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Rapid Geohazard Assessment System for the UK Natural Gas Pipeline Network

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The British Geological Survey (BGS) and National Grid Transco (NGT) have produced a new GIS for the rapid assessment of the potential for a significant geohazard to adversely affect any section of the UK natural gas pipeline transmission network. NGT is responsible for the safety and maintenance of the 18 000 km long high-pressure transmission network that supplies gas to business and domestic consumers across the UK.

Health and Safety Legislation in the UK requires NGT to demonstrate that the risks to individuals living and working in the vicinity of gas pipelines are adequately managed. In order to enhance its capabilities for assessing the risks due to geological ground conditions NGT required detailed information about the distribution and potential severity of geohazards across the UK. BGS, as the primary holder of national geological hazard data in the UK, were commissioned to design suitable GIS layers as part of the risk assessment methodology.

Of the many geohazards that affect the UK, landsliding and the dissolution of soluble rocks were considered to pose the greatest threat to the transmission network. Other hazards, such as clay shrinkage, running sand and compressible ground, were considered to be of significance only during pipeline construction and were not thought likely to cause rupture during operation. BGS national hazard datasets for landslide and dissolution hazard were truncated to buffer zones centred upon the pipeline. These data were enhanced by detailed information from the BGS National Landslide Database and Karst Database.

The result of this research was a set of continuous GIS layers that show the level of potential hazard from landsliding or dissolution of soluble rocks at any location on the pipeline network in the UK. NGT will be using this data to: improve their risk assessment methodology in this area; inform discussions on pipeline safety with their safety regulator and to improve their surveillance strategies where it is considered that geohazards represent a potential threat to the integrity of the pipeline.

National Geohazard Assessment

The British Geological Survey is the primary holder of geological and geological hazard data in Great Britain. BGS maintains several databases, containing site-specific details of different geohazard entities (e.g. sink-hole location) or events (e.g. landslide movements). BGS has also developed a series of digital data layers that provide a seamless nationwide assessment of geohazard susceptibility, usually accessed via a Geographical Information System (GIS) (Table 1).

Development of these databases and data layers date to the early 1980s (ref) as part of the …. Since their early development, each of the holdings has been maintained, resulting in an increase in the amount and detail of data stored. For instance in 2004, over 400 new landslide records were added to the National Landslide Database. Crucially, the software used to input, store and retrieve each of the holdings has also been updated regularly.

Geohazard assessments, providing continuous nationwide coverage of information about geohazards were first developed by the BGS in (ref GHASP). Ongoing collection of site-specific data, map revision and improvements in information technology have enabled the evolution of these datasets into a highly sophisticated geohazard assessment system based upon deterministic analyses of robust data holdings.

Table 1. Summary of BGS geohazard databases and national scale GIS hazard assessment layers.

Point Databases	Geohazard GIS layers
• National Landslide Database • National Karst Database (including evaporite • National Geotechnical Database • National Geochemical Database (G Base)	• Geohazard • Slope Instability • Dissolution of Soluble Rocks • Shrink-Swell • Compressible Ground • Collapsible Ground • Running Sand • Radon

The research described in this paper utilized information from the National Landslide Database, the National Karst Database and the then current iteration of the national geohazard assessment system - GeoHazArd SP (GHASP).

GHASP was originally constructed using a code system in which district geologists (experts in the geology of a particular UK region), supported by engineering geologists, identified geological hazards within their district. By this method, the susceptibility to landslide, dissolution of soluble rocks, running sand, shrink-swell, compressible soils and mining induced subsidence was determined for each postcode sector.

Landslide hazard was determined by the professional judgement of each district geologist. Assessments of hazards in each district were based upon known incidents of landsliding, the broad geotechnical character of each sector, typical gradients and observations of geomorphology made by the geologist and his/her mapping team. Where required, engineering geologists advised district geologists on geotechnical and geomorphological parameters. Although the system is essentially based upon empirical data and judgement; it was a practical method of collating and interpreting a great deal of complex and experiential information that would otherwise have been very difficult to use.

National Grid Transco High-Pressure Transmission Pipeline

National Grid Transco are responsible for the safety and maintenance of the high-pressure transmission pipeline network for the distribution, storage and supply of natural gas across Great Britain. The pipeline extends across most of the British mainland, with a total length of just over 18 000 Km (Figure 1).

Hazard Assessment Requirements

Health and Safety Legislation in the UK requires NGT to demonstrate that the risks to individuals living and working in the vicinity of gas pipelines are adequately managed. In order to enhance its capabilities for assessing the risks due to geological ground conditions NGT required detailed information about the distribution and potential severity of geohazards across the UK. BGS were commissioned to design suitable GIS layers as part of the risk assessment methodology.

Only geohazards involving ground movement were considered in this research. Although there are many types of ground movement that can affect a pipeline route and infrastructure, it was felt that hazards posed by the dissolution of soluble rocks and by landslides were the most relevant in the context of this assessment. Experience has shown that the size, engineering specification and performance parameters of pipelines within the transmission network meant that most other hazards have little effect on them.

Landslide Hazard

Landsliding is a common but largely unrecognised occurrence in Britain (Department of the Environment 1996). Landslide is the internationally accepted term for down slope movements of material under the influence of gravity that falls somewhere within a spectrum of mass movements ranging from rock avalanche to soil creep. These mass movements are part of the denudation process of weathering and erosion by which the land's surface is worn down. Although landslides are very common in Great Britain (and elsewhere) they frequently remain unrecognised due to their characteristic features being removed by natural processes (weathering and erosion) or agricultural activity.

A landslide occurs when the shear strength of a slope is exceeded by stresses due to the force of gravity. It does not move if the shear strength of the material that forms the slope is greater than the stress due to gravity. If the balance is altered so that stress exceeds available strength, movement down slope will occur until a stable slope profile is formed (i.e. until the stress is reduced or material strength is increased). Landslides are typically caused by a combination of one or more of the following factors:

- The removal of support from the bottom of a slope by marine erosion, river erosion, seepage erosion, landsliding of the lower slope, or excavation during construction work.
- Loading at the top of a slope caused naturally by landslides, debris flows, rock or soil falls, depositing earth material onto the slope from an active area higher up the slope, or artificially by construction works or land fill operations.
- An increase in the height of the water table often results in an porewater pressure between soil particles. This may lower the effective stress within the slope and result in a reduction in the shear strength of the soil.
- Fresh mudrocks will decrease in strength when weathered as stress relief causes their physical disintegration; swelling occurs as water is absorbed by their component clay minerals and the beneficial effects of soil suction are lost. In granular rocks and soils the strengthening effect of inter-particle cements may be lost as the cementing agents are dissolved.
- The geological structure of the slope and its surroundings may have a controlling effect on the incidence, nature and frequency of landslides. Discontinuities (bedding planes, fissures in clay soils, jointing in rocks, faulting and unconformities) all cause disruption in the continuity of the material provide paths for the flow of water and form planes of weakness within a rock or soil mass.
- Similarly folds in strata may collect groundwater and concentrate flow.

- Climate has a critical effect upon slope stability. The amount, intensity and location of rainfall leads to infiltration into the groundwater, can raise pore-water pressures and can physically remove and alter slopes by overland flow. The effectiveness of the infiltration will be affected by other factors such as vegetation cover and the time of year, both of which will influence the amount of water lost by evaporation. It is also possible that a period of very dry weather, which has caused ground shrinkage and cracking, will allow infiltration quickly and to a greater depth and reduce losses due to runoff.

The distribution of landslides in the UK is controlled by a number of factors including geology, slope gradient, hydrogeology and climate. This pattern is further complicated by the effects of past climates during which the prevailing weather in the UK was much colder and wetter, leading to intensive landslide activity. Such landslide activity has resulted in a legacy over much of the UK of 'relict' landslides which exist in a state of meta-stability, where only a small adjustment to the stress conditions in the landslide system can result in failure. An illustration of the broad distribution of landsides in the UK is provided in Figure 2.

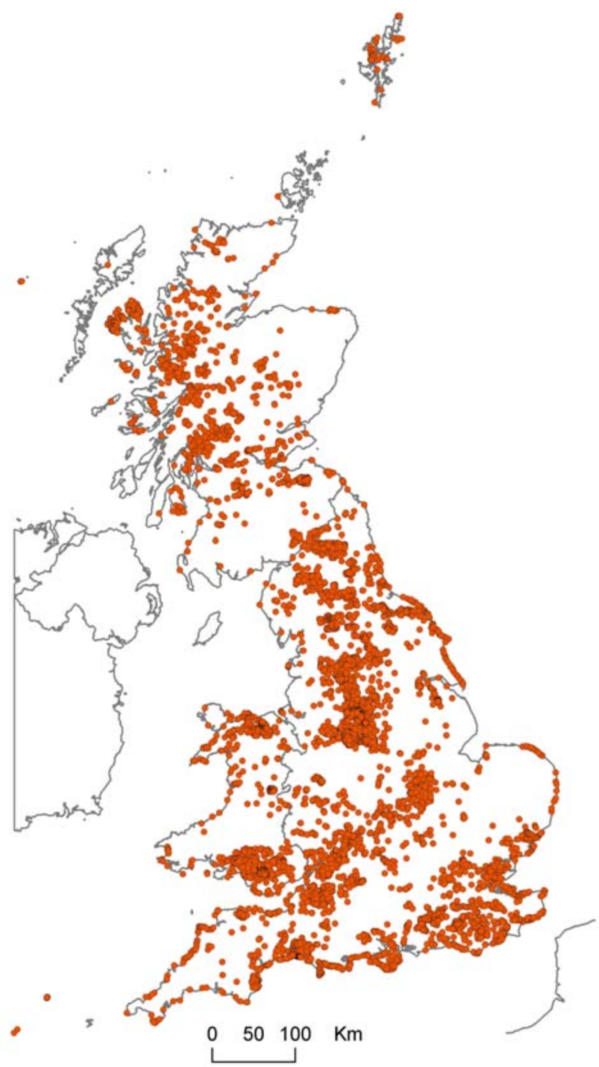

Figure 2. Distribution of recorded landslides in Great Britain as held in the BGS National Landslide Database.

The process of landsliding includes the movement of material by the act of falling, toppling, sliding and flowing (Varnes or some ref) see above) depending on the topography of the ground surface and the nature of the material of which it is composed. The impact that such movements have on rigid linear infrastructure such as a gas pipeline will vary between different situations but typical impacts include sudden impact, loading, longitudinal compression or tension and lateral deflection or shearing.

Dissolution of Soluble Rocks Hazard

Britain has five types of soluble (or karstic) rocks: limestone, dolomite, chalk, gypsum and salt, each with a different character and associated problems. Subsidence, often triggered by anthropogenic disturbance such as water or brine abstraction occurs widely, especially where karstic rocks are overlain by a thin superficial cover. These situations can cause significant engineering and foundation problems that may affect pipelines and their infrastructure.

Distribution of dissolution hazards from soluble rocks in Great Britain

Britain has four types of soluble (or karstic) rocks: limestone, chalk, gypsum and salt, each with a different character and associated problems (Figure 1) (Cooper et. al., 2001). Subsidence, often triggered by anthropogenic disturbances such as water or brine abstraction, occurs widely, especially where karstic rocks are overlain by a thin superficial cover. These situations can cause significant engineering and foundation problems that may affect pipelines and their infrastructure.

The limited occurrence of rocks susceptible to dissolution means that it is convenient to discuss each rock type individually.

Limestone

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 coalfield (Waltham, et al., 1997). Cambrian and Devonian Limestones, together with some Jurassic limestones locally also display karstic characteristics. The major problems associated with these karst areas are water supply protection, geological conservation and engineering problems. Subsidence associated with subsidence hollow (doline) formation does occur, but is generally not severe enough to affect pipelines.

Chalk

The Chalk is the most widespread carbonate rock in the country and of immense importance for water supply. It forms Great Britain's most important aquifer. In places it has solutionally enlarged fissures and conduits, notably sediment-filled dissolution pipes. Chalk dissolution also generates subsidence hazards and difficult engineering conditions associated with the development of clay filled pipes and fissures. Other problems also include irregular rockhead, localised subsidence, increased mass compressibility and diminished rock mass quality. It is not generally considered to be problematical to pipelines.

Dolomite

Dolomite is less soluble than limestone and produces fewer karst features. The caves in dolomite tend to be small and of limited extent while surface features are scarce. The main areas of dolomite are in the Permian sequence of north-east England and the rock has a low hazard rating.

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 (Figure 1) (Cooper, 1986, 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 high solubility rate of the gypsum 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 continuing development of subsidence features cause concern for pipelines crossing the area.

Salt

Salt in Great Britain occurs mainly in the Permian and Triassic strata of central and north-eastern England (Figure 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 is not fully understood, but the subsidence caused by them may be severe enough to cause concern for pipeline structures.

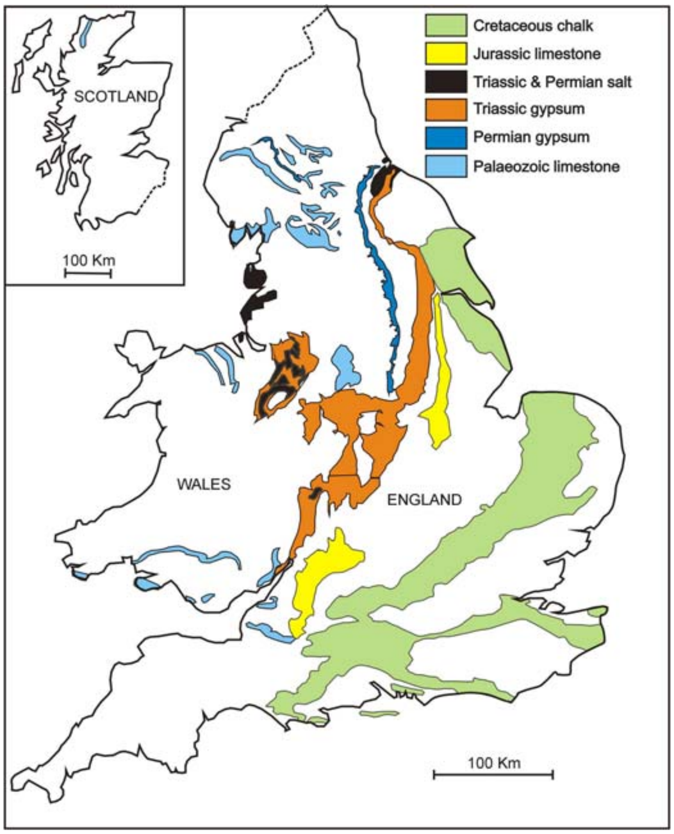

Figure 1 The distribution of the main soluble rocks in Great Britain (excluding Permian dolomite)

Subsidence and Collapse

Carboniferous and Devonian limestone:

Collapse dolines commonly form in the cover strata in areas of interstratal karst such as the Llangattock Plateau in South Wales. The rocks here comprise insoluble sandstones over karstified Carboniferous Limestones. The collapses here are rare and infrequent, but they have the potential to create very large collapses or areas of subsidence, with differential settlement.

Suffosion dolines are quite common in areas with a thin superficial cover such as till, river terrace and head deposits. Subsidence occurs where superficial deposits are gradually washed into fissures in the underlying karstic rocks, creating metastable cavities in the unconsolidated cover materials which subsequently collapse. This is probably the most common form of subsidence in karstic areas, and dolines can be quite large in size. These may also undergo repeated collapse, especially if infilled. In addition to major dolines, flushing out of sediment from infilled cavities or joints can be aggravated by the alteration or impediment of drainage. However, this is unlikely to cause major collapses. Very irregular rockhead is also typical of limestone karst areas.

In areas of bare karstic limestone, the collapse of near-surface cave systems crossed by a pipeline would be extremely rare, but if it did happen, it could create a significant collapse.

Triassic and Permian gypsum

Gypsum dissolution areas are prone to the formation of voids that can migrate upwards as breccia pipes through considerable thicknesses of the adjacent soft strata (Cooper, 1986, 1988, 1989, 1998). In the majority of the Triassic gypsum areas the gypsum is fairly thin and interbedded with moderately impervious strata, these areas are not very hazardous (Cooper and Saunders, 1999). In some of the Permian gypsum areas, there are very thick sequences of the rock. These are mainly interstratal karst, interbedded with aquifers making the adjacent gypsum very prone to dissolution. The thicknesses of gypsum present are considerable and the sizes of the subsurface voids are large. In these areas, appreciable voids can develop and break though to the surface causing significant subsidence features that in some places may reach 30 m or more across and many metres deep. These occur on a human rather than a geological time scale (Cooper, 1998) and may constitute hazards to pipelines or their infrastructure.

Figure 2. Subsidence crater (doline) caused by the dissolution of Permian gypsum beneath the village of Sutton Howgrave, North Yorkshire [SE 3146 7928]. The hole started to collapse in December 2000, the photograph was taken on 14th February 2001 when the hole was 5-6m in diameter and 11m deep with water at a depth of 8m. The crater is about 400m from the gas pipeline. Photo A.H.Cooper © NERC.

Triassic salt

Salt is the most soluble of the commonly present soluble rocks. Its solubility means that it is never seen at the surface in Great Britain and it generally occurs in areas with considerable thicknesses of superficial deposits. It is prone to natural dissolution and salt springs are commonly present where it occurs (Cooper, 2000, 2002). It is also a valuable mineral resource that has been exploited by shallow mining and brine extraction. Where near-surface brine has been exploited, or is being exploited at the moment, linear brine runs with their associated subsidence radiate from the extraction points. These runs can be a hundred metres or more in width and up to several kilometres in length. Even after brine extraction has ceased, these brine runs may continue to be active and become conduits for natural dissolution. In some of the salt areas, crater subsidence has also been reported.

Chalk

Flushing out of sediment from infilled dissolution pipes in the Chalk is quite likely to occur where drainage is altered or impeded, but probably unlikely to cause very large collapses. However the density of areas of subsidence in certain areas may be enough to create problems. Very irregular rockhead, causing differential settlement, many be a problem. Caves are rare and cavern collapse will only create very minor subsidence if any.

Jurassic Limestones

There is a possibility of solutionally enlarged sediment filled joints becoming washed out. However, these are unlikely to create cavities large enough to cause problems.

Lateral movement

Lateral movement is not generally associated with the subsidence caused by underground dissolution where subsidence hollows or dolines form at the surface. It is unlikely in most of the limestone areas, the Chalk and the gypsum areas. In areas of salt subsidence where there is thick superficial cover and where linear subsidence features form, lateral movement has been observed. This has been noted on the Crewe to Manchester railway line (Figure 3).

Figure 3. Lateral and vertical movements of the Crewe to Manchester railway line over an area of active salt dissolution and subsidence. Note the pylon bases with vertical adjustment and the lateral movement of the railway line. Photo A.H.Cooper © NERC.

GIS layer creation

To assess the hazards to the gas pipeline network, the digitised lines supplied to BGS were buffered at 250m (500m corridor) and cut against the enhanced BGS GHASP (formerly **G**eo-**HA**zard **S**usceptibility **P**ackage) dataset to produce a GIS layer indicating the areas where there may be high hazard ratings for the pipeline.

The GHASP dataset

The GHASP dataset was initially designed for assessment of geological hazards causing building damage. Some geological hazard areas included in it are not hazardous to pipelines, but are very hazardous to shallow foundations of buildings.

GHASP was originally constructed using a code system in which district geologists (experts in the geology of a particular UK region), supported by engineering geologists, identified geological hazards within their district. By this method, the susceptibility to landslide, dissolution of soluble rocks, running sand, shrink-swell, compressible soils and mining induced subsidence was determined for each postcode sector.

Landslide hazard was determined by the professional judgement of each district geologist. Assessments of hazards in each district were based upon known incidents of landsliding, the broad geotechnical character of each postcode sector, typical gradients and observations of geomorphology made by the geologist an his/her mapping team. Where required, engineering geologists who alongside their own professional knowledge and expertise had access to a considerable library of geotechnical data across the UK advised district geologists on geotechnical and geomorphological parameters.

Although the system is essentially based upon empirical data and judgement; it is a practical method of collating and interpreting a great deal of complex and experiential information that would otherwise have been very difficult to use. It has proven to be an effective tool for assessing hazards at a national and regional (1:50 000) scale and is still widely used by many BGS clients including engineering companies and members of the insurance industry.

The GHASP dataset has been modified to create more detailed geohazard polygons, in particular, areas deemed to be at greatest risk from landslide hazard. Each GHASP rating has been modified by comparison with the data in the BGS National landslide database and GIS system and the mass movement (landslide) layer in BGS DiGmap50. This comparison showed areas where additional data regarding landslide occurrence have been collected or become available since the GHASP rating system was devised. The delineated areas have been incorporated into the GIS and each given a hazard rating on a scale of one to five. Areas of known landslide deposits are given a hazard rating of five.

The landslide hazard assessment has been made using information at a scale of 1:50k and will not identify areas subject to small-scale landslide due to local geological conditions that are below the resolution of the data set. The detailed BGS datasets are still being populated and it is possible that in the future more information will come to light that will require some of the areas in this report to be reassessed.

Application

For the majority of the network there is little cause for concern. However, a significant proportion of the buffered zone defined in this research has been identified as being at some risk to landslide activity. This is partly due to the nature of the GHASP dataset that considers landslide hazard averaged over postcode sectors but is also a reflection of the widespread distribution of landslide hazard in the UK

Explanation of hazard ratings
The operational dataset for use by pipeline managers contains 6 hazard zones:

0. Slope instability problems are not likely under current conditions.
1. Slope instability problems are not likely to occur under current conditions but consideration of potential problems in adjacent areas impacting on the site should always be considered.
2. Slope instability problems may have occurred in the past or may occur in the future. Site inspections should consider specifically early signs of slope movement in the area.
3. Slope instability problems are probably present or may occur in the future. Site specific assessment of risk may be advisable. Site inspections should consider specifically early signs of slope movement in the area.
4. Slope instability problems almost certainly present and may be active. Site specific assessment may be required to assess risk. Periodic or continuous monitoring may be necessary. Possibility that remedial work will be required.
5. Landslide deposits present, slope instability problems almost certainly present and may be active. Site specific assessment required to assess risk. Periodic or continuous monitoring may be necessary. Possibility that remedial work will be required within the zone and possibly in adjacent areas.

Hazard ratings provided in this research relate to landslide susceptibility as a whole rather than to the specific different types of landslide as described in Sections 2.2.1-2.2.5 but described the susceptibility of an area to some form of landslide activity. They should be regarded as a guide with which further investigations at specific locations can be made.

TABLE 1. AREA OF TOTAL BUFFER ZONE AFFECTED BY LANDSLIDE HAZARD RATINGS

		Area in sq m	Area in sq km	Percentage Area of Buffer
Landslip CLASS	1	2 603 571 145	2604	31.0
	2	1 184 230 517	1184	14.1
	3	263 298 184	263	3.1
	4	56 378 052	56	0.7
	5	14 649 407	15	0.2
	All	4122127305	4122	49.1
Area Unaffected	0	4 280 776 097	4281	50.1

The information held by the British Geological Survey in its GIS databases has allowed the gas pipeline network in Great Britain to be assessed for the potential ground instability caused by the presence of soluble rocks. For the majority of the network and most soluble rock areas, there is little cause for concern. However, areas underlain by Triassic salt where there has been salt extraction, or where it is still taking place, could be problematical. In these areas subsidence events have commonly produced depressions many kilometres long and up to a hundred metres or more across.

There are a few areas underlain by Permian gypsum where subsidence has occurred near to the pipeline network and where future subsidence could occur. In general the historically recorded gypsum subsidences are between 5 and 30m across. However, larger ones do exist and all that can be said of their age is that they post-date the ice-age and thus formed in the past 12,000 years.

This operational dataset for use by pipeline managers contains five hazard zones.

1. Low: areas where soluble rocks are present, but very unlikely to cause any significant problems.
2. Low to moderate: areas where soluble rocks are present and unlikely to cause any significant problems.
3. Moderate: areas where soluble rocks are present in considerable amounts, but problems are unlikely except in very adverse and unusual conditions.
4. Moderate to high: areas where soluble rocks are present in considerable amounts and where some surface subsidence has occurred; possibly hazardous in adverse conditions such as enhanced surface or sub-surface water movement.

5 High: areas where considerable thicknesses of soluble rocks are present and where significant surface subsidence has been observed either due to natural or induced dissolution. A high possibility that surface subsidence may occur and that some of it may be severe enough to affect pipelines and their infrastructure.

Only hazard zone 5 presents areas that **may** include areas that constitute a significant hazard to pipelines in the vicinity. In any other areas outside these five zones, dissolution problems are not thought to occur.

Table 1. Areas of Total Buffer Zone affected by Soluble Rocks Hazard Ratings

		Area in sq m	Area in sq km	Percentage Area of Buffer
Solution Hazard CLASS	1	935 910 154	936	11.1
	2	159 083 780	159	1.9
	3	155 979 073	156	1.9
	4	21 262 753	21	0.3
	5	5 169 7342	52	0.6
	All	1323933102	1324	15.8
Area Unaffected	0	7 078 970 30	7079	84.2

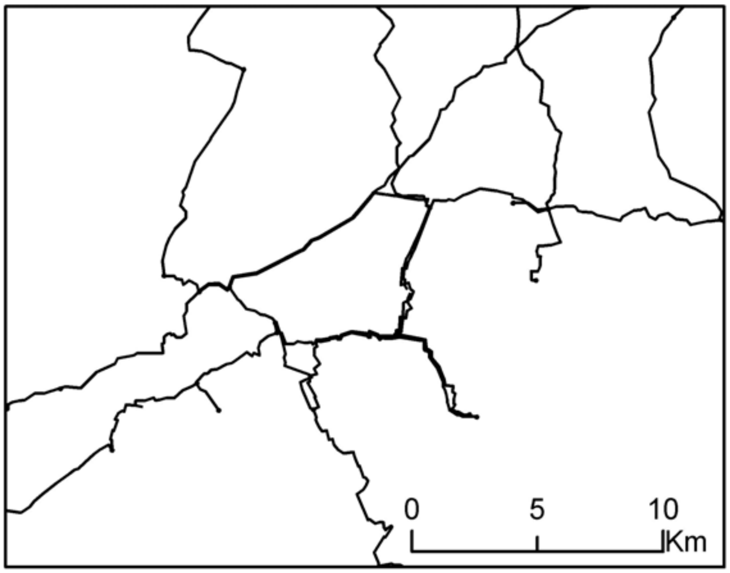

Figure 3. Sample of pipeline network data.

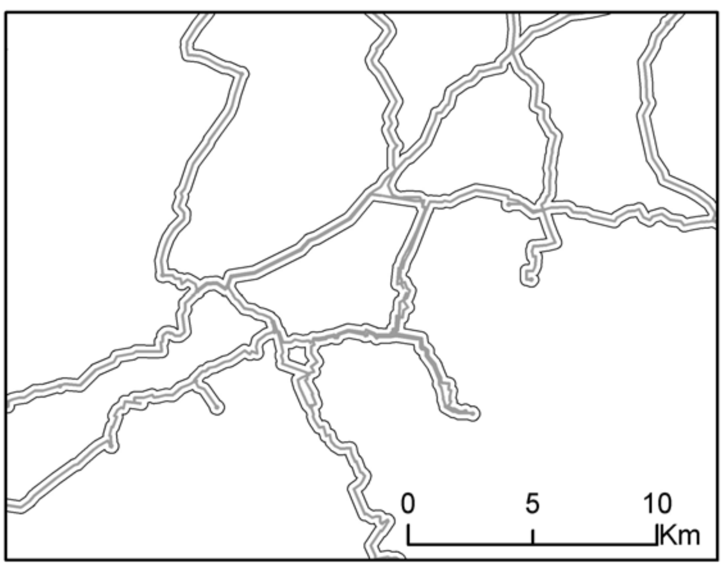

Figure 4.Buffer network applied to the pipeline section

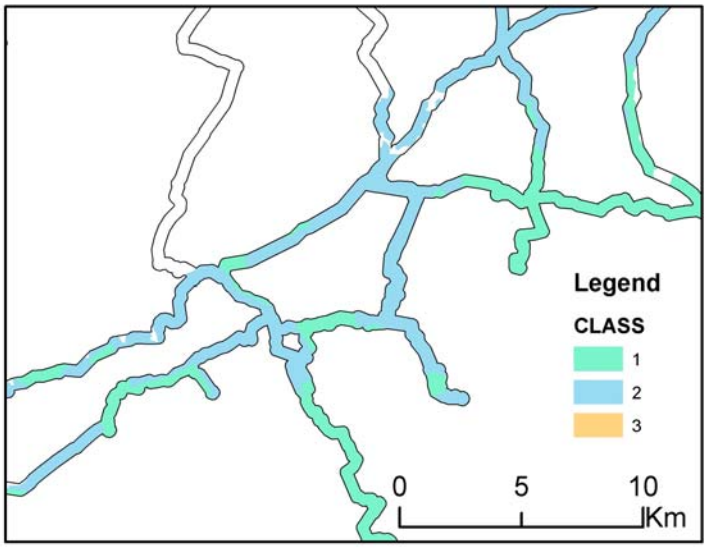

Figure 5. buffer