Karst geohazards in the UK: the use of digital data for hazard management

A.R. Farrant & A.H. Cooper

British Geological Survey, Keyworth, Nottingham NG12 5GG, UK (e-mail: arf@bgs.ac.uk)

Abstract

An essential prerequisite for any engineering or hydrogeological investigation of soluble rocks is the identification and description of their characteristic, observable and detectable dissolution features, such as stream sinks, springs, sinkholes and caves. The British Geological Survey (BGS) is creating a National Karst Database (NKD) that records such features across the country. The database currently covers much of the region underlain by Carboniferous Limestone, the Chalk, and particularly the Permo-Triassic gypsum and halite where rapid, active dissolution has caused significant subsidence and building damage. In addition to, and separate from, the identification of specific karst features, the BGS has created a National Karst Geohazard geographical information system (GIS). This has been created to identify areas that may potentially contain karst geohazards. Initially, all the soluble rock units identified from the BGS 1:50 000 scale digital geological map are extracted. Each soluble unit has been given an objective score, interpreted, as based on factors including lithology, topography, geomorphological position and characteristic superficial cover deposits. This national zonation of these soluble rocks can then be used to identify areas where the occurrence potential for karstic features is significant, and where dissolution features might affect the stability of buildings and infrastructure, or where karstic groundwater flow might occur. Both datasets are seen as invaluable scientific tools that have already been widely used to support site investigation, groundwater investigations, planning, construction and the insurance underwriting businesses.

Karst features, developed upon and within soluble rocks, are a well-known potential geohazard, and can cause significant engineering problems, such as subsidence and irregular rockhead ('top-of-rock') surfaces. These can pose difficulties for planning and development and be very costly for the construction and insurance industries. There have been numerous examples of subsidence and infrastructure damage resulting from unanticipated settlement and/or collapse of karst features (Waltham *et al.* 2005); in extreme cases they can cause properties to collapse and put lives at risk. More commonly, karstic rocks can make ground conditions more difficult, increasing design and construction costs. Underground cavities can also act as pathways along which hazardous liquid and gaseous contaminants can travel, commonly some distance from their source, thus posing another form of unanticipated environmental risk.

Databases and maps of karst hazards are important for understanding the severity of the problem, and they constitute useful tools for public governance choices in hazard avoidance that have relevance to planning, engineering, development and the insurance underwriting industry. Developers, planners and local government can be expected to operate effectively only if they have advance scientific warning about the hazards that might be present and have access to relevant geological information.

In the UK, karst is most typically associated with the locally varied limestone successions of Early Carboniferous age, referred to informally as the Carboniferous Limestone, but karst features are also found in a host of other carbonate and evaporite lithologies throughout the geological column (Fig. 1). The vast majority of karst features present in the UK are thought to be of Quaternary age, although many have had a complex evolution over one or more glacial–interglacial cycles,

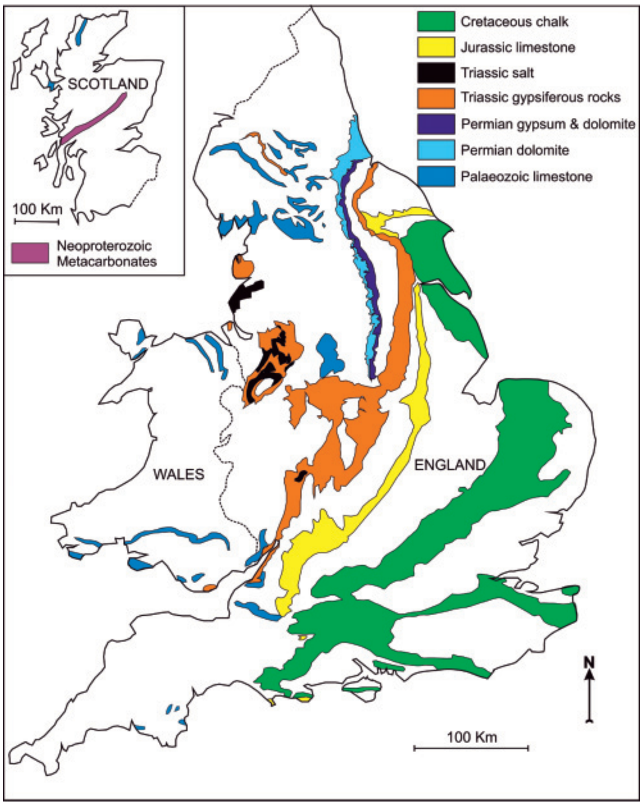

Fig. 1. Simplified map of the karstic rocks in the UK.

and some caves are potentially much older. Triassic palaeokarst is present in some areas (Simms 1990), but is generally of local extent. An overview of the UK karst has been given by Waltham *et al.* (1997).

Palaeozoic and Neoproterozoic limestones

The oldest rocks that exhibit karstic features in the UK are the thin metacarbonate beds preserved within parts of the Dalradian Supergroup of the Scottish Highlands. The features here are perhaps analogous to the Scandinavian stripe karst (Lauritzen 2001). Numerous small caves, sinkholes, stream sinks and springs have been recorded in the Appin and Schiehallion regions of the Scottish Highlands (Oldham 1975). However, many of these are in remote upland areas and generally pose little risk to infrastructure. Elsewhere in NW Scotland, Cambrian to Ordovician limestones and dolomites belonging to the Durness Group crop out in a long narrow belt along the line of the Moine Thrust and on the Isle of Skye. Several extensive well-developed karstic cave systems, for example the Allt nan Uamh system, and those in the Traligill valley have been described (e.g. Lawson 1988; Waltham *et al.* 1997), although again many of these are in remote upland areas.

Farther south, minor dissolution features and enlarged fractures have been identified from limestones of Wenlock (Silurian) age in the West Midlands and the Welsh Borders, but no significant cave systems are yet known. Limestones of Devonian age crop out in parts of Devon, particularly around Plymouth, Buckfastleigh and Torbay. Several well-developed cave systems are known in these areas (Oldham *et al.* 1986), along with stream sinks, 'losing' streams, karstic springs, sinkholes (dolines) and areas of irregular rockhead. Infrastructure problems with karstic cavities and buried sinkholes have been reported in the Plymouth area.

It is the Carboniferous Limestone that hosts the best-developed karst landscapes and the longest and most-developed cave systems in the country. It occurs widely throughout western and northern England and in Wales, and karst features are present on and within the majority of the outcrop (Waltham *et al.* 1997). Particularly well-developed karst occurs in the Mendip Hills, around the northern crop of the South Wales coalfield (Ford 1989), in the Derbyshire Peak District and in the Yorkshire Dales and adjacent areas, running up into the northern Pennines. Less well-known karst areas include the Forest of Dean, the southern crop of the South Wales coalfield from Glamorgan through the Gower to Pembrokeshire, in North Wales around the Vale of Clwyd, and around the fringes of the Lake District. In all these areas, well-developed karstic drainage systems, sinkholes and extensive cave systems are common, many of which are associated with significant allogenic drainage catchments as a source of the dissolution waters.

Fig. 2. A sinkhole formed after severe flooding in 1968 near Cheddar, Somerset [ST 4765 5620]. Superficial loessic cover sands have slumped into the underlying GB Cavern. An attempt was made to fill in the hole with old cars, which can still be seen in the cave below. Photo A. Farrant, copyright NERC.

The major challenges associated with these karst areas are water supply protection (both quality and quantity), geological conservation and practical engineering problems related to mitigating and accommodating the resulting subsurface voids. Subsidence associated with sinkhole formation is commonly encountered in remote and rural areas with little impact on property and infrastructure, but damage to houses, tracks and roads is locally a problem. Commonly of greater significance, many of these subsidence hollows are sites for illegal tipping of farm and other refuse or waste, which can cause rapid contamination of the groundwater and local drinking supplies (Fig. 2).

Permian dolomites and limestones

The Permian carbonates in the UK are dominated by magnesium-rich limestones and dolomites. The solubility of these rocks is characteristically lower than that of the pure limestones, and so karstic features are less well developed in this terrain. However, the dolomites are closely associated with bodies of gypsum, which typically are heavily karstified. Numerous small (generally less than a few tens of metres in length) cave systems are present along the outcrop of the magnesian limestones from near Mansfield in the south to Sunderland in the north. Some sinking streams are present as are numerous springs, but very few sinkholes are to be found (possibly because of infilling by agricultural practices over the centuries) and the rock is generally not problematical for engineering purposes. However, numerous open joints, incipient conduit systems on bedding planes, palaeokarst, and sediment-infilled fissures can be identified in road cuttings and quarries. Hydrogeologically, these rocks support a minor to moderate-sized aquifer, potentially susceptible to resource damage from pollution and land development, especially from landfill contamination from former infilled quarries.

In the Mendips, South Wales and parts of Devon, limestone-rich Permo-Triassic conglomerates (predominantly, but not exclusively derived from Carboniferous limestone uplands) can be expected to host karstic cave systems, perhaps the most famous example being Wookey Hole in Somerset.

Jurassic limestones

Jurassic limestones extend across much of central, southern and eastern England in a belt from Dorset to North Yorkshire, and in parts of western Scotland. Although the karst in these rocks is not as well developed as in the more massive Palaeozoic limestone terrain, karst features do occur, particularly in some of the Portlandian and Purbeck limestones in Dorset and Wiltshire, in the Cornbrash, and in the Corallian limestones around Oxford and on the southern flank of the North York Moors, where a cave system >1 km long has recently been discovered. Karst is also well developed in the Lincolnshire Limestone south of Grantham (Hindley 1965). Here, water supply protection is the main issue, although localized subsidence and areas of irregular rock-head are to be expected.

Cretaceous Chalk

The Chalk is the most widespread carbonate rock in the country and of immense importance for its water supply resource. It forms the UK's most important aquifer. Karst features occur in many parts of the Chalk outcrop, particularly along the margin of the Palaeogene cover (Farrant 2001). In these areas, the development of dissolutionally enlarged fissures and conduits can potentially cause problems for groundwater supply by creating rapid-transport contaminant pathways though the aquifer (Maurice *et al.* 2006). This is particularly important as parts of the Chalk outcrop underlie major transport corridors and urban areas; both of which are notorious suppliers of surface-gathered contaminants via runoff. Chalk dissolution also generates subsidence hazards and presents difficult ground conditions associated with the development of clay-filled pipes and fissures. These problems include irregular rockhead, localized subsidence, increased mass compressibility and diminished rock mass quality. Well-developed karstic groundwater flow systems occur in Dorset, near Salisbury, around Newbury and Hungerford, and in many parts of the Chilterns, particularly along the Palaeogene margin between Beaconsfield and Hertford (Waltham *et al.* 1997).

Triassic and Permian salt

In the UK, halite (rock salt) occurs mainly within the Triassic strata of the Cheshire Basin, and to a lesser extent in parts of Lancashire, Worcestershire and Staffordshire. It is also present in the Permian rocks of NE England and Northern Ireland (Notholt & Highley 1973). Where the saliferous Triassic rocks come to outcrop, most of the halite has dissolved and the overlying and interbedded strata can be expected to have collapsed or foundered, producing a buried salt karst hazard. This represents a more difficult site classification problem than perhaps elsewhere. These areas commonly have saline springs, indicative of continuing salt dissolution and the active nature of the karst processes. The salt deposits were exploited using these springs from before early Roman times to Victorian times, when more intense and organized brine and mined salt extraction was undertaken. Halite dissolves rapidly and subsidence, both natural and mining-induced, has affected the main Triassic salt fields including Cheshire, Staffordshire (Stafford), Worcestershire (Droitwich), coastal Lancashire (Preesall) and parts of Northern Ireland. Much of the salt mining has been by shallow brine extraction, the results of which also mimic the effects of natural karstification of the salt deposits.

Permian salt is present at depth beneath coastal Yorkshire and Teesside. Here the salt deposits and the karstification processes are much deeper than in the Triassic salt. The salt deposits are bounded up-dip by a dissolution front and collapse monocline (Cooper 2002). The depth of the salt dissolution means that very few karstic features are present, either as formed at or as migrated upward to the present ground surface, although some salt mining (brining) subsidence has occurred.

Triassic and Permian gypsum

Compared with the British limestone karst, gypsum karst occurs only in relatively small areas. It is present mainly in a belt 3 km wide and about 100 km long in the Permian rocks of eastern and northeastern England (Cooper 1989). Significant thicknesses of gypsum also occur along the eastern flank of the Vale of Eden (Ryder & Cooper 1993). It also locally occurs in the Triassic strata (Cooper & Saunders 1999), but the effects of karstification are much less severe than in the Permian rocks. The difference is mainly caused by the thickness of gypsum in the Permian sequence and the fact that it has interbedded dolomite aquifers. In contrast, the Triassic gypsum is present mainly in weakly permeable mudstone sequences. The gypsum karst has formed phreatic cave systems dissolved by water flow below the piezometric surface to depths of up to 70–80 m. The rapid solubility rate of the gypsum (Klimchouk *et al.* 1997) means that the karst is evolving on a human time scale. Active subsidence occurs in many places, especially around the town of Ripon (Cooper 1986, 1989, 1998) and to a lesser extent in the eastern part of urban Darlington (Lamont-Black *et al.* 2002); it also occurs in several other locations along the outcrop forming a belt about 100 km long and 3–5 km wide. The active nature of the dissolution and these continuing subsidence features cause difficult ground conditions for planning and development (Cooper & Saunders 1999; Paukštys *et al*. 1999; Cooper & Saunders 2002). Gypsum palaeokarst features also occur, especially along the coast of NE England and in the Firth of Forth off eastern Scotland (Cooper 1997).

The National Karst Database (NKD)

Geologists and engineers have recognized for some time that the availability of geoscience baseline data is essential for the public safety and engineering assessment of geological hazards. Understanding the severity of the problem is a prerequisite for hazard avoidance. Land developers, planners and local government can plan accordingly and responsibly if they can cite advance scientific–technical warning about the hazards that might be present and have access to relevant geological information. General guidance for the development of unstable land is written into British Government planning policy in the *Planning Policy Guidance Note 14: Development on Unstable Land* (Department of the Environment 1990), and the supplementary Annex 2 (Department of Transport, Local Government & the Regions 2002).

When this policy was implemented, rudimentary baseline data were collected in an initial database of natural cavities commissioned by the Department of the Environment and produced by a private geological consultancy, Applied Geology Ltd (1993). This is now held, and maintained as a legacy dataset, by the British Geological Survey (BGS), and is offered as a technical service by Peter Brett Associates, a private geological consultancy. This study demonstrated the national character and distribution of karst and other natural cavities, based on documentary evidence from a wide variety of sources. However, in many cases the spatial recording was not very accurate, commonly only to the nearest kilometre, and in many cases was based upon only the barest minimum of supporting data. Furthermore, the database was over-complex and many of the database fields remained empty. At the time the database fields were recognized as essential to the best understanding of mitigative prediction, and the decision was made to present the categorical need for such data, even if the bare minimum was not then available. Since that time, recent mapping, particularly in Chalk terrains, has shown that the previously available data significantly under-represents the actual density of karst features now generally known to be present. Moreover, many more karst features have been identified since 1993, both by more recent geological mapping, but also through the advent of more sophisticated remote sensing techniques such as LiDAR (light detection and ranging). Cavers have also opened up many newly discovered cave

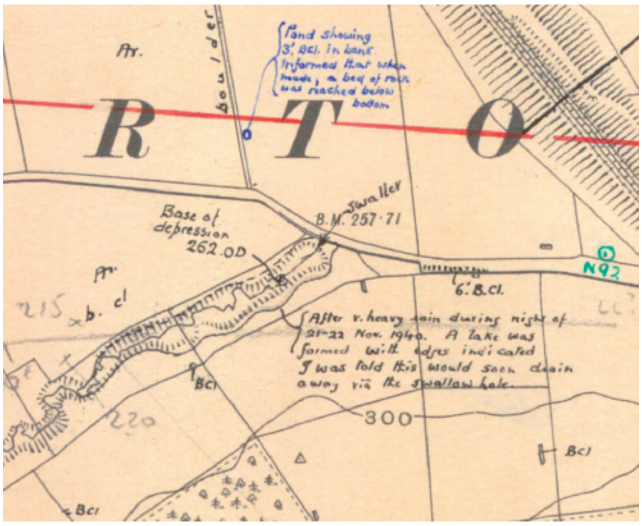

Fig. 3. Field geologist's field slip [OLL 131 NW (E)], compiled by F. B. A. Welch, surveyed in 1941, describing a stream sink in the Upper Lincolnshire Limestone Member (Jurassic), near Burton-le-Coggles [SK 9683 2595], and its response to a flood. The railway line is the East Coast Main Line.

systems, including one of Britain's longest cave systems, Ogof Draenen near Blaenavon (Farrant 2004), now known to be over 70 km in length, and also have discovered the country's deepest natural vertical cavern, the 145 m deep Titan shaft in Derbyshire's Peak Cavern. Documented speleological studies of cave systems can provide useful insights into the potential for karst geohazards to develop in the surrounding area (Klimchouk & Lowe 2002).

Much of the information in the relict Applied Geology dataset was extracted directly from published BGS maps, memoirs and reports. However, additional information now is available for systematic integration, as represented by historical unpublished geological field slips and notebooks held in the National Geological Data Centre in Keyworth. Karst features have been recorded routinely by field geologists on their field slips since the Survey's inception in 1835. However, they have only rarely been depicted on published map and reports, and the data contained on them can be difficult to access.

In 2000, as part of a drive to make its datasets more accessible for the common good, the BGS embarked on constructing a more comprehensive geographic information system (GIS) and database of karst information (Cooper *et al*. 2001), from which the National Karst Database was set up. The aim was to retrieve the karst data contained in the field slips and on paper maps held in the archives, and make them accessible in a GIS format. The BGS field slips and maps have now been scanned and many of them geo-rectified so that they can be viewed via an in-house customized GIS system. An example of a historical field slip from Lincolnshire is shown in Figure 3.

Additional fine-scale karst information is now being routinely gathered both in the field and from existing

Table 1. *Datafields gathered for sinkholes*

Sinkholes, record item	Parameters
Sinkhole name	Free text
Size	Size x, Size y, Size z, metres
Type	Compound, collapse, suffusion, solution, no data, buried
Shape	Round, oval, irregular, modified, compound, no data
Surface profile	Pipe, cone, inverted cone, saucer, complex, levelled (filled), no data
Infill deposits	British Geological Survey rock and stratigraphical codes with thicknesses
Subsidence type	Gradual, episodic, instantaneous, no data
Evidence of quarrying	Yes, no, no data
Primary data source	Field mapping, air-photo, site investigation, database, maps and surveys, literature, Lidar remote sensing, DoE database, no data
Reliability	Good, probable, poor, no data
Property damage	Yes, no, no data
Oldest recorded subsidence	dd/mm/yyyy
Intermediate subsidence events	dd/mm/yyyy
Most recent subsidence	dd/mm/yyyy
Other data	dd/mm/yyyy
References	Free text

DoE, Department of the Environment.

Table 2. *Datafields gathered for springs*

Springs, record item	Parameters
Spring name	Free text
Elevation	Metres
Situation	Open surface, borehole, concealed, submerged, submarine, underground inlet, no data
Proven dye trace	Yes, no
Flow	Ephemeral, fluctuating, constant, flood overflow, ebbing and flowing, no data
Water type	Normal–fresh, saline, sulphate, tufaceous, other mineral, no data
Size	Trickle, small stream, medium stream, large stream, small river, medium river, large river, no data
Primary data source	Field mapping, air-photo, site investigation, database, maps and surveys, literature, Lidar remote sensing, DoE database, no data
Artesian	Yes, no, no data
Thermal	Yes, no, no data
Karstic	Yes, no, no data
Uses	None, public, agricultural, industrial, other, no data
Character	Single discrete, multiple discrete, diffuse, no data
Reliability	Good, probable, poor, no data
Estimated discharge	Litres per second ($l\,s^{-1}$)
Other data	dd/mm/yyyy
References	Free text

documentary data sources. The information gathered during fieldwork is recorded either digitally on portable tablet computers or on pro forma field data sheets organized with the same datafields as the GIS and its underlying database. Documentary information is gathered from existing datasets such as scanned and geo-rectified copies of the geologists' field maps, historical and modern geo-rectified Ordnance Survey maps, cave surveys, academic papers and historical documents. The data are systematically entered into a customized GIS system, initially achieved using ArcView3 (Cooper *et al.* 2001), but now using ArcGIS9. The point-specific information and database tables are then copied to centralized Oracle databases. Other datasets such as the Applied Geology database and the Mendip Cave Registry data are being used to identify other sources of information where relevant.

Data on five main types of karst feature are collected: sinkholes (or dolines), stream sinks, caves, springs, and incidences of associated damage to buildings, roads, bridges and other engineered works. The details gathered are listed in Tables 1–5 (for sinkholes, springs, stream sinks, caves and building damage, respectively). For each of these datasets, in common with all BGS databases, the information added to the system has common header data including National Grid coordinates, date entered, user number and reliability.

For sinkholes, the data can be entered either as a polygon covering the known extent of the feature, where spatial data exist, or as a point, where the sinkhole is too small to be represented or if no spatial data are available. The type description of sinkhole is adapted from the classification of Culshaw & Waltham (1987). The size of springs and stream sinks is necessarily subjective, depending on the time of year and rainfall, but a proxy for the average flow can be obtained from the observed channel width and depth (of both the influent and effluent channels). For the majority of historical information gathered from published maps and geologists' field maps and slips, no precise description of spring or stream sink flow is available for direct entry to the NKD. In many cases, some of the dataset entries can be estimated or obtained from other data sources. Information gathered for caves is also collected as either point data for cave entrances, or, if they are known, as linear data for the approximate centre lines of the caves

Table 3. *Datafields gathered for stream sinks*

Stream sinks; record item	Parameters
Sink name	Free text
Elevation	Metres
Proven dye traces	Yes, no, no data
Morphology	Discrete compound, discrete single sink, diffuse sink, losing stream, ponded sink, cave entrance, concealed sink, no data
Flow	Perennial, intermittent, ephemeral (flood), estavelle, no data
Size	Trickle, small stream, medium stream, large stream, small river, medium river, large river, no data
Primary data source	Field mapping, air-photo, site investigation, database, maps and surveys, literature, Lidar remote sensing, DoE database, no data
Reliability	Good, probable, poor, no data
Estimated discharge	Litres per second ($l\,s^{-1}$)
Other data	Free text
References	Free text

Table 4. *Datafields gathered for natural cavities*

Natural cavities, record item	Parameters
Cavity name	Free text
Length	Metres
Vertical range	Metres
Elevation	Metres
Type	Open cave natural, infilled cave natural, gull cave, lava tube, boulder, peat cave, sea cave, stoping cavity, palaeokarst, hydrothermal borehole cavity, no data
Rock units penetrated (bedrock and superficial)	British Geological Survey rock and stratigraphical codes
Primary data source	Field mapping, air-photo, site investigation, database, maps and surveys, literature, Lidar remote sensing, DoE database, no data
Streamway	Yes, no, no data
Other entrance	Yes, no, no data
Evidence of mining	Yes, no, no data
Reliability	Good, probable, poor, no data
Other data	Free text
References	Free text

themselves. It is possible to include full cave surveys, but there are often copyright issues that need to be addressed before these data entries can be included. In these situations, the cave location is documented, and

Table 5. *Datafields gathered for property damage*

Property damage, record item	Parameters
Address	Free text
Postcode	Postcode format
Elevation	Metres
Damage survey 1	Date (dd/mm/yyyy), notes, damage rating (1–7)
Damage survey 2	Date (dd/mm/yyyy), notes, damage rating (1–7)
Damage survey 3	Date (dd/mm/yyyy), notes, damage rating (1–7)
Suspected cause	Natural subsidence, mining subsidence, landslip, compressible fill, building defect
Reliability	Good, probable, poor, no data
Other data	Free text
References	Free text

reference to the survey made in the reference table where appropriate. Many sites are multiple features; for example, many stream sinks are also cave entrances, whereas sinkholes might also be sites of building or infrastructure damage.

Since the database was set up in 2002, much information has been added to the system. Data covering most of the evaporite karst areas of the UK have now been added, along with data covering about 60% of the Chalk, and 30% of the Carboniferous Limestone outcrops. To date, over 800 caves, 1300 stream sinks, 5600 springs and 10 000 sinkholes have been recorded, and many of the classic upland karst areas have yet to be included.

Other karst datasets

Other karst datasets are available in the UK, most of which have been collated by members of the caving community. These data generally cover the more well-known Carboniferous and Devonian limestone karst areas, which contain most of the accessible caves.

The British Caving Association (BCA) maintains a registry of karstic sites in the form of a National Cave Registry. It holds limited information about each site with links to more comprehensive information in regional cave registries maintained by regional caving organizations, including the Mendip Cave Registry and the Cambrian Cave Registry. The Mendip Cave Registry is manned by volunteer registrars who form the membership of the group. Its aim is to record all available information relating to the caves and stone mines in the counties of Bristol, Somerset and Wiltshire. It has around 8000 documented sites of speleological interest. These include caves, stream sinks, springs and sites where cavers have dug in their efforts to discover new caves. The Cambrian Cave Registry is currently being digitized and is scheduled to be available on-line sometime in 2008. The Black Mountain Cave Register, part of the Cambrian Cave Registry, used to be accessible on-line, but is no longer available. The regional caving councils, supported by the BCA, also hold databases containing information about caves and access arrangements.

The Cave Database (http://www.cavedatabase.co.uk/) is an open access website to which anyone can add cave-related links. However, its coverage is patchy, and the data are not complete. In addition, the website may be at risk of being compromised by the gratuitous inclusion of links that are not cave related, or data that have not been checked.

CAPRA, the Cave Archaeology and Palaeontology Research Archive based in the University of Sheffield, has compiled a gazetteer of English, Scottish and Welsh caves, fissures and rock-shelters that contain human remains. This is available on the CAPRA website (Chamberlain & Williams 1999, 2000*a*, *b*).

The Chelsea Spelaeological Society has compiled a dataset of natural and man-made cavities in SE England. These have been published as a series of paperback publications (some co-authored with the Kent Underground Research Group) that are available from the Society. Most of the data relate to dene-holes and Chalk mines, but some natural chalk caves are included, such as those at Beachy Head in Sussex (Waltham *et al.* 1997).

Many of the lesser known karst areas, including much of the Chalk outcrop, are not covered by these schemes. These areas still contain significant densities of karst geohazards, and are commonly located in more densely populated areas. Moreover, a significant drawback of these databases is that they only provide information on known karst features. Predicting the whereabouts of karst features such as buried sinkholes and undiscovered near-surface cavities is more difficult. Combining available baseline karst data with other digital spatial data, such as bedrock and superficial geology, superficial deposit thickness and digital terrain models, within a GIS can provide a powerful tool for predicting karst geohazards.

National Karst Geohazard GIS (GeoSure)

Over the past decade, the BGS has invested considerable resources in the production of digital geological map data for the UK. Digital geological maps (DiGMap) are now available for most of the country at the 1:50 000 scale, and complete coverage at the 1:250 000 and 1:625 000 scales. A significant part of the country is also covered at the 1:10 000 scale. All these datasets include the bedrock, and the 1:625 000, 1:50 000 and 1:10 000 scale datasets also include data for the superficial deposits. Each polygon of digital geological data is attributed with a two-part code (the LEX-ROCK code) that gives its stratigraphy and its lithology. For example, the Seaford Chalk Formation is represented by the code SECK_CHLK, whereas the Carboniferous Gully Oolite Formation has the code GUO_OOLM. A comprehensive list of all the LEX codes used can be found in the BGS Lexicon of Named Rock Units, which is available on the Internet at http://www.bgs.ac.uk/lexicon/ lexicon_intro.html. Here, each named unit will eventually be defined and its upper and lower boundaries described. The lithological codes (ROCK) are based on the BGS Rock Classification Scheme, and are also explained and listed on the Internet at http://www.bgs.ac.uk/data/dictionaries.html and can be searched by name or code.

The availability of the digital geological maps has allowed the BGS to produce a set of predictive datasets for geological hazards, known and marketed as ‘GeoSure’. Several derived datasets have been produced using a variety of algorithms to provide geohazard data for soluble rocks (dissolution), landslides (slope instability), compressible ground, collapsible rocks, shrink–swell deposits and running sand.

The GeoSure dissolution dataset can be used to identify areas where there is potential for a range of karstic features to develop. Such features include potential geohazards such as sinkholes, dissolution pipes, natural cavities and areas prone to dissolution-generated irregular rockhead, as well as hydrological features such as stream sinks, estavelles and karstic springs. It can also be used to highlight areas where karstic groundwater flow might be significant to the public interest. This is a distinct, separate dataset that complements and validates the NKD.

The first iterations of the GeoSure dissolution dataset used the bedrock codes as the basis for a purely lithology-based system that was enhanced by local knowledge and manual subdivision. More recently, the technique used to create the GeoSure GIS has been upgraded, and now employs a scoring system in a GIS environment using a range of additional datasets. This has several advantages over the purely lithology-based system. It allows greater flexibility in rating hazard levels, and can give a more precise hazard rating for a given area of actual ground being considered for some public purpose. It allows differential weighting to be given to different controlling factors depending on the underlying karstic lithology. It is a more robust system and can be tailored to the quality of the input data.

Methods

The GeoSure dissolution layer is but one of five layers of geoscience data that can be brought into consideration for general and specific land classification, planning and development purposes. The dissolution layer has been created by identifying a suite of factors that can influence the style and degree of karst features likely to develop at any one place. Each of these factors, such as bedrock lithology, geomorphological domain and superficial deposit thickness is represented in the GIS as a separate theme. Each of these themes is then categorized and given a score, to give an indication of the contribution it might make to the overall degree of soluble rock hazard, in a similar manner to the more detailed site-specific method for the Chalk proposed by Edmonds (2001). Those with a strong influence will have a high score, those with a slight influence will have a low score. Some factors, such as very thick superficial deposit cover, might even have a negative score if they significantly reduce the particular hazard or damage potential for karst features to develop.

The karst geohazard layer is created in the GIS software by intersecting all the datasets into one, creating a mosaic of intersected polygons. For each resulting polygon, the sum total of each of the contributing factors is then used to give an overall potential hazard score. These scores can then be categorized to give a hazard rating (A–E) for a particular area. The hazard rating categories can be tailored to suit the quantitative needs of different end-users; for example, a high hazard rating important for those planning a tunnelling scheme might not be pertinent for a home owner. The geological manifestations of carbonate karst compared with those of gypsum and salt karsts are different, so the evaporites have a slightly different set of determinative parameters and are thus software-calculated separately. In addition, the actual scores used for each factor can be updated when new or more detailed baseline information, such as a new version of the digital geological map, becomes available.

Bedrock lithology

The type, style and scale of karst geohazard is strongly influenced by its intrinsic bedrock lithology, which can commonly be used as a proxy for a particular rock unit's overall mass fracture properties and hydrological characteristics.

All the known soluble and karstic rocks (with the exception of units containing gypsum and halite, which are described below) were extracted from the BGS DiGMap 1:50 000 scale digital geological database and grouped on the basis of their LEX-ROCK codes into four broad lithological groupings: Cretaceous chalks; Palaeozoic limestones (including Neoproterozoic metacarbonates); Jurassic limestones and oolites, and Triassic conglomerates and Permian dolomites.

These broad groupings reflect the different style of karst landscape evolution that these rock units support. For example, the style and type of karst features developed on the Chalk is very different from that developed on the Carboniferous Limestone.

Each of the 480 geological units extracted from the DiGMap database was then given a score based on its LEX-ROCK code. Those rock units that either are known to be, or have the potential to be, highly karstic, such as some of the Carboniferous Limestone units, are given a high score, whereas those rock units that are less karstic, but still within the range of 'soluble' rocks, such as some of the Jurassic oolites, have a lower score. The rest of the guiding factor datasets were then cut against this modified bedrock layer to create the final hazard layer specific to the karst areas of the UK. The scores used to weight each of the guiding factors can be adjusted slightly according to the lithological groupings to reflect the style and degree of karstification, as well as on a local basis, where and if new, project or use-related data are available.

In addition, a set of typically non-soluble lithologies that are known to host karstic features were also extracted. In areas of interstratal karst, the overlying cover rocks are liable to subside into cavities in the underlying limestone, creating cover-collapse sinkholes. The Twrch Sandstone Formation (part of the Marros Group, which replaces the term Millstone Grit in South Wales) is a classic example of a non-soluble lithology that locally hosts sinkholes and stream sinks. Some mapped formations contain both soluble and non-soluble lithologies, and this is reflected in the GIS by the overall score given to the particular formation. More detailed geological datasets may allow further subdivision of the individual soluble or non-soluble lithologies within a particular formation.

Superficial deposit domains

The superficial geology of an area has a strong influence on the development potential of karst features. Areas underlying only a thin cover of superficial deposits commonly have a greater incidence of near-surface karst features such as suffosion sinkholes. This situation is caused mainly by concentration of surface runoff on the cover strata, thereby generating discrete point recharge into the susceptible underlying bedrock and, ultimately, concentrating dissolution. The unconsolidated deposits can also slump and ravel into dissolutionally enlarged fissures in the underlying limestone, creating dissolution pipes, cavities and, ultimately, sinkholes. These types of sinkhole are common in areas with a thin cover of glacial deposits overlying the Carboniferous Limestone, as in the Yorkshire Dales, or areas of clay-with-flints over the Chalk in southern England.

Details of all the superficial deposits that overlie soluble bedrock polygons were extracted from the BGS DiGMap 1:50 000 scale digital geological database and cut against the soluble bedrock polygons. The superficial polygons were then grouped into a set of superficial deposit domains that reflect their genetic origins (Table 6), based on LEX-ROCK codes. Each of these

Table 6. *Superficial deposit domain groupings*

Domain	Characteristics
Unmantled domain	Areas with no superficial cover, or where the cover has been eroded away
Marine domain	All marine and intertidal superficial deposits
Raised beach domain	All types of raised beach deposits
River valley domain	Fluvial deposits such as alluvium, valley peat and valley gravels
River terrace domain	All types of river terrace deposits
Weathered mantled domain	Residual and/or weathering deposits such as clay-with-flints, loessic deposits and cover-sands, and hill peat
Dry valley domain	Head, coombe and valley gravels
Glacial domain	Tills and glacial moraine deposits

domains is given a score. In the case of marine superficial deposits the score is negative, which reflects the lower potential for karst to develop in areas covered by marine deposits such as estuarine alluvium.

The accuracy of both the solid and superficial polygons is based on the baseline geological data, which in turn are dependent on the quality and quantity of exposure, and the antiquity of the original geological mapping.

Superficial thickness

Each superficial unit will also have a score depending upon how thick it is. Areas with a very thin superficial cover will have a high score, reflecting the greater likelihood of point recharge effects and their subsequent influence on sinkhole formation, with lower scores obtaining where the superficial units are relatively thick. For superficial deposit thicknesses greater than a specified limiting value the score will become negative, reflecting their negative influence on the development of sinkholes. This value is based on observations of the density and size of known sinkholes in areas with a superficial cover. The influence of superficial deposits on the development of karst features is clearly demonstrated in the Yorkshire Dales. Here, limestone areas with a thick, dense, and low-permeability glacial till cover (for example, beneath the boulder clay of drumlins), generally have very few sinkholes (although older, relict sediment-filled palaeokarst features may be preserved beneath the basal till), whereas areas with a thin superficial cover are commonly pockmarked with suffosion sinkholes. The superficial thickness is taken from the BGS Superficial Deposits Thickness Model, divided into six categories, and scored accordingly.

Superficial permeability

The permeability of the superficial deposit also has a definite controlling effect on the likelihood of dissolution features developing in the underlying bedrock. Highly permeable units such as sandy river terrace deposits have a higher score than lower-permeability clay-rich deposits. This reflects the ease with which the water can flow through the deposit, creating an irregular rockhead and dissolution pipes pocking the bedrock interface. The permeability information is derived from the existing BGS Superficial Permeability database and has been divided into four categories and scored accordingly.

Slope angle

A nationwide digital slope model has been created using NextMap™ data. The slope angles have been categorized into a range of values, cut against the bedrock theme and scored accordingly. Flat or gently sloping areas will have the highest score, principally because it is in these areas in the UK that sinkholes, dissolution pipes and areas of irregular rockhead are known to be most likely to develop. On steeper terrains, slope processes tend to erode karst features rather than enhance them.

Glacial limit

The limits of the extents of the Devensian and Anglian glaciations have exerted only a minor degree of influence on the magnitude of karstification in the UK. In areas south of the glacial limits, many relict karst features occur, preserved on the landscape. In contrast, areas within the limit of the last Devensian glaciation have been subjected to locally extensive erosion and many karstic features developed in the Pleistocene interglacials have been eroded away. This dataset divides the country into polygons defined by the various recognizable glacial limits (Anglian, Devensian and Loch Lomond). Areas outside the maximum glacial limit will have the highest score as they will be most weathered.

Expert GIS polygons

In addition to the polygons derived from existing digital datasets, three new datasets characterizing the relationship between a soluble rock and adjacent impermeable strata were created (Fig. 4). These three polygon sets have been created manually using digital geological and topographical maps, cave surveys, detailed local knowledge, the National Karst Database and overviews of karst geomorphology in general.

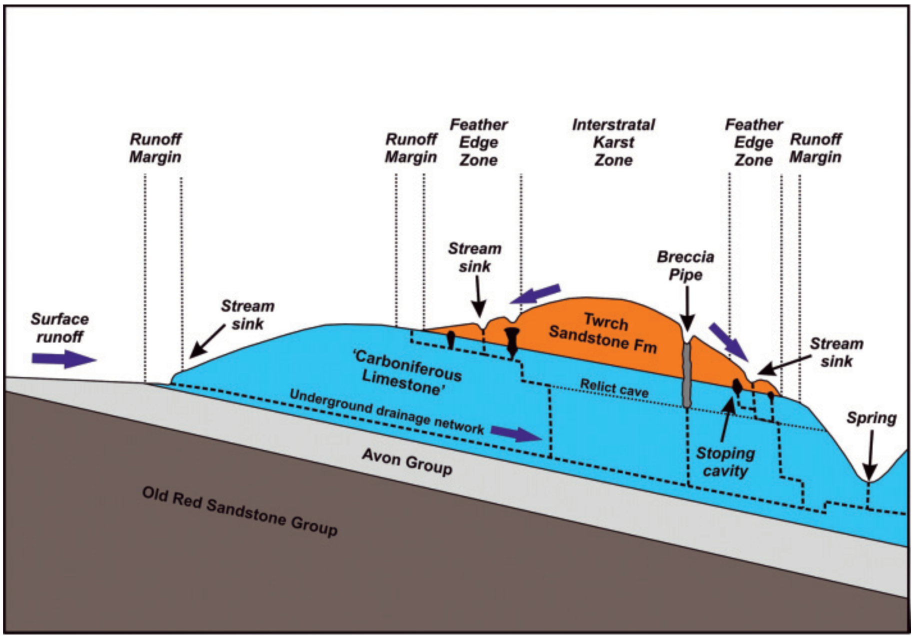

Fig. 4. A schematic cross-section through the north crop of the South Wales coalfield, showing the relationships between the runoff margin and the feather edge zones along the contact between relatively soluble and insoluble rocks. An area of interstratal karst occurs where the Twrch Sandstone overlies karstified Carboniferous Limestone.

Runoff margin

The greatest concentrations of potentially hazardous, surface karst features are commonly associated with contact margins between a relatively impermeable rock body and one or more soluble lithologies, creating a line of infusion along which surficial runoff is directed onto the soluble rock mass. There are several broad types of situation where this relationship can arise. It occurs where younger sandstones or mudstones overlie the soluble lithology; for example, where the Palaeogene Reading Formation overlies the Chalk in southern England, or where the Twrch Sandstone Formation overlies the Carboniferous Limestone in South Wales. It also occurs in dipping strata where older rocks form the higher ground; a classic example is the contact between the Avon Group (Lower Limestone Shales) and the Carboniferous Black Rock Limestone Formation in the Mendips. Alternatively, a similar karst contact might arise as a result of faulting or an unconformity.

This zone of enhanced surface karst is represented in the GIS by a manually picked polygon along the margin between a non-karstic rock and a karstic unit where the non-karstic rock is topographically higher. The relative accuracy of the zone is partially dependent on the underlying geological data. Although depicted as a distinct zone in the GIS, in reality its margins are likely to be gradational.

Feather edge

Karstic features also occur in non-karstic rocks that overlie a soluble lithology. Examples include the numerous, large, well-developed sinkholes (Fig. 5) developed on the Twrch Sandstone Formation on Mynydd Langynidr in South Wales (Waltham *et al.* 1997). These are caused by the collapse of the overlying sandstone and mudstone into cavities in the underlying Carboniferous Limestone, and they can develop through a considerable thickness (perhaps as much as 30 m) of cover strata. Similar, smaller features occur in the Reading

Fig. 5. A large sinkhole and stream sink developed on the South Wales Lower Coal Measures Formation, Mynydd Llangattwg, South Wales [SO 1766 1527]. Subsidence here has been caused by the collapse of the Carboniferous Limestone at depth. The collapse column has migrated up more than 40 m through the overlying Twrch Sandstone Formation into the 'Coal Measures'. The water reappears in the Cascade Inlet in the 31 km long Agen Allwedd cave system, over 200 m below the surface. Photo A. Farrant, copyright NERC.

and Thanet Sand Formations overlying the Chalk (Edmonds 1983). Karst features such as sinkholes, stream sinks and dissolution pipes are particularly common where the cover strata thin to a feather edge at the contact with the underlying soluble strata.

This zone is also represented in the GIS by a manually picked polygon along the 'feather-edge' of the impermeable deposit. This zone will be given a high score, as the bedrock lithology is generally insoluble and would otherwise have a very low score; for example, the Reading Formation on the Chalk. As with other manually picked lines, the relative accuracy of the zone is partially dependent on the underlying geological data, and, again, in reality its margins are likely to be gradational.

Interstratal karst

In parts of South Wales, the Forest of Dean and the Mendip Hills, significant areas of interstratal karst occur. This is where karstic drainage systems have developed in the Carboniferous Limestone below a significant thickness of impermeable rocks such as the Twrch Sandstone Formation or the Cromhall Sandstone Formation in the Forest of Dean. In this scenario, there might be little or no surface expression of karst, but extensive caves or karstic groundwater flow systems can occur at depth (sometimes over 100 m below the surface), such as Ogof Draenen near Abergavenny (Farrant 2004), and the Wet Sink–Slaughter Risings system near Joyford in the Forest of Dean (Waltham *et al.* 1997). Areas of significant interstratal karst have been identified and digitized, making use of geological and topographical maps, groundwater tracing experiment results, cave surveys and assistance of expert local knowledge.

All the above datasets are intersected with each other and the scores for each summed to create the final hazard layer. For example, a flat area of the Carboniferous Black Rock Limestone situated adjacent to an area of impermeable strata within the runoff area, with no superficial deposits in the Mendip Hills would score highly, and be given an E hazard rating. In contrast, an area of bare Carboniferous Black Rock Limestone on a moderate slope would generate a more modest score corresponding to a C rating (Fig. 6). An area on the feather edge of Twrch Sandstone overlying the Carboniferous Limestone scores highly, putting it in a D hazard category. Similarly, an area of gently sloping Seaford Chalk with a thin cover of clay-with-flints would also score highly and be given a D rating, whereas an area of New Pit Chalk on a scarp slope would generate a low score, and be given an A rating. It is important to note that the relative scale, style and type of karst features present in each area may be different. Some smaller scale, less obvious karst features such as chalk dissolution pipes may pose more of an engineering hazard than some larger karst features such as deep caves.

Figure 6a and b shows an example from the Mendip Hills in Somerset where a mature karst landscape has developed on the Carboniferous Limestone. The greatest density of karst features predictably occurs along the margin of the Avon Group mudstone and within a thin cover of Mesozoic strata capping the limestone, but some lesser degree of surface karst should also be noted to occur across this zone, and within the Triassic Mercia Mudstone Group conglomerates.

The information given to accompany the overall hazard ratings can then be tailored to suit the type of end-user, be it a home owner, insurer or estate manager (Table 7).

Gypsum and salt karst areas

Gypsum and salt are so much more soluble than carbonate rocks that they tend to form buried and interstratal karst and the rocks themselves are rarely seen at the surface. For this reason many of the influences that can be factored into the karst prediction for the carbonate rocks do not apply to such interpretations for gypsum and salt terrains. The lithology of the superficial deposits has less influence and slope angle largely becomes irrelevant. Superficial deposit thickness does have a mitigative bearing, but not until it is very thick (greater than about 30 m) and relatively less permeable. The thick superficial deposits also tend to occur in areas where groundwater movement is already restricted or below sea level. For salt- and gypsum-bearing strata a slightly different delimitation approach is being employed; the scoring method is being investigated for revision in the gypsum or salt application, but has not yet been quantified to make it practical. The technique used relates almost exclusively to the use of manually picked polygons created by someone with extensive knowledge of the local geology and karst. The initial data from which the polygons are created are based on the BGS digital geological map information, and enhanced by information from the National Karst Database and local or published knowledge, to identify and delimit the subject dissolution problem areas.

Permian gypsum-bearing strata

The Permian gypsum sequence in eastern England forms an interstratal karst with thick sequences of gypsum, sandwiched between fractured-dolomite aquifers. The main gypsum-bearing strata are the Hayton and Billingham anhydrite–gypsum sequences that equate in part to the Edlington and Roxby Formations at outcrop. The Brotherton Formation dolomite, sandwiched between the two gypsum sequences, is heavily affected by karstic subsidence and collapse (Fig. 7) emanating

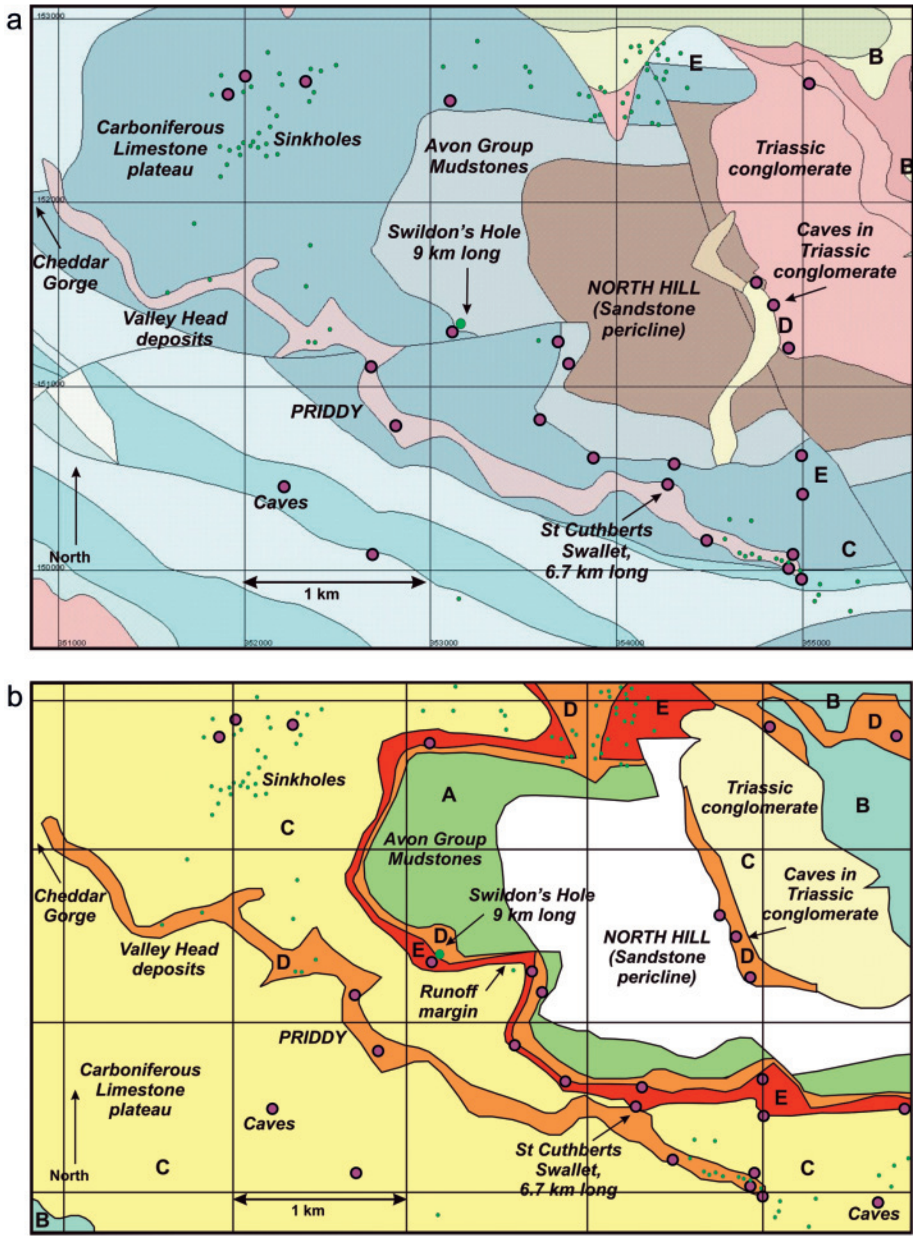

Fig. 6. (**a**) The digital 1:50 000 bedrock and superficial geological map of the North Hill area of the Mendip Hills, near Bristol [ST 540 514], with data from the National Karst Database superimposed; purple circles are caves or stream sinks; small green circles are sinkholes. The blue colours are the Carboniferous Limestone formations, the grey is the Avon Group (see **b**). North Hill comprises Devonian Portishead Formation (brown), with pink Triassic conglomerates to the NE. A thin deposit of valley head runs along the dry valley though Priddy. (**b**) The GeoSure hazard map for this area with data from the National Karst Database superimposed; purple circles are caves or stream sinks; small green circles are sinkholes. Much of the bare Carboniferous Limestone plateau gives a rating of C, although locally unmapped loessic cover sands give rise to higher densities of sinkholes north of Priddy. A thin zone around the margins of the Avon Group give a rating of E; this area is where the majority of the caves and stream sinks are found. Many suffosion sinkholes occur in the valley head deposits in Priddy, which has a D rating. The Avon Group consists of a sequence of interbedded limestones and mudstones, which is weakly karstic overall, hence the A rating. The Triassic conglomerates to the NE of North Hill host several significant cave systems and stream sinks, and are rated C, except along the margins of the Portishead Formation, where they have a D rating.

from dissolution within the underlying Edlington Formation–Hayton gypsum, but the dolomite itself only locally contains dissolution features. The amount of dissolution is controlled by the amount of water flow through either or both of the sequences. The Permian gypsum sequence is a useful case example showing that both river valleys and buried river valleys can have a profound effect on the concentration of dissolution features. The most subsidence-prone areas occur where either or both these features cut through the sequence and where water feeds down-dip in the carbonate aquifers, to discharge as sulphate-rich artesian springs

Table 7. *Possible text to accompany hazard ratings tailored for different potential end-users*

Hazard rating	General characteristics	Indicative implications for					
		Planners	Developers or geotechnical engineers	Householders	Insurance or financial institutions	Environmental health or waste disposal	Farmers and estate managers
1 or A	Areas where soluble rocks are present, but unlikely to cause problems except under exceptional conditions	No constraints to land use caused by land instability within site	Normal desk study and walkover survey of site	No maintenance or use implications caused by land instability	No increased cost because of land instability present	Possible concern about groundwater contamination	No restrictions on land use because of land instability, concerns about groundwater contamination
2 or B	Areas with significant soluble rocks, but few dissolution features and no subsidence; unlikely to cause problems except with considerable surface or subsurface water flow	No constraints to land use caused by land instability within site	Normal desk study and walkover survey of site. Consideration of stability of site surroundings	No maintenance or use implications caused by land instability	Increased cost because of land instability unlikely. Slight liability because of groundwater pollution possible	Concern about groundwater contamination	No restrictions on land use because of land instability, concerns about groundwater contamination
3 or C	Areas with significant soluble rocks, where there are dissolution features, and no or very little recorded subsidence, but a low possibility of it occurring naturally or in adverse conditions such as high surface or subsurface water flow	Report on implications for stability should be submitted if changes to surface drainage or new construction are proposed	Site investigation should consider specifically the land stability of the site and surroundings. Care should be taken with local drainage into the bedrock	Consideration of implications for stability should be made if changes to surface drainage or new construction are planned	Increased cost because of land instability possible. Some liability because of groundwater pollution possible	Potential for site integrity to be damaged by minor ground movements. Concern about groundwater contamination	Consider minor changes in land use, surface runoff and drainage to prevent groundwater contamination and reduce the likelihood of subsidence
4 or D	Areas with very significant soluble rocks, where there are numerous dissolution features and/or some recorded subsidence with a moderate possibility of localized subsidence occurring naturally or in adverse conditions such as high surface or subsurface water flow	Land use changes involving loading, infilling, excavation or changes to surface drainage may affect stability, and assessment and mitigation measures should accompany application. Conservation measures should be considered	Specialist site investigation for stability assessment might be necessary before construction. Construction work might cause subsidence. Surface drainage should not be allowed to affect the karst system or groundwater	Do not load the land, and obtain specialist advice before undertaking building work. Do not dispose of surface drainage to the ground. Maintain drainage infrastructure	Increased cost because of land instability probable. Liability because of groundwater pollution possible	Possible damage to contaminative structures, tanks, drainage, sewers, pipelines, etc. Inspection of structures recommended. Areas prone to pollution and groundwater contamination	Consider some changes in land use, surface runoff and drainage to prevent groundwater contamination and reduce the likelihood of subsidence

Table 7 *Continued.*

Hazard rating	General characteristics	Indicative implications for					
		Planners	Developers or geotechnical engineers	Householders	Insurance or financial institutions	Environmental health or waste disposal	Farmers and estate managers
5 or E	Areas with very significant soluble rocks, where there are numerous dissolution features and/or considerable recorded subsidence with a high possibility of localized subsidence occurring naturally or in adverse conditions such as high surface or subsurface water flow	Land use changes involving loading, infilling, excavation or changes to surface drainage may affect stability. Permission for development might require investigation and remedial works as part of development. Permission for development might not be possible. Conservation measures should be considered	Specialist land stability assessment necessary. Investigation, remediation and/or mitigation works might be necessary to stabilize the area. Construction work might cause subsidence. Surface drainage must not affect the karst system or groundwater	Consider obtaining specialist advice to advise on need for stabilization work and/or land management plan to maintain stability. Do not dispose of surface drainage into the ground. Maintain drainage infrastructure	Increased cost because of land instability very probable. Liability because of groundwater pollution probable	Significant possibility of damage to contaminative structures, tanks, drainage, sewers, pipelines, etc. Regular inspection of structures recommended. Areas very prone to pollution and groundwater contamination	Consider major changes in land use, surface runoff and drainage to prevent groundwater contamination and reduce the likelihood of subsidence

Fig. 7. Sinkhole formed by the dissolution of Permian gypsum in the village of Sutton Howgrave [SE 3246 7928] near Ripon, North Yorkshire. The hole started to collapse in December 2000, the photograph was taken on 14 February 2001 when the hole was 5–6 m in diameter and 11 m deep with water at a depth of 8 m. Photo A. H. Cooper, copyright NERC.

in the valleys. Not enough digital information is currently available to characterize the hydrogeology, so the manually picked polygon approach is currently taken by utilizing the National Karst Database to define the areas that appear to be most susceptible to subsidence.

The point-specific information contained within the National Karst Database allows the manually picked polygons for the feather edge zone to be delimited, so that the lower parts of the overlying non-karstic Sherwood Sandstone Group, which are prone to interstratal subsidence, are also included in the susceptible belt. The subsidence-prone zone is determined by combining the digitized geological outcrop limits of the Edlington, Brotherton and Roxby Formations with this feather edge zone of the Sherwood Sandstone Group. The superficial deposits across much of the susceptible belt are very thick, but the thickness of gypsum is sufficient over most of the area for its dissolutional removal to cause subsidence to migrate upwards through the superficial cover to the surface, creating large sinkholes. In some places with thick gypsum (10–30 m), such as to the east of Darlington, where the superficial cover is extremely thick (30–40 m) and the ground has low relief, there is a lower hydrostatic head driving the dissolutional water-system. Here there is less likelihood of point subsidence, but because the superficial deposits contain water-saturated sand lenses and beds, subsidence can occur by the limited flow-displacement of loose, overlying ('running') sand into the underlying gypsum karst cavities. The result of this is the formation of upward-propagating, large shallow bowl-shaped subsidence areas.

In the Vale of Eden the gypsum sequence (consisting of a series of gypsum beds A–D) is sandwiched between mudstones. Consequently, less water reaches the gypsum, and karstic features occur mainly at the base of the superficial deposits or in areas where there is concentrated water flow towards local rivers and streams. Because of this, the outcrop of the A–B–C–D gypsum beds and the zones between them are manually amalgamated to produce a combined area. The Permian-aged gypsum of the Vale of Eden and the anhydrite exposed along the coast are included in this area.

For the Permian gypsum karst areas, the manually picked polygons are classified into five groupings, as follows.

A, very low potential: areas where gypsum is present, but the deposits are known to be thin, where the adjacent rocks are not aquifers and there is no recorded subsidence.

B, low: areas where gypsum is present in substantial thicknesses, but where the adjacent rocks are not aquifers and where there is no recorded subsidence.

C, moderate: areas where gypsum is present in substantial thicknesses, where the adjacent rocks might or might not be aquifers, but where there is no recorded subsidence. Mainly the majority of the Permian gypsum in the Vale of Eden and some of the Permian-aged gypsum of eastern England.

D, high: areas where gypsum is present in substantial thicknesses, where the adjacent rocks are aquifers and where there is some recorded subsidence. Mainly the Permian-aged gypsum of eastern England, including Darlington, Tadcaster and Church Fenton.

E, very high: areas where gypsum is present in substantial thicknesses, where the adjacent rocks are aquifers, where buried valleys cut through the sequence and where there are numerous records of continuing subsidence. Mainly the Permian-aged gypsum of eastern England south of the general line Darlington–Ripon–Brotherton.

Triassic gypsum-bearing strata

Triassic gypsum-bearing strata are widespread, but mainly contain thick gypsum beds in the Staffordshire, south Derbyshire and south Nottinghamshire areas. Karstic features are sporadic with some caves, sinkholes and stream sinks present. In addition, some localized building damage has occurred. The expert zones defined for the Triassic-aged gypsum terrain are subdivided as follows.

A, very low potential: areas where gypsum is present, but the deposits are known to be thin, where the adjacent rocks are not aquifers, where the superficial cover is thick and there is no recorded subsidence. Mainly the Triassic Mercia Mudstone Group where fibrous gypsum and thin-bedded gypsum has been recorded and the low-lying areas with relatively thick, lower-permeability superficial cover.

B, low: areas where gypsum is present in substantial thicknesses, but where the adjacent rocks are not aquifers and where there is no recorded subsidence.

C, moderate: areas where gypsum is present in substantial thicknesses, where the adjacent rocks might or might not prove to be aquifers, where there is no recorded active subsidence, but where subsidence features are present. Mainly the Triassic-aged Mercia Mudstone Group where relatively thick gypsum is present.

D, high: areas where gypsum is present in substantial thicknesses, where the adjacent rocks might or might not prove to be aquifers, and where there is some recorded subsidence.

Permo-Triassic halite-bearing strata

The subdivisions applied to the salt areas are basically the same as those applied to the gypsum. The difference comes in the mechanisms of collapse and the fact that salt is much more soluble and much more rapidly dissolved than gypsum. The salt areas are all buried beneath considerable thicknesses of overlying brecciated and collapsed rock, or thick superficial deposits.

Hazard assessment of many of the salt areas is complicated by the fact that room-and-pillar salt mining and brine pumping have also commonly occurred in the areas where natural dissolution has occurred. The hazard zones are defined as follows.

A, very low potential: areas where salt is present, but the deposits are known to be thin and they are covered with impervious material.

B, low: areas where salt is present in substantial thicknesses, but where the deposits are covered with a significant thickness of impervious material, or areas where there is good evidence that the majority of the salt has naturally dissolved during geological time.

C, moderate: areas where salt is present in substantial thicknesses and present at rockhead (wet rockhead) or beneath a thin cover of impervious rock.

D, high: areas where salt is present in substantial thicknesses, present at rockhead (wet rockhead) and where salt springs are present in the area.

E, very high: areas where salt is present in substantial thicknesses, present at rockhead (wet rockhead) and where wild brining or nearby underground salt mining has occurred, salt springs are present and there is some recorded subsidence in the vicinity; mainly the Triassic-aged salt of Cheshire, Staffordshire and Worcestershire.

Discussion

Clearly, the GeoSure dataset provides only an indication of where dissolution features might occur, and does not give actual locations of karst features, nor does it serve to service the direct need for site classification at single development locations. Furthermore, the National Karst Database does not provide details of all karst features and neither dataset should be used as a substitute for detailed site investigation work, or a more detailed hazard assessment, such as that proposed by Edmonds (1983). Whether these karst geohazards constitute a potential risk depends on the views of the end-user; for example, a cave might pose a problem for a construction company, but be a boon for a caving enthusiast, whereas an irregular rockhead might be a potential hazard to a construction company excavating a tunnel, but not pose a risk to a home owner whose house has good foundations.

Fig. 8. Numerous sinkholes formed by a large burst water main at Littleheath Road, Fontwell, Sussex [SU 944 077] in late 1985. At least 63 collapses are visible, eight in gardens, four on the road and the remainder in the field. The burst water main was near the digger in the top right of the view. The site is on solifluction deposits overlying Culver Chalk, close to the Palaeogene margin. Photo copyright Sealand Aerial, Chichester, reproduced under licence.

Clearly, given the very localized nature of karst features, not all areas categorized as being of high risk will have subsidence or contain karst features, and this uncertainty needs to be communicated. For property owners, the presence of a moderate or high dissolution rating (class E or D) does not mean that any particular property will collapse or subside, but it acts as a warning that the geological conditions make the area prone to subsidence under certain circumstance; for example, if leaking sewers or water pipes wash out clay-infilled dissolution pipes. Karst features are generally stable under natural or light loading conditions, until exceptional circumstances such as severe flooding or a burst water main occur (Fig. 8). Changes to the natural hydrological regime caused by changes in the nature of surface runoff, excavating or loading the ground, groundwater abstraction, leaking services and inappropriate drainage can also trigger subsidence in otherwise generally stable areas (Waltham *et al.* 2005). Neither of these datasets predict when such events will occur, but they can prove useful for a variety of single users and organizations (Table 7) who have the obligation of protecting the public from adverse effects of land utilization.

Planners can utilize the datasets to inform the zoning of areas for development and building control, thus protecting the public from severe subsidence problems (Paukštys *et al.* 1999). Developers and geotechnical engineers can use the information to help with linear route planning, site design and hazard avoidance. Householders can be better informed about potential geological hazards when purchasing properties and be aware of situations that can aggravate the natural situation, so that situations such as letting pipes leak, or emptying a swimming pool onto the garden and causing a house to collapse (Edmonds 2005) can be avoided. For the insurance and financial industries the datasets can mean they are better informed about the potential risks they take, but except in exceptional circumstances the data should not be used as a reason for refusing to provide insurance, although they might justify a loading of the premium. Considering the sensitivity of karst to transport of pollution, it is also important that the datasets provide both related baseline information (such as the locations of stream sinks and sinkholes) and generalized information about the susceptibility of specific geological units to develop karstic features. Finally, the datasets can be used to inform farmers and estate managers about their land and some of the constraints that they should consider when dealing with it.

Acknowledgements. Many thanks go to S. Thorpe, N. Williams, A. Richardson, H. Cullen and S. Doran, who entered many of the data. K. Adlam is thanked for setting up the National Karst Database and GIS. J. Walsby is thanked for supporting the GeoSure project, and R. Newsham is thanked for processing data and providing GIS help. D. Lowe and V. Banks kindly read through the text and provided useful comments. M. Culshaw, A. Waltham and A. Gibson are thanked for their help. This paper is published with the permission of the Executive Director, British Geological Survey.

References

Applied Geology Ltd 1993. *Review of instability due to natural underground cavities in Great Britain.* Applied Geology Ltd, Royal Leamington Spa.

Chamberlain, A. T. & Williams, J. P. 1999. A Gazetteer of English Caves, Fissures and Rock Shelters Containing Human Remains. Capra. 1. World Wide Web Address: http://capra.group.shef.ac.uk/1/caves.html.

Chamberlain, A. T. & Williams, J. P. 2000*a*. A Gazetteer of Scottish Caves, Fissures and Rock Shelters Containing Human Remains. Capra. 2. World Wide Web Address: http://capra.group.shef.ac.uk/2/scotland.html.

Chamberlain, A. T. & Williams, J. P. 2000*b*. A Gazetteer of Welsh Caves, Fissures and Rock Shelters Containing Human Remains. Capra. 2. World Wide Web Address: http://capra.group.shef.ac.uk/2/wales.html.

Cooper, A.H. 1986. Foundered strata and subsidence resulting from the dissolution of Permian gypsum in the Ripon and Bedale areas, North Yorkshire. *In:* Harwood, G.M. & Smith, D.B. (eds) *The English Zechstein and Related Topics.* Geological Society, London, Special Publications, **22**, 127–139.

Cooper, A.H. 1989. Airborne multispectral scanning of subsidence caused by Permian gypsum dissolution at Ripon, North Yorkshire. *Quarterly Journal of Engineering Geology,* **22**, 219–229.

Cooper, A.H. 1997. Gypsum karst of Great Britain. *International Journal of Speleology,* **5**, 195–202.

Cooper, A.H. 1998. Subsidence hazards caused by the dissolution of Permian gypsum in England: geology, investigation and remediation. *In:* Maund, J.G. & Eddleston, M. (eds) *Geohazards in Engineering Geology.* Geological Society, London, Engineering Special Publications, **15**, 265–275.

Cooper, A.H. 2002. Halite karst geohazards (natural and man-made) in the United Kingdom. *Environmental Geology,* **42**, 505–512.

Cooper, A. & Saunders, J.M. 1999. Road and bridge construction across gypsum karst in England. *In:* Beck, B., Pettit, A.J. & Herring, G. (eds) *Hydrogeology and Engineering Geology of Sinkholes and Karst 1999. Proceedings of the 7th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Harrisburg–Hershey, PA.* Balkema, Rotterdam, 407–411.

Cooper, A.H. & Saunders, J.M. 2002. Road and bridge construction across gypsum karst in England. *Engineering Geology,* **65**, 217–223.

Cooper, A.H., Farrant, A.R., Adlam, K. & Walsby, J.C. 2001. The development of a national Geographic Information System (GIS) for British karst geohazards and risk assessment. *In:* Beck, B. & Herring, G. (eds) *Geotechnical and Environmental Applications of Karst Geology and Hydrology. Proceedings of the 8th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Louisville, KY.* Balkema, Lisse, 125–130.

Culshaw, M.G. & Waltham, A.C. 1987. Natural and artificial cavities as ground engineering hazards. *Quarterly Journal of Engineering Geology,* **20**, 139–150.

Department of the Environment 1990. *Planning Policy Guidance Note 14: Development on Unstable Land.* HMSO, London.

Department of Transport, Local Government and the Regions 2002. *Planning Policy Guidance Note 14. Development on Unstable Land. Annex 2: Subsidence and Planning.* The Stationery Office, London.

Edmonds, C.N. 1983. Towards the prediction of subsidence risk upon the Chalk outcrop. *Quarterly Journal of Engineering Geology,* **16**, 261–266.

Edmonds, C.N. 2001. Predicting natural cavities in Chalk. *In:* Griffiths, J.S. (ed.) *Land surface evaluation for engineering practice.* Geological Society, London, Engineering Special Publications, **18**, 29–38.

Edmonds, C.N. 2005. Subsidence over a chalk pipe at Chalfont St. Peter, UK. *In:* Waltham, A.C., Bell, F.G. & Culshaw, M.G. (eds) *Sinkholes and Subsidence. Karst and Cavernous Rocks in Engineering and Construction.* Praxis, Chichester, 309–312.

Farrant, A.R. 2001. Karst development in the Southern English Chalk. *In:* Beck, B. & Herring, G. (eds) *Geotechnical and Environmental Applications of Karst Geology and Hydrology. Proceedings of the 8th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Louisville, KY.* Balkema, Lisse, 77–82.

FARRANT, A.R. 2004. Ogof Draenen. *In:* GUNN, J. (ed.) *Encyclopedia of Cave and Karst Science.* Fitzroy Dearborn, London, 310–312.

FORD, T.D. (ED.) 1989. *Limestones and Caves of Wales.* Cambridge University Press, Cambridge.

HINDLEY, R. 1965. Sink-holes on the Lincolnshire limestone between Grantham and Stamford. *East Midland Geographer,* **3**, 454–460.

KLIMCHOUK, A. & LOWE, D. 2002. Implications of speleological studies for karst subsidence hazard assessment. *International Journal of Speleology,* **31**.

KLIMCHOUK, A., LOWE, D., COOPER, A. & SAURO, U. 1997. Gypsum karst of the world. *International Journal of Speleology,* **5**.

LAMONT-BLACK, J., YOUNGER, P.L., FORTH, R.A., COOPER, A. & BONNIFACE, J. 2002. A decision logic framework for investigating subsidence problems potentially attributable to gypsum karstification. *Engineering Geology,* **65**, 205–215.

LAURITZEN, S.-E. 2001. Marble stripe karst of the Scandinavian Caledonides, An end member in the contact karst spectrum. *Acta Carsologica,* **30**, 47–92.

LAWSON, T.J. 1988. *The Limestone Caves of Scotland Part 2: Caves of Assynt.* Grampian Speleological Group Occasional Publication, **6**.

MAURICE, L.D., ATKINSON, T.C., BARKER, J.A., BLOOMFIELD, J.P., FARRANT, A.R. & WILLIAMS, A.T. 2006. Karstic behaviour of groundwater in the English Chalk. *Journal of Hydrology,* **330**, 63–70.

NOTHOLT, A.J.G. & HIGHLEY, D.E. 1973. *Salt.* Mineral Dossier No. 7, Mineral Resources Consultative Committee. HMSO, London.

OLDHAM, A.D. 1975. *The Caves of Scotland, except Assynt.* Tony Oldham, Bristol.

OLDHAM, A.D., OLDHAM, J.E.A. & SMART, J. 1986. *The Concise Caves of Devon.* Anne Oldham, Crymyrch.

PAUKŠTYS, B., COOPER, A.H. & ARUSTIENE, J. 1999. Planning for gypsum geohazards in Lithuania and England. *Engineering Geology,* **52**, 93–103.

RYDER, P.F. & COOPER, A.H. 1993. A cave system in Permian gypsum at Houtsay Quarry, Newbiggin, Cumbria, England. *Cave Science,* **20**, 23–28.

SIMMS, M.J. 1990. Triassic Palaeokarst in Britain. *Cave Science,* **17**, 93–102.

WALTHAM, A.C., SIMMS, M.J., FARRANT, A.R. & GOLDIE, H. 1997. *Karst and Caves of Great Britain: Geological Conservation Review.* Chapman and Hall, London.

WALTHAM, A.C., BELL, F.G. & CULSHAW, M.G. 2005. *Sinkholes and Subsidence. Karst and Cavernous Rocks in Engineering and Construction.* Praxis, Chichester.

Received 29 August 2007; accepted 4 March 2008.