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KARST, GIS AND GEOLOGICAL HAZARD PLANNING AND MANAGEMENT IN GREAT BRITAIN.

di Cooper A.H., Farrant A.R., Price S.
British Geological Survey, Keyworth, Nottingham, NG12 5GG

Introduction

The British Geological Survey (BGS) database of karst features for the United Kingdom include dolines, cave entrances, stream sinks, resurgences and building damage; data for approximately half of the country has so far been gathered. BGS makes and utilises digital geological map data, which includes lithological and stratigraphical information for bedrock and superficial deposits. By incorporating this digital map data with digital elevation slope models and karst data, BGS has generated a derived dataset assessing the likelihood of subsidence due to karst collapse. This dataset is informed and verified by the karst database and marketed as part of its GeoSure suite; the karst layer includes areas of limestone, chalk, gypsum and salt. It is currently used by environmental regulators, the insurance and construction industries plus the BGS semi-automated enquiry system. The karst database and GeoSure datasets can be combined and manipulated using GIS to make other datasets that deal with specific problems. Sustainable drainage systems, some of which use soak-aways into the ground are being encouraged in the UK, but in karst areas they can cause problems. Similarly, open loop ground source heat pumps may induce subsidence if installed in certain types of karst such as chalk with overlying sand deposits. Groundwater abstraction also has the potential to trigger subsidence in karst areas. GIS manipulation of the karst information will allow the UK to be zoned into areas suitable, or unsuitable, for such uses; it has the potential to become part of a suite of planning management tools for local and National Government to assess the long term sustainable use of the ground.

1. Soluble rocks and karst in the UK

Britain has five main types of soluble (or karstic) rocks; dolomite, limestone, chalk, gypsum and salt, each with a different solubility and dissolution rate generating individual characteristics and associated problems (Fig. 1). Subsidence, often triggered by anthropogenic disturbance of the surface water, groundwater or water abstraction occurs widely, especially where karstic rocks are overlain by a thin superficial cover. These can cause significant engineering and foundation problems of such concern that they are the subject of Government Planning Guidance Policy (Department of the Environment, 1990 and Department of Transport, Local Government and the Regions, 2002). Aquifer vulnerability and the rapid transmission of groundwater and contaminants are of particular concern in some areas, especially those underlain by these karstic rocks. Consequently, aquifer

ahc@bgs.ac.uk

protection zones are delineated by the Environment Agency to fulfil the Groundwater Regulations (2009) that were introduced to accord with the Water Framework Directive (2000/60/EC) and Groundwater Directive on the Protection of Groundwater Against Pollution and Deterioration (2006/118/EC).

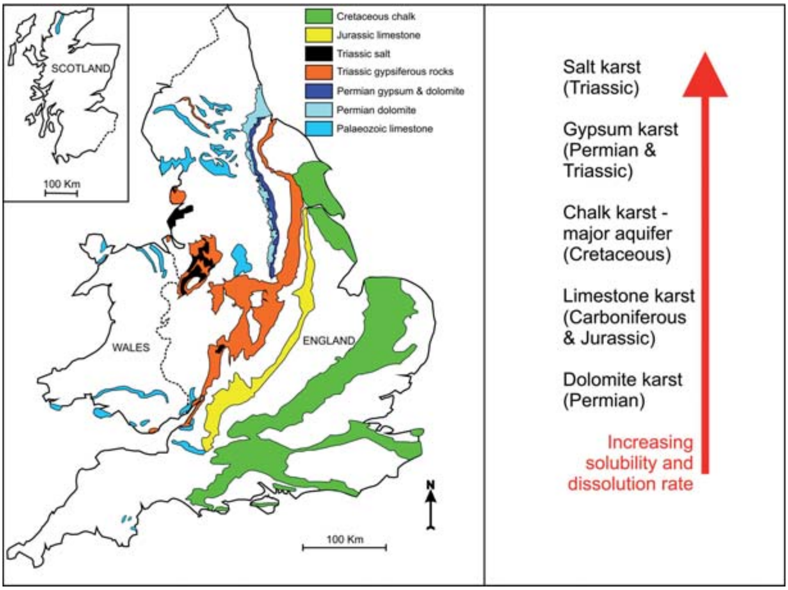

Fig. 1 - Soluble rock types and their distribution in the UK.

1.1 Limestones

The Carboniferous Limestone hosts the best-developed karst landscapes and the longest cave systems in the country. Although karst features are widespread, the best-developed karst occurs in the Yorkshire Dales, the Peak District, the Mendip Hills and around the margins of the South Wales coal-field. Cambrian and Devonian Limestones, together with some Jurassic limestones also display karstic characteristics (WALTHAM *et al.,* 1997). The major problems associated with these karst areas are water supply protection, geological conservation and engineering problems. Subsidence associated with sinkhole (doline) formation does occur, but generally often in remote and rural areas with little impact on property and infrastructure. However, these subsidence hollows are often sites for illegal tipping of farm and other refuse or waste which can cause rapid contamination of the groundwater and local drinking supplies.

1.2 Dolomite

Permian dolomite is present, mainly in north-east England, but because of its lower solubility few karstic features have been recorded, except where it is associated with gypsum.

1.3 Chalk

The Chalk is the most widespread carbonate rock in the country and of immense importance for water supply. It forms the UK's most important aquifer. In places, the development of solutionally enlarged fissures and conduits can potentially cause problems for groundwater supply by creating rapid contaminant pathways though the aquifer, especially in areas adjacent to impermeable Palaeogene strata. This is particularly important as the Chalk often underlies major transport corridors and several large urban areas. Chalk dissolution also generates subsidence hazards and difficult engineering conditions (Edmonds, 1983; Farrant, 2001; McDowell *et al.,* 2008) associated with the development of clay filled pipes and fissures. These problems include irregular rockhead, localised subsidence, increased compressibility and diminished rock mass quality.

1.4 Gypsum
Gypsum karst is present mainly in a belt 3km wide and about 100km long in the Permian rocks of eastern and north-eastern England (Fig. 1) (Cooper, 1986, 1989, 1998). It also locally occurs in the Triassic strata, but the effects of it are much less severe than those 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, but the rapid solubility rate of the gypsum (James *et al.,* 1981) means that the karst is evolving on a human time scale. Active subsidence occurs in many places, especially around the town of Ripon. The active nature of the dissolution and the ongoing subsidence features, cause difficult conditions for planning and development.

1.5 Salt
Salt in Great Britain occurs mainly in the Permian and Triassic strata of central and north-eastern England (Fig. 1). Many towns on the Triassic strata have "wich" or "wych" in their names indicating that they are sited on former salt springs emanating from actively dissolving salt karst (Cooper, 2002). These places became the focus for shallow mining and near-surface "wild" brine extraction, a technique that exacerbated the salt karstification. In some of these areas subsidence is still occurring. Most extraction of natural brine has ceased and modern exploitation is mainly in dry mines or by deep controlled brine extraction leaving brine-filled cavities. Since the cessation of natural brine pumping, the saline ground water levels have returned towards their pre-pumping state. Brine springs are becoming re-established and natural karstification and subsidence may be expected to occur. The exact nature of the brine flow, and how it might interact with mined and brined areas, has yet to be studied.

2. BGS National Karst Database

2.1 The Database
The British Geological Survey has developed a database of karst features and about half the country has now been included. This dataset has utilised and improved on information that was initially gathered for the UK Government database of natural cavities (Applied Geology Limited, 1993). Initially the karst database was gathered using a bespoke ArcView interface, but now it is running on ArcMap9.2. In addition to holding the data in GIS format the point information and database tables are held within the main BGS Oracle database. Five main entities are gathered in the database with information about 1. sinkholes

(dolines), 2. springs, 3. caves, 4. stream sinks and 5. building damage. All the entries have a point location and the sinkholes that are big enough to be digitised at a 1:10,000 scale also have their outline digitised and gathered as a polygon. The database fields for each of these entities are listed by Farrant and Cooper (2008). The mapping of building damage is particularly sensitive for recording even small amounts of subsidence (Gutiérrez and Cooper 2002) and the full building damage classification is reviewed and presented by Cooper (2008a).

2.2 Capture of Karst Database information in the field

The karst database GIS interface was initially set up as an office-based collection system (Cooper et al., 2001). More recently BGS has implemented a digital field data capture system known as BGS SIGMAmobile (Jordan 2010). This interface running on rugged waterproof Tablet PCs with built-in GPS allows the capture of field data with interfaces for recording map information, field records and sections (Fig. 2). The karst database has been incorporated as a function in BGS SIGMAmobile (Fig. 3) so that the 5 sets of karst-related information can be gathered directly in the field and uploaded to the main BGS database on return to the office. There is also the functionality of recording landslides in the format of the BGS landslides database. At the time of writing BGS SIGMAmobile is available free and can be downloaded from the internet (BGS 2010a). The condition of its use is that any improvements and modifications that are developed must be provided to BGS for inclusion in later releases.

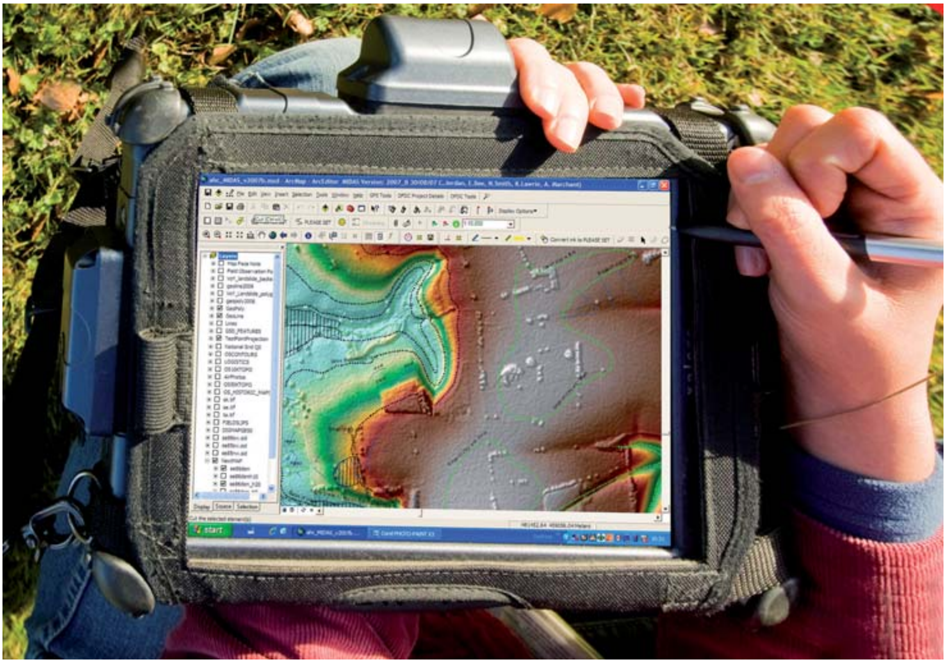

Fig. 2 - A BGS·SIGMAmobile tablet PC running the field data capture software; NextMap digital elevation model from Intermap Technologies.

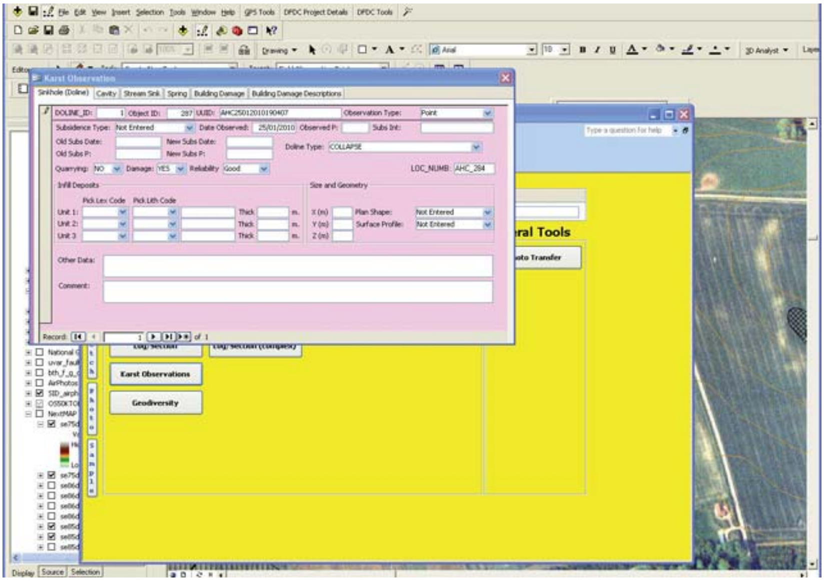

Fig. 3 - The BGS·SIGMAmobile karst (doline) data capture screen.

3. Generating the GeoSure datasets for soluble rocks

3.1 The GeoSure hazard layers

BGS produces a series of six map layers for the country indicating the susceptibility to certain hazards. These layers include landslides, compressible ground, shrink-swell clays, running sands, collapsible ground (loess etc) and soluble rocks (Harrison and Forster. 2006). The datasets are marketed under the name of GeoSure, supplied to BGS resellers and utilised in products such as house stability reports, they are also extensively used by insurance companies to limit their local exposure to geological hazards. In addition, the information is now being more widely used by the Environment Agency to help with planning and the environmental protection of karst aquifers. In addition, these datasets have been utilised to assess linear routes for roads and pipelines (Gibson *et al.*, 2005).

The soluble rocks layer for GeoSure has been produced by utilising the digital geological map data (bedrock and superficial), superficial deposit thickness, DTM slope model and the karst database plus expert knowledge. Because of their different solubilities and geological situations different algorithms are utilised to assess the different rock types. In many places expert polygons have also been digitised to cope with marginal situations that cannot be derived from the basic geological map information. For the main limestone and chalk units with their overlying superficial deposits a scoring scheme has been developed (Farrant and Cooper, 2008). For the gypsum and salt areas where the deposits are largely buried beneath thick superficial deposits the bedrock geology and karst database (to assess the concentration of sinkholes) has been used (Cooper 2008b). The manipulation of the numerous digital layers has been undertaken using ArcGIS and the final results are a 5 subdivision ranking of 1 (or A) to 5 (or E) where 1 is low susceptibility and 5 is very high. The inputs into the assessment and their characteristics are described below:

3.2 BGS digital map data

The British Geological Survey has digitised all the published legacy1:50,000 scale geological map data for the country. It now produces all its information digitally and the majority of the country is now available at a working scale of 1:50,000. Four datasets have been gathered, the bedrock geology (including faults, mineral veins, coal seams etc), the superficial geology, mass movement deposits (mainly landslides) and artificial deposits (mainly made ground and excavations). In addition a significant amount of the country, especially urban areas, has been digitised from the 1:10,000 scale dataset, the scale at which most of the surveying has been done. For these areas the same four dataset layers are collected.

For this digital information each map polygon is attributed with a 2-part seed indicating the lithology and the stratigraphy. The lithological codes are listed on the internet in the BGS Rock Classification Scheme (RCS – BGS 2010b) with an internet search facility (BGS 2010c). The stratigraphy is listed within the BGS Stratigraphical Lexicon that can also be searched on the internet (BGS. 2010d). Recently the whole 1:50,000 scale map dataset for the bedrock and superficial geology has been made available on the internet for free public non-commercial use under the banner of OpenGeoscience with a free geology viewer (BGS 2010 e and f).

3.3 Bedrock geology

The major controlling factor of the karstic rocks is the rock type. Basic information about this is held in DiGMapGB by the polygon seeds for lithology (detailed above). In addition, some stratigraphical units, such as those with thick jointed limestones, are more prone to the development of large concentrations of karstic features and sinkholes. The karst database, literature and local knowledge also help to delineate these units. Once identified, the lithological or combined lithological and stratigraphical seeds for the polygons allow these more prone units to be selected from the digital map dataset. It is possible to identify the formations and geological units that have certain characteristics such as the soluble halite, gypsum, limestone and chalk areas. It is also possible to rank and score the individual formations for their susceptibility to karstification and sinkhole formation.

3.4 Superficial deposit geology

The nature of the superficial deposits and the geological history of these units have a strong bearing on the susceptibility of areas to sinkhole formation. Some domains such as the weathered mantled domain comprising residual and weathering deposits are particularly prone to collapse and given a high score. In many areas, such as the chalk of southern England, the overlying materials also have a strong influence on the number of cavities and sinkholes that can develop. Impervious capping materials concentrate runoff around their margins and these marginal areas are more prone to sinkhole formation. Permeable capping materials such as superficial sands and gravels can span cavities caused by dissolution at the interface between the superficial materials and the underlying soluble rock, but these materials can fail dramatically if water is able to dissolve the underlying bedrock. Like the bedrock, the superficial deposits are coded with a two-part seed for the lithology and stratigraphy so the largely impervious or mainly pervious capping materials can be identified; this selection is informed by the BGS Superficial Permeability database. Utilising their geological settings, the deposits can be grouped together into domains and given scores dependent on their severity to sinkhole (doline) development

3.5 BGS superficial deposit thickness data

The thickness and lithology of the superficial deposits that conceal the soluble rocks can have a large influence on the susceptibility to collapse. Using the large amounts of borehole information that BGS holds (indexed on GeoIndex – BGS 2010g) the contact between the superficial deposits and the bedrock has been identified. This has allowed the generation of a superficial deposit thickness model (BGS 2010h). This has been utilised to identify areas where the superficial deposits are so thick that they protect the underlying soluble rocks from further dissolution. Areas of chalk in Yorkshire overlain by 30 or more metres of glacial till near the coast are included in this scenario and given a negative score which reduces their impact in the final results.

3.6 NextMap ™ Digital Terrain Model and slope model

The slope angle in chalk and limestone rocks exposed at and near surface has a strong influence on the susceptibility to sinkhole development. Steep slopes allow the water to run off and reduce the severity of the dissolution, and rates of surface erosion may be greater than the rate of sinkhole formation. Conversely, flattish areas can develop karstic depressions at surface or beneath thin covering deposits. The British Geological Survey uses slope information from the NextMap Britain elevation data from Intermap Technologies to calculate this factor, which generates another score to be added to the resultant mark.

3.7 Expert GIS polygons

While the digital map polygons allow the soluble rocks at surface to be identified they do not cater for marginal and interstratal effects. Marginal effects occur as two main types: runoff margin and feather edge (Fig. 4). The runoff margin zone occur in situations where an aquitard, such as a mudstone, either overlies or occurs adjacent to a soluble rock such as a limestone. Here the drainage from the impervious strata may be directed onto the adjacent limestone creating a zone where preferential dissolution of the limestone can occur. In these situations, karst features such as stream sinks, sinkholes and caves are often particularly common. A feather-edge margin occurs where these aquitards are sufficient thin to allow water flow to the underlying soluble rock. Here karstic features such as cover collapse sinkholes and stream sinks can develop within the overlying material. Depending on the lithology and fracture characteristics of the overlying material, these sinkholes can develop through several tens of metres of cover strata. These areas can only be identified manually or from the karst database. Where such situations are identified, the increasing cover thickness away from the feather edge of the deposits tends to limit the degree of karstification, so the width of the affected areas are manually determined and digitised. Both the runoff margin and feather edge areas are given a score. Interstratal karst is present where the karstic rocks pass beneath or are interlayered with non-karstic rocks. In this situation, for example, sandstone sequences overlying limestones or gypsum, the insoluble rocks may themselves be susceptible to sinkhole formation caused by collapse of the soluble rocks at depth. This susceptibility and the extent of the area affected can only be determined manually, but it is informed by the distribution of sinkholes recorded in the karst database (Farrant and Cooper, 2008).

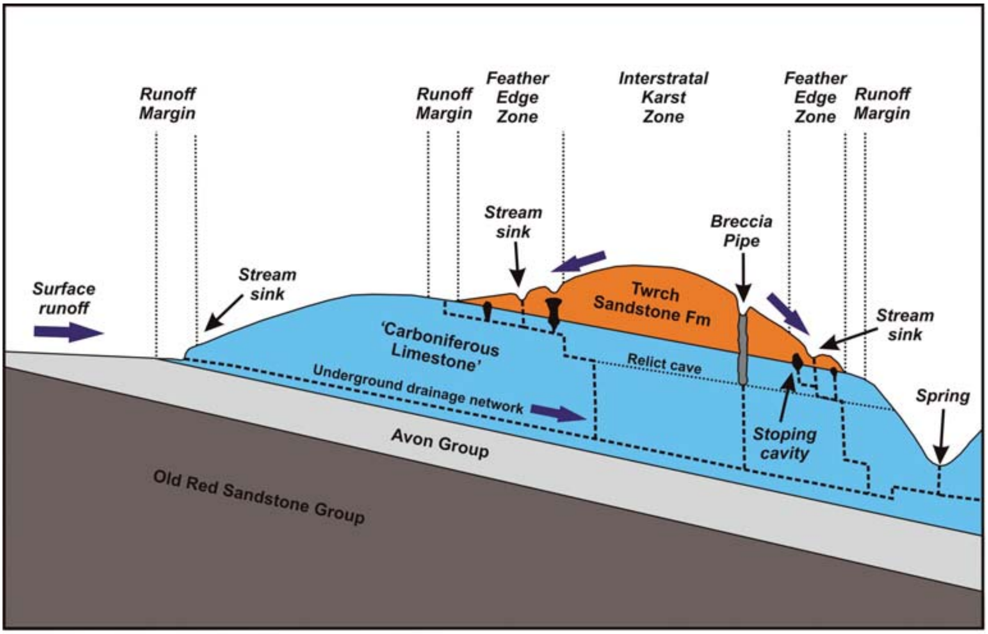

Fig. 4 - Schematic section through the north crop of the South Wales coalfield showing the relationships between the runoff margin, feather edge zone and interstratal karst zone.

4. New uses for the GeoSure dataset?

4.1 Information to inform the development of sustainable drainage systems (SUDS)

Sustainable **D**rainage **S**ystems (SUDS) are being encouraged in the UK to help mitigate the effects of flooding caused by development which is increasing the rapidity of surface runoff (Woods-Ballard *et al.* 2007). In the UK, the draft Flood and Water Management Bill will include provision for the implementation of National Standards for SUDS (DEFRA 2010). Identifying safe areas for the sustainable installation of SUDS in light of developing legislation, will ensure that their long-term performance is maintained while minimising their potential environmental impacts In many areas they can be effective and safe, with various solutions available including soak-aways, holding ponds and porous pavements and surface materials. In some areas, the installation of infiltration based SUDS may be inappropriate. For example, disposal of surface water into the ground may lead to pollution of groundwater or increase the susceptibility to geohazards. In karst areas any water disposal method that infiltrates drainage through the ground has the potential to wash fine materials out of the covering deposits and induce sinkhole development (Fig. 5). This is a well-documented phenomenon alongside US highways where drainage ditches commonly cause the development of sinkholes adjacent to the road (Waltham *et al.,* 2005). Sinkholes caused by leaking pipes are well documented (McDowell, 2005; Waltham *et al.,* 2005) and soak-aways are an anthropogenic trigger that has caused subsidence in Mosul city, Iraq (Jassim *et al.,* 1997).

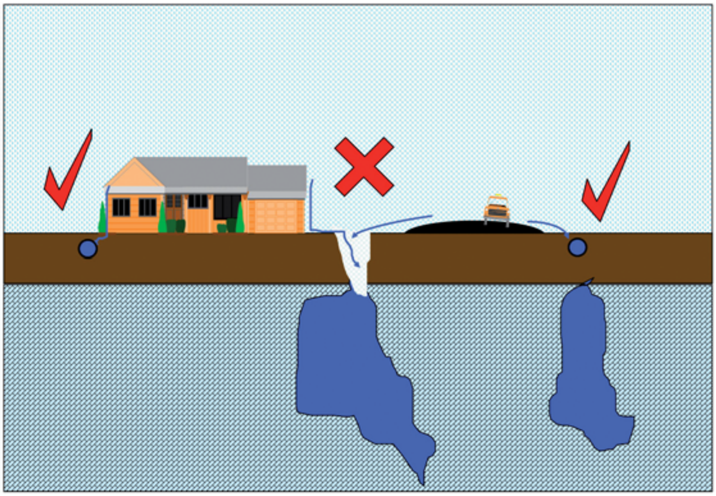

Fig. 5 - Disposal of surface water in karstic areas can trigger subsidence, such areas are unlikely to be suitable for SUDS that use soakaways.

In addition to karstic collapses inappropriate disposal of surfacewater can increase the susceptibility to landslides, collapsible ground and shrink-swell problems. The information derived for the various GeoSure layers can be applied to a Sustainable Drainage Systems decision support dataset that would inform and possibly help regulate the installation of such facilities. Some areas will be inappropriate because of high groundwater levels and potential groundwater flooding, especially in the chalk. Some areas will be inappropriate because of karst, shrink-swell clays and landslides. In other areas groundwater quality may be impacted but this is dependant in part, on the attenuation capacity of the geological subsurface. Conversely, some will be suitable where there are free-draining deposits and deep water tables or clay deposits suitable for the installation of surface lagoons.

4.2 Information to help with the safe implementation of ground source heat pumps

Ground source heat pumps are becoming popular as a source of green energy, but their uncontrolled and uninformed installation could cause future problems and liabilities. The installation of open loop ground source heat pumps in the chalk aquifer of the London region is subject to controls by the Environment Agency with respect to groundwater source abstraction licences and discharge consents which are granted for limited times (Fry, 2009; Le Feuvre and St John Cox, 2009). However, the development of ground source heat pumps in the chalk of the London area have also highlighted the need to carry out the Rossum Sand Test to assess the risk of sand being transported from the Thanet Sand Formation into the wells (Chen, 2009). This leads to a further potential problem that is not addressed: that of subsidence caused by the collapse of the Thanet Sand Formation into karstic cavities in the underlying chalk. This is the failure mechanism that was responsible for the destruction of four houses in Bromley on the outskirts of London in April 2006. This also forced the temporary closure of a main railway line and the evacuation of 20 houses (BBC 2010; Faber Maunsell, 2006). The exact triggering mechanism of this collapse is not known, but similar collapses in the future could be induce by the installation of open loop ground source heat pumps in this sequence. Similarly, other karstic sequences could also be affected and information needs to be made available to inform the regulators.

The GeoSure information, which gives an indication of the susceptibility to karstic collapse is suitable to inform on karstic areas where it is unwise to install open loop ground source heat pump systems. In these areas there should be a presumption to install closed loop systems (Fig. 6). This type of synthesis could be allied with information on the ground thermal conductivity and terrestrial heat flow plus other controlling factors (Busby *et al.,* 2009) to produce a national ground source heat pump suitability map.

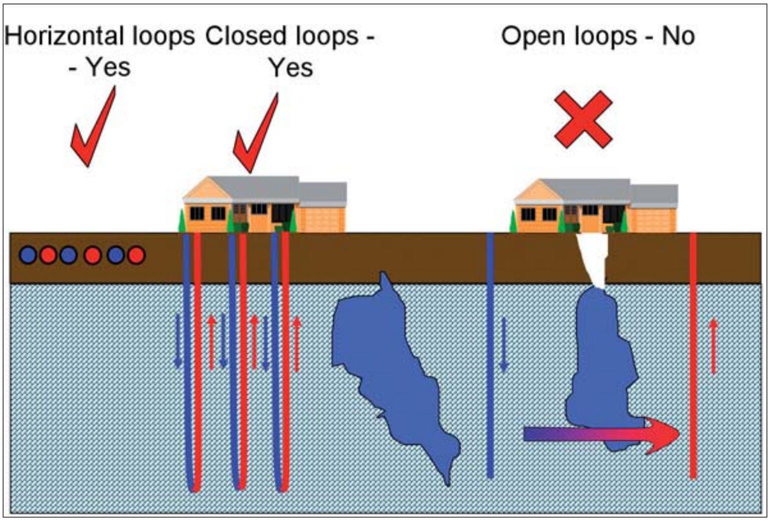

Fig. 6 - Subsidence problems in karst areas that could be caused by open loop ground source heat pumps; closed loop systems are unlikely to cause such problems.

4.3 Groundwater abstraction and aquifer protection

In the UK the protection and licensing of ground water abstraction is managed by the Environment Agency. Based on groundwater modelling, groundwater protection zones have been calculated for groundwater supplies and the information is available on the internet (Environment Agency 2010) with an interactive searchable map "What's in your backyard?". Groundwater protection areas benefit from regulations on the amount of fertilizers that can be applied to the ground and regulations with respect to pollutants entering the ground. For the modelling, the overall nature of the aquifers and covering materials have been taken into account, but the amount of karstification and details of the karst are not generally known or built in to the modelling. Using tracer tests, it has been shown in many limestone areas, and some chalk areas, that the presence of karstic conduits can permit the very rapid transmission of pollutants (Maurice *et al.,* 2006). In Lithuania the presence of sinkholes is taken into account when assessing the aquifer vulnerability

in karst areas and the agricultural regulation around them (PAUKSTYS *et al.,* 1999). It is feasible to utilise the BGS GeoSure information to help with the modelling of the susceptibility of karst areas to groundwater pollution via sinkholes.
All karstic areas are prone to subsidence caused by natural or induced fluctuations in the local groundwater levels. These can be changed dramatically by groundwater abstraction and local groundwater recharge, both of which can cause subsidence. Consequently, the effective management of karstic aquifers should also try to control the rapidity and amount of the fluctuations in the piezometric surface. Large-scale abstraction for industry or irrigation can cause subsidence. Irrigation of fields is also proven to cause an increase in subsidence features in geologically susceptible areas (GUTIÉRREZ *et al.,* 2008). Currently in the UK there is no regulation of groundwater abstraction that specifically considers the susceptibility of areas to subsidence induced in the karstic rocks. The GeoSure soluble rocks dataset could be utilized to inform the regulators of areas where ground water abstraction could cause karstic collapses.

5. Conclusions

The use of digital map information allied with the karst database and local knowledge have allowed the construction of the GeoSure soluble rocks derived dataset which gives a measure of the susceptibility of areas to karstic subsidence. This dataset is already being used to assess areas for insurance and site characterization purposes. In addition, it has potential to be used as a part of the tools for the design or regulation of sustainable drainage systems (SUDS) geothermal heat pump installations and groundwater abstraction.

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