongly dependent on initial fracture aperture, those discontinuities that are slightly wider than others at the start of karstification permit higher flow rates. These wider fractures dissolve faster, attracting even more flow, and therefore grow more rapidly than narrower fractures. The non-linear dissolution kinetics of calcite mean that solutions take a very long time to approach saturation, enabling solutional enlargement to penetrate further into the subsurface. Through time these pathways are slowly extended and once a pathway connects through to a spring ('breakthrough'), more rapid dissolution eventually forms fully connected networks of self-organized karstic solutional voids between stream sinks and springs (Dreybrodt 1996; Dreybrodt *et al.* 2005; Ford and Williams 2007; Worthington and Ford 2009). The time it takes to achieve breakthrough is dependent on fracture density, spacing and connectivity, and the degree of matrix porosity. The second mechanism is mixing corrosion (Bögli 1964), which is particularly important in well fractured aquifers or those with significant matrix porosity. This occurs where two groundwaters that are saturated with respect to calcite but with different pCO_2, mix. This generates an undersaturated solution, enabling further dissolution (Bögli 1964; Dreybrodt *et al.* 2010). Mixing corrosion is often concentrated along stratigraphical discontinuities which allow water from different sources to mix. This can occur at depth over long periods of time and helps generate secondary permeability which can be utilized by later conduit development. These processes enable the formation of solutional conduits and fissures within the aquifer, including in areas away from surface karst stream sinks and at depth (Farrant *et al.* 2021, 2023).

Karst inception horizons (Lowe 1992; Filipponi *et al.* 2009) are particularly important in determining where solutional voids develop, and how well connected they are. They are typically lithological horizons which are more susceptible to dissolution, either because they are particularly soluble or contain *in situ* sources of acidity, or because they are located on a low permeability horizon which results in the concentration of flow above, or they allow mixing of saturated solutions facilitating dissolution. The distribution and density of stratigraphical discontinuities and primary fractures also influence where and how karstic permeability is developed. This can lead to stratigraphical compartmentalization of an aquifer leading to significant vertical heterogeneity. This is apparent in the Chalk aquifer of the Chiltern Hills (Karapanos *et al.* 2021; Marsili *et al.* 2023). The development of high transmissivity zones along marl seams which act as inception horizons in the New Pit Chalk Formation has led to artesian conditions in boreholes, with the overlying lower permeability Chalk acting as a partially confining unit (Marsili *et al.* 2023). Understanding the differences in flows at different stratigraphical levels is therefore another important factor when delineating catchments. Faults and joints can also be important, providing flow pathways that can be enlarged by dissolution, and facilitating vertical flow between inception horizons. Faults can sometimes create barriers to groundwater flow where they are impermeable, which may result in concentration of flow and karstification next to the barrier.

All these geological factors are key to catchment and regional scale conceptual hydrogeological models. Some groundwater models have incorporated some of these concepts. For example, Medici *et al.* (2019*b*) used a pipe network within an EPM model to represent karst features in the Permian limestones identified from field studies. Soley *et al.* (2012) developed a sophisticated conceptual model of the Wessex area of Southern England and used the MODFLOW-VKD code to represent zones of enhanced permeability associated with some of the major Chalk inception horizons in the regional groundwater model. The model was able to simulate many borehole groundwater levels and river flows quite well, although there were also sites where simulated flows or water levels were substantially different to observed data. This is perhaps unsurprising given the complexity of the karst in this area (Maurice *et al.* 2023*b*). However, many groundwater models used for the English carbonates do not include stream sink recharge and karstic conduit flow, and some are modelled as a single aquifer layer (e.g. Karapanos *et al.* (2021) note that the karstic Chilterns area of the Chalk is modelled as a single layer). It is challenging to represent karst in groundwater modelling (Jeannin *et al.* 2013, 2021), and to identify karstic flowpaths in the Chalk, Jurassic and Permian carbonates. However, the new data and understanding of karst in these aquifers offers an opportunity for better integration of karst data and concepts which should result in advances in both modelling and karst understanding. The KARSYS approach (Jeannin *et al.* 2013) was developed specifically to integrate geology and karst into groundwater models, and developing and adapting this for the UK carbonate karst aquifers could potentially yield useful results.

(3) *Tracer tests and borehole studies:* Tracer tests are a key tool in catchment delineation in karst (Gunn 2007). Whilst there are challenges in conducting tracer tests where there is high dilution and attenuation, the tracer test data compiled in the BGS karst reports show that there have been many successful tests in the Chalk and Jurassic limestones which have proved connections. Nevertheless, only a very small proportion of stream sinks in these aquifers have been tested with tracers, and more tracer testing would lead to substantially improved understanding of karstic networks. Successful catchment-scale tracer tests can also be conducted in these aquifers from boreholes. These types of tests are useful where there is good conceptual understanding suggesting a connection between a borehole and a spring or abstraction which can be tested with tracers. In this case, single borehole dilution testing should be conducted first in the injection borehole to identify suitable outflowing horizons that can be targeted in the larger scale tracer test. Single borehole dilution testing and/or geophysical logging, combined with borehole imaging, are also useful tools for investigating inception horizons and conduits formed by mixing dissolution (Schurch and Buckley 2002; Maurice *et al.* 2012).

Groundwater velocities and the directions of groundwater flowpaths can vary substantially under different flow conditions (Stanton and Smart 1981; Gunn 2017), and therefore conducting multiple tracer tests from the same injection point is recommended.

(4) *Vulnerability assessments:* In karst aquifers, an intrinsic vulnerability assessment approach to groundwater protection and catchment management may be more appropriate than groundwater modelling (Dörfliger *et al.* 1999; Pochon *et al.* 2008). In Europe, methods have been developed to assess the vulnerability of an individual

spring or abstraction to determine what type of protection/ catchment management measures are most appropriate for that site (e.g. Pochon *et al.* 2008; Sinreich *et al.* 2014). A similar type of karst classification system has been developed and tested on 20 chalk borehole abstractions in southern England (Maréchal *et al.* 2021). The method was based on scores relating to surface karst and caves in the catchment, conduits intercepted by the borehole, water quality indicators of rapid flow and maximum coliform counts in the borehole water, tracer tests, and transmissivity. Results for the 20 abstractions were highly variable, suggesting that the method is useful for differentiating between sites with higher and lower vulnerability due to karst. The method could be usefully applied more widely and used to inform site specific groundwater protection and management strategies.

Other methods determine spatial variations in intrinsic vulnerability across catchment areas to enable catchment management or groundwater protection to be targeted at the more vulnerable parts of the catchment, overcoming the problem of not knowing exactly where the conduit networks are (e.g. Dörfliger *et al.* 1999; Ravbar and Goldscheider 2009). These have been widely applied in Europe, including for SPZ area delineation. Given the data compilation and new understanding of karst in the Chalk, Jurassic and Permian carbonates, the development of a new karst-based vulnerability assessment method tailored to these aquifers could be complimentary to the general groundwater vulnerability mapping approach (Environment Agency 2017), and a useful means of incorporating conceptual understanding of karst into groundwater management. For the English Chalk a catchment vulnerability approach was developed by Edmonds (2008*b*). More recently a catchment intrinsic vulnerability approach was developed to create a domains map of the Chalk Group in southern England (Solent and South Downs area). This used six factors to produce five domains with varying likelihood of rapid flow in the unsaturated zone across the area (Cullen-Gow *et al.* 2022). This type of approach could be developed further to contribute to Source Protection Zone delineation, particularly for abstractions identified as having high vulnerability due to karst, using the site specific vulnerability assessment. Delineation of Source Protection Zones is particularly challenging in karst aquifers (Gunn 2007; Environment Agency 2019; Maurice *et al.* 2023*a*). Entire catchment areas are likely to have some flow that occurs within 50 days resulting in extremely large SPZ1 areas, which could be reduced using a catchment intrinsic vulnerability approach.

Conclusions and future research

There is unequivocal evidence that the Chalk, Jurassic and Permian carbonates of England are karst aquifers with rapid flow, and karst features including caves, stream sinks and dolines. Springs and abstractions can have flows and yields of hundreds of litres per second indicating karst flowpaths developed over multi-kilometre scales (which has been confirmed at some sites by tracer tests from stream sinks or from boreholes). These aquifers can therefore be highly vulnerable to pollution through direct recharge via stream sinks and more broadly in areas where protective cover is absent. With the possible exception of the Corallian limestones of Yorkshire, they have substantially less cave development and generally lower proportions of rapid recharge and flow than the UK Carboniferous limestones. They also have greater matrix porosity, and higher fracture density providing many alternative flow pathways. There are therefore more opportunities for attenuation via flow and storage in smaller voids, and through dispersion and diffusion of contaminants.

The proportions of point recharge and rapid groundwater flow vary substantially at large and small spatial scales. This demonstrates the need for karst investigations (tracer tests, borehole studies, water balance, and better conceptual models of groundwater flow incorporating karst data and understanding) in local and catchment scale studies in these aquifers.

Given the karstic nature of these aquifers, further development of karst specific methods of management and protection would be beneficial. This might include the application of the Environment Agency (2019) method of delineating Source Protection Zones in karst aquifers (not currently applied for most Chalk and Jurassic abstractions where SPZs are defined using EPM models); and karst intrinsic vulnerability approaches for assessing how much a spring or abstraction borehole is likely to be impacted by karst, and/or for identifying areas of higher and lower vulnerability/likelihood of rapid recharge within a catchment.

Other key knowledge gaps for future research include developing better understanding of the proportion of rapid recharge in these aquifers and how this varies. Better datasets are needed on locations and flows of stream sinks, losing/gaining rivers, and springs. Data on stream sink quality are currently rare. The spatial distribution and extent of high transmissivity zones formed by mixing dissolution along inception horizons also remains poorly understood. Another potential avenue is to consider how to integrate karst, geology, and groundwater information; for example, developing the KARSYS approach to groundwater modelling (Jeannin *et al.* 2013) or something similar, for application in these types of karst aquifer. Tracer testing remains a key tool for proving groundwater connections, but more sensitive tracer testing techniques that can prove connections in highly attenuating/diluting situations are needed. Developing methodologies to reduce the cost and risk of tracer experiments would help improve the uptake of this technique.

Karst aquifers with limited cave development are perhaps an area of karst science that has been somewhat neglected, yet these are some of the most important aquifers for public water supply. They pose particular challenges in characterization and management. With increasing water resource quantity and quality challenges, karst approaches offer new opportunities to improve groundwater management and protection.

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Data availability Requests for the data used to support the findings of this study should be made to the British Geological Survey.

References

Alexander, L.S. 1981. *The Hydrogeology of the Chalk of South Dorset*. Unpublished PhD thesis, University of Bristol.

Allen, D.J. and Crane, E.J. (eds) 2019. *The Chalk Aquifer of the Wessex Basin*. British Geological Survey Research Report **RR/11/002**.

Allen, D.J., Brewerton, L.T. *et al.* 1997. *The Physical Properties of Major Aquifers in England and Wales*. British Geological Survey Technical Report **WD/97/34**. Environment Agency R&D Publication 8.

Allshorn, S.J.L., Bottrell, S.H., West, L.J. and Odling, N.E. 2007. Rapid karstic bypass flow in the unsaturated zone of the Yorkshire chalk aquifer and implications for contaminant transport. *Geological Society, London, Special Publications*, **279**, 111–122, https://doi.org/10.1144/SP279.10

Atkinson, T.C. 1977. Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). *Journal of Hydrology*, **35**, 93–110, https://doi.org/10.1016/0022-1694(77)90079-8

Atkinson, T.C. and Farrant, A.R. 2015. *Field Excursion to the Lincolnshire Limestone: Karst Development, Source Protection and Landscape History*, https://nora.nerc.ac.uk/id/eprint/511288/

Atkinson, T.C. and Smart, P.L. 1981. Artificial tracers in hydrogeology. *In:* Argent, C.R. and Griffin, D.J.H. (eds) *A Survey of British Hydrogeology 1980*. Royal Society, London, 173–190.

Atkinson, T.C. and Smith, D.I. 1974. Rapid groundwater flow in fissures in the Chalk: an example from South Hampshire. *Quarterly Journal of Engineering Geology*, **7**, 197–205, https://doi.org/10.1144/GSL.QJEG.1974.007.02.05

Atkinson, T.C., Smith, D.I., Lavis, J.J. and Whitaker, R.J. 1973. Experiments in tracing underground waters in limestones. *Journal of Hydrology*, **19**, 323–349, https://doi.org/10.1016/0022-1694(73)90106-6

Ballesteros, D., Farrant, A., Nehme, C., Woods, M., Todisco, D. and Mouralis, D. 2020. Stratigraphical influence on chalk cave development in Upper Normandy, France: implications for chalk hydrogeology. *International Journal of Speleology*, **49**, 187–208, https://doi.org/10.5038/1827-806X.49.3.2319

Banks, D., Davies, C. and Davies, W. 1995. The Chalk as a karstic aquifer: evidence from a tracer test at Stanford Dingley, Berkshire, UK. *Quarterly Journal of Engineering Geology*, **28**, S31–S38, https://doi.org/10.1144/GSL.QJEGH.1995.028.S1.03

Barker, J.A. and Foster, S.S.D. 1981. A diffusion exchange model for solute movement in fissured porous rock. *Quarterly Journal of Engineering Geology and Hydrogeology*, **14**, 17–24, https://doi.org/10.1144/GSL.QJEG.1981.014.01.02

Barnes, S. 1999. Karstic groundwater flow characteristics in the Cretaceous Chalk aquifer, Northern Ireland. *Quarterly Journal of Engineering Geology*, **32**, 55–68, https://doi.org/10.1144/GSL.QJEG.1999.032.P1.04

Barton, B.M.J. and Perkins, M.A. 1994. Controlling the artesian boreholes of the South Lincolnshire Limestone. *Water and Environment Journal*, **8**, 183–196, https://doi.org/10.1111/j.1747-6593.1994.tb00911.x

Bickerton, M., Petts, G., Armitage, P. and Castella, E. 1993. Assessing the ecological effects of groundwater abstraction on chalk streams: three examples from eastern England. *Regulated Rivers: Research & Management*, **8**, 121–134, https://doi.org/10.1002/rrr.3450080115

Bögli, A. 1964. Corrosion par mélange des eaux. *International Journal of Speleology*, **1**, 61–70, https://doi.org/10.5038/1827-806X.1.1.9

Booker, I.R. 1977. *The Significance of Swallow Holes in the Hydrology of the Southern Lincolnshire Limestone*. Progress Report to University of East Anglia 1976–1977.

Bricker, S.H., Barron, A.J.M., Hughes, A.G., Jackson, C. and Peach, D. 2014. From geological complexity to hydrogeological understanding using an integrated 3D conceptual modelling approach–insights from the Cotswolds, UK. *In:* Sharp, J.M. (ed.) *Fractured Rock Hydrogeology*. CRC Press, London, 99–114.

Bristow, C.R. 1995. *Geology of the Tisbury District (Wiltshire)*. British Geological Survey Technical Report **WA/95/82**.

Burgess, A.S. 1970. *Engineering Geology and Geohydrology of the Magnesian Limestone of Northern England*. PhD thesis, Durham University.

Cairney, T. and Hamill, L. 1977. Interconnection of surface and underground water resources in south-east Durham. *Journal of Hydrology*, **33**, 73–86, https://doi.org/10.1016/0022-1694(77)90099-3

Churcher, R.A., Butler, B. and Bartlett, P.D. 1970. A further report on the caves of the Isle of Portland. *Transactions of the Cave Research Group of Great Britain*, **12**, 291–298.

Clark, H. and Waters, E. 2002. The Karst of the Wardour Vale. *Shepton Mallet Caving Club Journal*, **II**, 62–74.

Cook, S.J., Fitzpatrick, C.M., Burgess, W.G., Lytton, L., Bishop, P. and Sage, R. 2012. Modelling the influence of solution-enhanced conduits on catchment-scale contaminant transport in the Hertfordshire Chalk Aquifer. *Geological Society, London, Special Publications*, **364**, 205–225, https://doi.org/10.1144/SP364.14

Cooper, A.H. 1998. Subsidence hazards caused by the dissolution of Permian gypsum in England: geology, investigation and remediation. *Geological Society, London, Engineering Geology Special Publications*, **15**, 265–275, https://doi.org/10.1144/GSL.ENG.1998.015.01.27

Cooper, A.H. 2020. Geohazards caused by gypsum and anhydrite in the UK: including dissolution, subsidence, sinkholes and heave. *Geological Society, London, Engineering Geology Special Publications*, **29**, 403–423, https://doi.org/10.1144/EGSP29.16

Cooper, R.G., Graham, N. and Read, M. 1995. Solutional cave passages intersected by mass movement rifts in the Isle of Portland, Dorset. *Studies in Speleology*, **10**, 29–35.

Cooper, A.H., Odling, N.E., Murphy, P.J., Miller, C., Greenwood, C.J. and Brown, D.S. 2013. The role of sulphate-rich springs and groundwater in the formation of sinkholes over gypsum in eastern England. *In:* Land, L., Stephenson, D.H. and Brad, J. (eds) Sinkholes and the Engineering and Environmental Impacts of Karst: Proceedings of the Thirteenth Multidisciplinary Conference, May 6–10, 2013, Carlsbad, New Mexico. National Cave and Karst Research Institute (NCKRI), Carlsbad, New Mexico, 141–150.

Cradock-Hartopp, M.A. and Steel, M.A. 1979. *Spring Survey of the Magnesian Limestones of the East Midlands*. Institute of Geological Sciences Hydrogeological Department Report No. **WD/79/1**.

Cullen-Gow, H., Farrant, A.R., Richardson, J, Maurice, L. and McKEnzie, A. 2022. *User Guide: BGS Conceptual Domains for Rapid Karstic Groundwater Flow in the Unsaturated Zone Dataset*. BGS Open Report **OR/22/031**.

Dale, J. and Thomas, C. 2015. Chapter 33: caves of the North York Moors. *In:* Waltham, T. and Lowe, D. (eds) *Caves and Karst of the Yorkshire Dales*, **2**. British Cave Research Association, Buxton, 33.1–33.13.

Davis, G.M. and Horswill, P. 2002. Groundwater control and stability in an excavation in Magnesian Limestone near Sunderland, NE England. *Engineering Geology*, **66**, 1–18, https://doi.org/10.1016/S0013-7952(01)00100-4

Dörfliger, N., Jeannin, P.-Y. and Zwahlen, F. 1999. Water vulnerability assessment in karst environments: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). *Environmental Geology*, **39**, 165–176, https://doi.org/10.1007/s002540050446

Drew, D.P. and Smith, D.I. 1972. An unconformity cave: Cloford Quarry, Eastern Mendip, Somerset. *Proceedings of the University of Bristol Spelæological Society*, **13**, 89–104.

Dreybrodt, W. 1996. Principles of early development of karst conduits under natural and man-made conditions revealed by mathematical analysis of numerical models. *Water Resources Research*, **32**, 2923–2935, https://doi.org/10.1029/96WR01332

Dreybrodt, W., Gabrovšek, F. and Romanov, D. 2005. *Processes of Speleogenesis: A Modelling Approach*. Karst Research Institute at ZRC SAZU, ZRC Publishing, Lubljana.

Dreybrodt, W., Romanov, D. and Kaufmann, G. 2010. Evolution of caves in porous limestone by mixing corrosion: a model approach. *Geologia Croatica*, **63**, 129–135, https://doi.org/10.4154/gc.2010.09

Edmonds, C.N. 1983. Towards the prediction of subsidence risk upon the Chalk outcrop. *Quarterly Journal of Engineering Geology and Hydrogeology*, **16**, 261–266, https://doi.org/10.1144/GSL.QJEG.1983.016.04.03

Edmonds, C.N. 2008*a*. Karst and mining geohazards with particular reference to the Chalk outcrop, England. *Quarterly Journal of Engineering Geology and Hydrogeology*, **41**, 261–278, https://doi.org/10.1144/1470-9236/07-206

Edmonds, C. 2008*b*. Improved groundwater vulnerability mapping for the karstic chalk aquifer of southeast England. *Engineering Geology*, **99**, 95–108, https://doi.org/10.1016/j.enggeo.2007.11.019

El Janyani, S., Dupont, J.P., Massei, N., Slimani, S. and Dörfliger, N. 2014. Hydrological role of karst in the Chalk aquifer of Upper Normandy, France. *Hydrogeology Journal*, **22**, 663–677, https://doi.org/10.1007/s10040-013-1083-z

Environment Agency 2017. *New Groundwater Vulnerability Mapping Methodology in England and Wales Report* **SC040016/R**.

Environment Agency 2019. *Manual for the Production of Groundwater Source Protection Zones*. March 2019.

Farrant, A.R. and Cooper, A.H. 2008. Karst geohazards in the UK: the use of digital data for hazard management. *Quarterly Journal of Engineering Geology and Hydrogeology*, **41**, 339–356, https://doi.org/10.1144/1470-9236/07-201

Farrant, A.R., Woods, M.A., Maurice, L., Haslam, R., Raines, M. and Kendall, R. 2016. *Geology of the Kilham Area and Its Influence on Groundwater Flow*. British Geological Survey Commissioned Report **CR/16/023**.

Farrant, A.R., Maurice, L.D., Mathewson, E., Ascott, M., Earl, G., Wilkinson, D. and Howe, S. 2021. Caves and karst of the Chalk in East Sussex, UK: implications for groundwater management. *Cave and Karst Science*, **48**, 65–83, https://bcra.org.uk/pub/candks/index.html?j=143

Farrant, A.R., Maurice, L., Ballesteros, D. and Nehme, C. 2023. The genesis and evolution of karstic conduit systems in the Chalk. *Geological Society, London, Special Publications*, **517**, 15–37, https://doi.org/10.1144/SP517-2020-126

Filipponi, M., Jeannin, P.Y. and Tacher, L. 2009. Evidence of inception horizons in karst conduit networks. *Geomorphology*, **106**, 86–99, https://doi.org/10.1016/j.geomorph.2008.09.010

Foley, A.E. 2006. *The Use and Development of Some Groundwater Tracing Techniques for Wellhead Protection: Studies From the Corallian Limestone of Yorkshire*. PhD thesis, University College London.

Foley, A.E. and Worthington, S.R. 2023. Advances in conceptualizing transport in chalk aquifers. *Geological Society, London, Special Publications*, **517**, 75–91, https://doi.org/10.1144/SP517-2020-173

Foley, A., Cachandt, G., Franklin, J., Willmore, F. and Atkinson, T. 2012. Tracer tests and the structure of permeability in the Corallian limestone aquifer of norther England, UK. *Hydrogeology Journal*, **20**, 483–498, https://doi.org/10.1007/s10040-012-0830-x

Ford, T.D. and Hooper, M.J. 1964. The caves of the Isle of Portland. *Transactions of the Cave Research Group of Great Britain*, **7**, 13–37.

Ford, D.C. and Williams, P.W. 2007. *Karst Hydrogeology and Geomorphology*. John Wiley and Sons.

Gibson, R., Bliss, M. and Shackleton, R. 1976. Caves of the Magnesian limestone. *Yorkshire Subterranean Society Journal*, **1**, 9–22.

Gunn, J. 2007. Contributory area definition for groundwater source protection and hazard mitigation in carbonate aquifers. *Geological Society, London, Special Publications*, **279**, 97–109, https://doi.org/10.1144/SP279.9

Gunn, J. 2015. *Groundwater in Carboniferous Carbonates: Field Excursion to the Derbyshire 'White Peak' District 26th June 2015*. International Conference on Groundwater in Karst, 20–26 June 2015, Birmingham, https://nora.nerc.ac.uk/id/eprint/511287/1/KG%40B%202015%20Carboniferous%20field%20guide.pdf

Gunn, J. 2017. Karst conduit complexity demonstrated by a dye tracing experiment from Rowter Hole, Castleton, Derbyshire, UK. *Cave and Karst Science*, **44**, 99–108, https://bcra.org.uk/pub/candks/index.html?j=132

Hakoun, V., Bailly-Comte, V. *et al.* 2020. *Karst Typology in Europe: State of the Art*. GeoERA RESOURCE project Deliverable 5.1.

Harold, C. 1937. *The Flow and Bacteriology of Underground Water in the Lee Valley*. Metropolitan Water Board 32nd Annual Report, 89–99.

Higgins, M. 2018. Wadworth Woods – Sinks in the Magnesian Limestone. *Derbyshire Caving Association Newsletter*, **147**, 8–10.

Hopson, P.M, Farrant, A.R. *et al.* 2006. *Geology of the Salisbury Sheet Area*. British Geological Survey Internal Report **IR/06/011**.

Hughes, A.G., Vounaki, T. *et al.* 2011. Flood risk from groundwater: examples from a Chalk catchment in southern England. *Journal of Flood Risk Management*, **4**, 143–155, https://doi.org/10.1111/j.1753-318X.2011.01095.x

JBA 2017. *Skerne Magnesian Limestone. Skerne Catchment Assessment*. Report for the Environment Agency.

Jeannin, P.Y., Eichenberger, U., Sinreich, M., Vouillamoz, J., Malard, A. and Weber, E. 2013. KARSYS: a pragmatic approach to karst hydrogeological system conceptualisation. Assessment of groundwater reserves and resources in Switzerland. *Environmental Earth Sciences*, **69**, 999–1013, https://doi.org/10.1007/s12665-012-1983-6

Jeannin, P.Y., Artigue, G. *et al.* 2021. Karst modelling challenge 1: results of hydrological modelling. *Journal of Hydrology*, **600**, 126508, https://doi.org/10.1016/j.jhydrol.2021.126508

Kačaroğlu, F. 1999. Review of groundwater pollution and protection in karst areas. *Water, Air, and Soil Pollution*, **113**, 337–356, https://doi.org/10.1023/A:1005014532330

Karapanos, I., Jaweesh, M., Yarker, D.R., Sage, R.C., Marsili, A. and Powers, E.M. 2021. Evidence of layered piezometry system within the Chalk aquifer in parts of SE England. *Quarterly Journal of Engineering Geology and Hydrogeology*, **54**, pp.qjegh2019-175, https://doi.org/10.1144/qjegh2019-175

Kendall, P.F. and Wroot, H.E. 1924. *The Geology of Yorkshire*. Privately printed, Vienna.

King, E. 1994. *An Investigation Into the Effects on Groundwater of a Factory Discharging Into the Tributaries of the West Glen River, Southwest Lincolnshire*. MSc Thesis, University of East Anglia.

Krumbholz, J.F., Krumbholz, M., Wadas, S.H. and Tanner, D.C. 2024. Characterisation of the fracture-and karst-controlled geothermal reservoir below Munich from geophysical wireline and well information. *Geothermal Energy*, **12**, 9, https://doi.org/10.1186/s40517-024-00286-6

Lamont-Black, J. and Mortimore, R. 1999. Predicting the distribution of dissolution pipes in the chalk of southern England using high resolution stratigraphy and geomorphological domain characterisation. *In*: *Hydrogeology and Engineering Geology of Sinkholes and Karst: Proceedings of the Seventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst*. 10–14 April 1999, Harrisburg-Hershey, PA, 97–102.

Lamplugh, G.W., Smith, B. and Mill, H.R. 1914. *The Water Supply of Nottinghamshire from Underground Sources*. *Memoirs of the Geological Survey*. HMSO, London.

Laverty, M. 1983. Some karst near Oxford. OUCC Proceedings 11, https://www.oucc.org.uk/procs/proc11/oxford_karst.htm

Lee, L.J.E., Lawrence, D.S.L. and Price, M. 2006. Analysis of water-level response to rainfall and implications for recharge pathways in the Chalk aquifer, SE England. *Journal of Hydrology*, **330**, 604–620, https://doi.org/10.1016/j.jhydrol.2006.04.025

Le Mesnil, M., Moussa, R., Charlier, J.B. and Caballero, Y. 2020*a*. Impact of karst areas on runoff generation, lateral flow and interbasin groundwater flow at the storm-event timescale. *Hydrology and Earth System Sciences Discussions*, **2020**, 1–26, https://doi.org/10.5194/hess-25-1259-2021

Le Mesnil, M., Charlier, J.B., Moussa, R., Caballero, Y. and Dörfliger, N. 2020*b*. Interbasin groundwater flow: characterization, role of karst areas, impact on annual water balance and flood processes. *Journal of Hydrology*, **585**, 124583, https://doi.org/10.1016/j.jhydrol.2020.124583

Lowe, D.J. 1992. *The Origin of Limestone Caverns: An Inception Horizon Hypothesis*. PhD thesis, Manchester Polytechnic.

MacDonald A.M., Brewerton L. and Allen D.J. 1998. Evidence for rapid groundwater flow and karst type behaviour in the Chalk of Southern England. *Geological Society of London, Special Publications*, **130**, 95–106, https://doi.org/10.1144/GSL.SP.1998.130.01.09

Mangin, A. 1975. *Contribution à l'étude Hydrodynamique des Aquiferes Karstiques*. PhD thesis, Université de Dijon, Revu.

Maréchal, J.C., Bailly-Comte V. *et al.* 2021. *Karst Aquifer Typology Tool*. Geoera Resource Project Report (Deliverable 5.3), https://repository.europe-geology.eu/egdidocs/resource/geoera+resource+chaka+deliverable+53+karst+typolo.pdf

Marsh, T., Black, A., Acreman, M. and Elliott, C. 2000. River flows. *In:* Acreman, M. (ed.) *The Hydrology of the UK, A Study of Change*. Routledge, London, Chapter 5.

Marsili, A., Karapanos, I., Jaweesh, M., Yarker, D.R., Powers, E.M. and Sage, R.C. 2023. Artesian conditions in the Chilterns Chalk aquifer (NW of the London Basin) and the implications for surface water–groundwater interactions. *Geological Society, London, Special Publications*, **517**, 125–144, https://doi.org/10.1144/SP517-2020-144

Mathewson, E., Maurice, L.D. and Farrant, A.R. 2021. *BGS Karst Report Series: C6. Karst in the Chalk of the North Downs*. British Geological Survey Open Report **OR/20/064**.

Mathewson, E., Maurice, L., Farrant, A.R. and Atkinson, T.C. 2022. *BGS Karst Report Series: J2. Karst in the Jurassic Limestones of Central England*. British Geological Survey Open Report **OR/21/060**.

Matthews, D.S. 2024. *The Influence of Karst on Hydrogeology and Water Quality in the Chalk*. PhD thesis, University of Leeds.

Matthews, D., Bottrell, S., West, L.J., Maurice, L., Farrant, A., Purnell, S. and Coffey, D. 2024. Comparing the fate and transport of MS2 bacteriophage and sodium fluorescein in a karstic chalk aquifer. *Pathogens*, **13**, 168, https://doi.org/10.3390/pathogens13020168

Maurice, L. and Ascott, M. 2021. *Source Protection Zones in the Chalk*. British Geological Survey Open Report **OR/21/074**.

Maurice, L. and Guilford, T.C. 2011. The hydrogeology of Ogof Draenen: new insights into a complex multi-catchment karst system from tracer testing. *Cave and Karst Science*, **38**, 23–30, https://www.bcra.org.uk/pub/candks/index.html?j=112

Maurice, L., Atkinson, T.C., Barker, J.A., Bloomfield, J.P., Farrant, A.R. and Williams, A.T. 2006. Karstic behaviour of groundwater in the English Chalk. *Journal of Hydrology*, **330**, 63–70, https://doi.org/10.1016/j.jhydrol.2006.04.012

Maurice, L.D., Atkinson, T.C., Barker, J., Williams, A.T. and Gallagher, A. 2012. The nature and distribution of flowing features in a weakly karstified porous limestone aquifer. *Journal of Hydrology*, **438-439**, 3–15, https://doi.org/10.1016/j.jhydrol.2011.11.050

Maurice, L., Bunting, S., Farrant, A. and Mathewson, E. 2020. *BGS Karst Report Series: C4. Karst in the Chalk of the Chilterns and the Berkshire and Marlborough Downs*. British Geological Survey Open Report **OR/20/044**.

Maurice, L., Mathewson, E. and Farrant, A.R. 2022*a*. *BGS Karst Report Series: J1 Karst in the Jurassic Limestone Corallian Group of Northern England*. British Geological Survey Open Report **OR/22/009**.

Maurice, L., Mathewson, E. and Farrant, A.R. 2022*b*. *BGS Karst Report Series: C7. Karst in the Chalk of the South Downs*. British Geological Survey Open Report **OR/21/057**.

Maurice, L., Mathewson, E. and Farrant, A.R. 2022*c*. *BGS Karst Report Series: C9. Karst in the Chalk of the Isle of Wight*. British Geological Survey Open Report **OR/21/073**.

Maurice, L., Farrant, A.R., Mathewson, E. and Atkinson T. 2023*a*. Karst hydrogeology of the Chalk and implications for groundwater protection. *Geological Society, London, Special Publications*, **517**, 39–62, https://doi.org/10.1144/SP517-2020-267

Maurice, L.D., Mathewson, E. and Farrant A.R. 2023*b*. *BGS Karst Report Series: C5. Karst in the Wessex Chalk (Hampshire and Wiltshire)*. British Geological Survey Open Report **OR/22/053**.

Maurice, L.D., Farrant, A.R. and Mathewson, E. 2023*c*. *BGS Karst Report Series: C3. Karst in the Chalk of East Anglia*. British Geological Survey Open Report **OR/22/062**.

Maurice, L.D., Farrant, A.R. and Mathewson, E. 2023*d*. *BGS Karst Report Series: J3. Karst in the Jurassic Great and Inferior Oolite Groups of Southern England*. British Geological Survey Open Report **OR/23/002**.

Maurice, L.D., Cooper, A.H., Farrant, A.R., Mathewson, E. and Murphy, P.J. 2024*a*. *BGS Karst Report Series: P1. Karst in the Northern Outcrop of Permian Limestones*. British Geological Survey Open Report **OR/23/036**.

Maurice, L.D., Cooper, A.H., Farrant, A.R., Mathewson, E. and Murphy, P.J. 2024*b*. *BGS Karst Report Series: P2. Karst in the Southern Outcrop of Permian Limestones (and Associated Gypsum)*. British Geological Survey Open Report **OR/23/057**.

Medici, G., West, L.J. and Banwart, S.A. 2019*a*. Groundwater flow velocities in a fractured carbonate aquifer-type: implications for contaminant transport. *Journal of Contaminant Hydrology*, **222**, 1–16, https://doi.org/10.1016/j.jconhyd.2019.02.001

Medici, G., West, L.J., Chapman, P.J. and Banwart, S.A. 2019*b*. Prediction of contaminant transport in fractured carbonate aquifer types: A case study of the Permian Magnesian Limestone Group (NE England, UK). *Environmental Science and Pollution Research*, **26**, 24863–24884, https://doi.org/10.1007/s11356-019-05525-z

Murphy, P.J. 2000. Evidence for karstification of the Permian strata east of Leeds. *Proceedings of the Yorkshire Geological Society*, **53**, 25–30, https://doi.org/10.1144/pygs.53.1.25

Murphy, P.J. 2003. Sinkhole development on the Permian strata east of Leeds, U.K. *In:* Beck, B.F. (ed.) Proceedings of the 9th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. American Society of Civil Engineers, 175–183.

Murphy, P.J. and Lowe, D.J. 2021. Karstification of the Upper Permian limestones and dolostones in northeastern England: 1 review. *Cave and Karst Science*, **48**, 115–120, https://www.bcra.org.uk/pub/candks/index.html?j=144

O'Connor, M. and Graham, G. 2017. *The Caves of the Isle of Portland*. Wessex Cave Club Occasional Publication Series 3 No. 3 1995, updated 2017.

Owen, M. 1991. Groundwater abstraction and river flows. *Water and Environment Journal*, **5**, 697–702, https://doi.org/10.1111/j.1747-6593.1991.tb00687.x

Palumbo-Roe, B., Banks, V.J. and Brauns, B. 2019. *Characterising the Hyporheic Zones in the Skerne Catchment*. British Geological Survey Commissioned Report **CR/19/004**.

Perrin, J. and Luetscher, M. 2008. Inference of the structure of karst conduits using quantitative tracer tests and geological information: example of the Swiss Jura. *Hydrogeology Journal*, **16**, 951–967, https://doi.org/10.1007/s10040-008-0281-6

Pochon, A., Tripet, J.P., Kozel, R., Meylan, B., Sinreich, M. and Zwahlen, F. 2008. Groundwater protection in fractured media: a vulnerability-based approach for delineating protection zones in Switzerland. *Hydrogeology Journal*, **16**, 1267, https://doi.org/10.1007/s10040-008-0323-0

Poole, N. 1988. Walditch Cave. The Dream. *Descent*, **82**, 30–31.

Price, N.J. 1979. *Groundwater Flow Between Chalk Swallow Holes and the Havant and Bedhampton Springs, Hampshire*. MSc thesis, Department of Civil Engineering, University of Southampton.

Ravbar, N. 2013. Variability of groundwater flow and transport processes in karst under different hydrologic conditions. *Acta Carsologica*, **42**, https://doi.org/10.3986/ac.v42i2.644

Ravbar, N. and Goldscheider, N. 2009. Comparative application of four methods of groundwater vulnerability mapping in a Slovene karst catchment. *Hydrogeology Journal*, **17**, 725–733, https://doi.org/10.1007/s10040-008-0368-0

Reeve, T.J. 2021. Caves in the Chalk: a personal perspective from 50 years of observations. *Cave and Karst Science*, **48**, 43–56, https://www.bcra.org.uk/pub/candks/index.html?j=143

Richards, H.M. and Brincker, J.A.H. 1908. The potential dangers of water derived from wells in the Chalk. *Proceedings of the Royal Society of Medicine*, **i**, 191–203, https://doi.org/10.1177/003591570800101110

Robertson, J.S., Croll, J.M., James, A. and Gay, J. 1966. Pollution of underground water from pea silage. *Monthly Bulletin of the Ministry of Health and the Public Health Laboratory Service*, **25**, 172–178.

Rushton, K.R., Owen, M. and Tomlinson, L.M. 1992. The water resources of the Great Oolite aquifer in the Thames Basin, UK. *Journal of Hydrology*, **132**, 225–248, https://doi.org/10.1016/0022-1694(92)90180-4

Schurch, M. and Buckley, D. 2002. Integrating geophysical and hydrochemical borehole log measurements to characterise the Chalk aquifer, Berkshire, United Kingdom. *Hydrogeology Journal*, **10**, 610–627, https://doi.org/10.1007/s10040-002-0220-x

Sinreich, M., Pronk, M. and Kozel, R. 2014. Microbiological monitoring and classification of karst springs. *Environmental Earth Sciences*, **71**, 563–572, https://doi.org/10.1007/s12665-013-2508-7

Skilton, H. and Wheeler, D. 1989. The application of bacteriophage as tracers of chalk aquifer systems. *Journal of Applied Bacteriology*, **66**, 549–557, https://doi.org/10.1111/j.1365-2672.1989.tb04577.x

Smart, P.L. 1977. Catchment delimitation in karst areas by the use of quantitative tracer methods. *In:* Proceedings of the Third International Symposium of Underground Water Tracing, Bled, Yugoslavia, 291–298.

Smart, P.L., Edwards, A.J. and Hobbs, S.L. 1991. Heterogeneity in carbonate aquifers; effects of scale, fissuration, lithology and karstification. *In:* Proceedings of the 3rd Conference on Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terranes, 4–6 December Nashville, Tn, 373–387.

Soley, R.W.N., Power, T., Mortimore, R.N., Shaw, P., Dottridge, J., Bryan, G. and Colley, I. 2012. Modelling the hydrogeology and managed aquifer system of the Chalk across southern England. *Geological Society, London, Special Publications*, **364**, 129–154, https://doi.org/10.1144/SP364.10

Sparrow, A. 1975. Caves and mines of south Wiltshire. *Belfrey Bulletin V*, **29**, 12–15.

Sparrow, A. 1977. More caves of south Wiltshire. *Belfrey Bulletin*, **30**, 49–51.

Sperling, C.H.B., Goudie, A.S., Stoddart, D.R. and Poole, G.G. 1977. Dolines of the Dorset chalklands and other areas in southern Britain. *Transactions of the Institute of British Geographers*, **2**, 205–223, https://doi.org/10.2307/621858

Stanton, W.I. and Smart, P.L. 1981. Repeated dye traces of underground streams in the Mendip Hills, Somerset. *Proceedings of the University of Bristol Speleological Society*, **16**, 47–58.

Taylor, A.B., Yarker, D.R. and Karapanos, I. 2024. Predicted variable river response at high and low flows due to groundwater abstraction changes in Chalk catchments. *Quarterly Journal of Engineering Geology and Hydrogeology*, **57**, qjegh2023-074, https://doi.org/10.1144/qjegh2023-074

Walsh, P.T. and Ockenden, A.C. 1982. Hydrogeological observations at the Water End swallow hole complex, North Mimms, Hertfordshire. *Transactions of the British Cave Research Association*, **9**, 184–194.

Waltham, A.C., Simms, M.J., Farrant, A.R. and Goldie, H.S. 1997. *Karst and caves of Great Britain*. Geological Conservation Review Series. JNCC.

Ward, R.S. and Williams, A.T. 1997. *A Tracer Test in the Chalk Near Kilham, North Yorkshire*. British Geological Survey Technical Report **WD/97/7**.

Ward, R.S., Williams, A.T., Barker, J.A., Brewerton, L.J. and Gale, I.N. 1998. *Groundwater Tracer Tests: A Review and Guidelines for Their Use in British Aquifers*. British Geological Survey Report No. **WD/98/19**. Keyworth, Nottingham, UK.

Wardrop, D.R., Salmon, S. and Blackburn, J.K. 2012. Water recharge into the Magnesian limestone aquifer. *In:* Hunger, E. and Walton, G. (eds) *Proceedings of the 16th Extractive Industry Geology Conference*. EIG Conferences Ltd, 124–132, https://static1.squarespace.com/static/54199a46e4b05afa19b4e68c/t/54577748e4b06ff24652799b/1415018312957/Wardrop+124-132.pdf

Waters-Marsh, P.J. 1984. *Tracer Investigation of Bogg Hall Karst, Kirkbymoorside, North Yorkshire* MSc thesis, University of East Anglia.

Wetherell, A. 2023. Rivers, streams and wetlands–the Chalk and its water-dependent ecosystems. *Geological Society, London, Special Publications*, **517**, 275–289, https://doi.org/10.1144/SP517-2020-140

Whitaker, W., Matthews, W., Mill, H.R. and Thresh, J.C. 1910. *The Water Supply of Hampshire (Including the Isle of Wight) With Records of Sinkings and Borings*. Memoirs of the Geological Survey. HMSO, London.

Worthington, S.R. 1999. A comprehensive strategy for understanding flow in carbonate aquifers. *Karst Modelling*, **5**, 30–37.

Worthington, S.R. 2024. Seasonal nitrate variation as a tracer of preferential flow in bedrock aquifers. *Journal of Hydrology*, **643**, 132015, https://doi.org/10.1016/j.jhydrol.2024.132015

Worthington, S.R.H. and Ford, D.C. 2009. Self-organized permeability in carbonate aquifers. *Groundwater*, **47**, 326–336, https://doi.org/10.1111/j.1745-6584.2009.00551.x

Xanke, J., Stevanović, Z. *et al.* 2024. Flooding and flood water storage in karst systems of the Mediterranean region. *Hydrogeology Journal*, **32**, 1587–1605, https://doi.org/10.1007/s10040-024-02811-0

York Caving Club 2014. *The Journal of York Caving Club and North York Moors Caving Club*. Number 2: 2010 to 2013, https://yorkcavingclub.org.uk/publications/journal2/

Younger, P.L. 1995. Hydrogeology. *In:* Johnson, G.A.L. (ed.) *Robson's Geology of Northeast England*, Vol. 56, 2nd edn. Transactions of the Natural History Society of Northumbria, Newcastle upon Tyne, 353–359.