Geohazards caused by rising groundwater in the Durham Coalfield, U.K.

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Abstract: Geohazards caused by rising groundwater can have a considerable effect on the built environment, especially where this is underlain by former coal mines, such as those found in County Durham, UK. Reactivation of faults and the expulsion of gas are two specific geohazards that are known to occur and be potentially dangerous and threatening to human health. However, little substantive research has been undertaken into these problems to date. This paper will present research undertaken recently to understand the various potential geohazards that can be activated directly by rising groundwater associated with cessation of pumping from deep mine systems. The geohazards considered include landslides, ground subsidence, seismicity, gas emission, impacts on structures, salinisation and health hazards, and these will be examined in the context of the Durham Coalfield. Numerical modelling has allowed a detailed examination of the effect of rising groundwater on a variety of geohazards, and the results from this study will be presented in this paper.

Résumé: Geohazards provoqué par les eaux souterraines se levantes peut avoir un effet considérable sur l'environnement établi, particulièrement où ceci est été à la base par les anciennes mines de houille, telles en tant que ceux trouvés dans le comté Durham, R-U. La réactivation des défauts et l'expulsion du gaz sont deux geohazards spécifiques qui sont connus pour se produire et être potentiellement dangereux et menaçants à la santé humaine. Cependant, peu de recherche substantive a été entreprise dans ces problèmes jusqu'ici. Cet article présentera la recherche entreprise récemment pour comprendre les divers geohazards potentiels qui peuvent être activés directement par les eaux souterraines se levantes liées au cessation du pompage des systèmes profonds de mine. Les geohazards considérés incluent des éboulements, l'affaisement de terre, la séismicité, l'émission de gaz, des impacts sur des structures, le salinisation et des risques sanitaires, et ceux-ci seront examinés dans le contexte du bassin houiller de Durham. Modeler numérique a permis un examen détaillé de l'effet des eaux souterraines de montée sur une variété de geohazards, et les résultats de cette étude seront présentés en cet article.

Keywords: environmental urban geotechnics, regional planning, geological hazards, hydrogeology, water table, abandoned mines

INTRODUCTION

The Durham Coalfield, in the North-East of England was one of the largest coalfields in the history of British coal exploitation. Mining from this region continued over several centuries, only recently ending in the last decade or so. Much of the coal extracted from this coalfield came from deep underground mines, which necessitated a series of groundwater controls systems including deep pumping extraction. As these mines became uneconomic closure followed and pumping was ceased or reduced. Following this rising groundwater has been observed over the region in recent years, in a number of areas. The rising of post closure groundwater levels has been variable across the region, partly due to patterns of cessation of pumping and partly due to the permanent alterations of the geology and hydrogeology that have resulted from past deep mining activity. Associated with this rising groundwater is the potential for a number of geohazards to occur, which can cause significant nuisance and cost through damage to the built and urban environments.

This paper aims to review the recent changes in groundwater levels in the Durham coalfield region, together with the development of a predictive numerical model aimed at establishing likely steady state groundwater levels in the region following complete cessation of pumping. From this geohazards and their consequences to the built environment associated with these changes in groundwater level after cessation of pumping will be considered.

GEOLOGY AND HYDROGEOLOGY OF THE DURHAM COALFIELD

Geological setting of the Durham Coalfield

The Durham Coalfield lies within Durham County in the North-East of England. The River Tyne is on its northern boundary with the Northumberland Coalfield to the north. On the south and east side lie hills of Permian rocks. The River Wear flows through the region in a north-easterly direction towards the North Sea. To the west of the Carboniferous Coal Measures, lie the Pennine Hills that run down the centre of England from the Scottish border to the English Midlands. In terms of bedrock the Durham Coalfield consists of mainly Carboniferous and Permian aged rocks. Carboniferous rocks are divided into the Alston Group, Stainmore Group and Westphalian rocks; the Coal Measures are Westphalian in age. Permian rocks consist mainly of limestone, sandstone and dolomite. The Geological succession is given in more detail in Table 1.

Overall, the geology is generally relatively simple as this region has not undergone severe geological structural deformation (Johnson 1995). There are three phases to the structural geology in the Durham Coalfield, namely, pre-Upper Carboniferous, Late Carboniferous-Early Permian and post-Permian. The deposition of the Carboniferous cover rocks was strongly influenced by this first phase of movement (Johnson 1995). During the second phase most of the faulting and folding in the Carboniferous rocks occurred. One of the principal fractures in the Carboniferous rocks it that of the Butterknowle fault. Subsequent uplift followed a period of erosion, which removed the whole of the southern Coal Measures and varying amounts of the Middle Coal Measures/earlier rocks.

Table 1. Geological succession in the Durham Coalfield (after Yu 2006)

<table>
<tr><th colspan="2">Period</th><th colspan="2">Formation</th><th>Typical Rocks and Description</th><th>Conditions of deposition</th></tr>
<tr><td colspan="2">Quaternary</td><td colspan="2">Quaternary</td><td>Deposition mostly from glacial or periglacial activities</td><td>Glacial</td></tr>
<tr><td colspan="2">Tertiary</td><td colspan="2">Hebburn Dyke (intrusive)</td><td>Tholeiite</td><td></td></tr>
<tr><td colspan="2" rowspan="3">Triassic</td><td colspan="2">Mercia Mudstone Group
(formerly Keuper Marl)</td><td>Mudstone with Seaton Carew Formation at base</td><td>Uncertain</td></tr>
<tr><td colspan="4">Unconformity</td></tr>
<tr><td colspan="2">Sherwood Sandstone Group
(formerly Bunter Sandstone)</td><td>Brick red micaceous arkose, reddened with age</td><td>Flat alluvial plain</td></tr>
<tr><td rowspan="13">Permian</td><td rowspan="12">Upper</td><td colspan="2">Roxby Formation
(or Upper Permian Marl)</td><td>Red siltstone and mudstone with gypsum veins; some sandstone</td><td>Deltaic or alluvial plain</td></tr>
<tr><td colspan="2">Sherburn Anhydrite Formation
(or Upper Anhydrite)</td><td>Gypsum and anhydrite</td><td>Shallow sea or Deltaic</td></tr>
<tr><td colspan="2">Rottern Marl Formation</td><td>Red siltstone and mudstone with gypsum veins</td><td>Shallow sea or Deltaic</td></tr>
<tr><td colspan="2">Billingham Anhydrite Formation</td><td>Gypsum and anhydrite</td><td>Shallow sea or Deltaic</td></tr>
<tr><td rowspan="8">Magnesian Limestone</td><td>Seaham Formation</td><td>Calcite mudstone with calcite concretions</td><td>Shallow sea</td></tr>
<tr><td>Fordon Evaporate and Seaham Residue Formation</td><td>Anhydrite and halite; some dolomite; the Residue comprises buff-brown clay with dolomite and limestone</td><td>Shallow sea</td></tr>
<tr><td>Roker Dolomite Formation (or Hartlepool and Roker Dolomite)</td><td>Dolomite</td><td>Shallow sea</td></tr>
<tr><td>Concretionary Limestone Formation</td><td>Laminated and unlaminated dolomite with varying proportions of calcite concretions; also collapse breccias</td><td>Deep water of high salinity, Basin margin slope</td></tr>
<tr><td>Hartlepool Anhydrite Formation (or the Middle Magnesian Limestone)</td><td>Anhydrite; some dolomite</td><td>Shallow sea</td></tr>
<tr><td>Ford Formation
(or the Middle Magnesian Limestone)</td><td>Dolomite (lagoonal, reef and basin facies)</td><td>Tropical barrier reef coast</td></tr>
<tr><td>Raisby Formation
(or the Lower Magnesian Limestone)</td><td>Limestone and calcitic dolomite</td><td>Gently inclined marine slope</td></tr>
<tr><td>Marl Slate Formation</td><td>Laminated bituminous dolomite</td><td>Barred basin</td></tr>
<tr><td>Lower</td><td colspan="2">Yellow Sands Formation</td><td>Sandstone, mostly weakly cemented</td><td>Arid desert</td></tr>
<tr><td colspan="6">Unconformity</td></tr>
<tr><td rowspan="9">Carboniferous</td><td rowspan="5">Upper</td><td colspan="2">Intrusive igneous sills and dykes</td><td>Quartz dolerite</td><td></td></tr>
<tr><td colspan="2">Upper Coal Measures</td><td>Mudstone, siltstone and subordinate sandstone; coals and seatearth</td><td>Delta Plain</td></tr>
<tr><td colspan="2">Middle Coal Measures</td><td rowspan="2">Mudstone, siltstone, sandstone, seatearth and coals</td><td>Delta Plain</td></tr>
<tr><td colspan="2">Lower Coal Measures</td><td>Delta Plain</td></tr>
<tr><td colspan="2">Upper Limestone Group and Longhoughton Grit (Millstone Grit) Series (Stainmore Group♣)</td><td>Marine limestone, shale, sandstone, seatearth and coal (order in Yoredale facies); sandstone and grit stone</td><td>Deltaic and marine</td></tr>
<tr><td rowspan="4">Lower</td><td colspan="2">Middle and Lower Limestone Group (Alston Group ♣)</td><td>Marine limestone, shale, sandstone, seatearth and coal (order in Yoredale facies)</td><td>Deltaic and marine</td></tr>
<tr><td colspan="2">Scremerston Coal Group
(Orton Group♣)</td><td>Coal, shale, sandstone, limestone</td><td>Deltaic and marine</td></tr>
<tr><td colspan="2">Fell Sandstone Group</td><td>Mostly sandstone</td><td>Delta</td></tr>
<tr><td colspan="2">Cementstone Group</td><td>Shale and limestone</td><td>Occasional marine</td></tr>
<tr><td colspan="2">Devonian</td><td colspan="2">Old Red Sandstone facies</td><td>Sandstone</td><td>Non-marine, Low land</td></tr>
<tr><td colspan="6">♣ Units in Durham Coalfield</td></tr>
</table>

Subsequent sedimentation occurred on the surface of the remaining Carboniferous rocks (Smith 1994). Tertiary movements developed in North-East England causing flexuring, faulting and eastward tilting of these later sediments. These movements are responsible for much of the faulting observed today, including re-activation of many of the major faults, such as the Pennine Fault (Turner et al. 1995). Movement along these faults resulted in uplift of the Lower Carboniferous Alston Group above younger low-lying Permo-Triassic rocks along the Pennine escarpment.

Hydrogeology

Little has been published on the hydrogeology of the Durham coalfield due to the limited amount that groundwater plays (about 10%) for public water supply (Younger 1995). The hydrogeology can be described according to the stratigraphical sequences. The hydrogeology of the pre-Carboniferous, although based on a limited dataset, shows very little groundwater circulation. By comparison, the Carboniferous strata are considered a minor aquifer. Figure 1 shows the basic distribution in relation to hydrogeology across the Durham Coalfield in relation to Carboniferous outcrops.

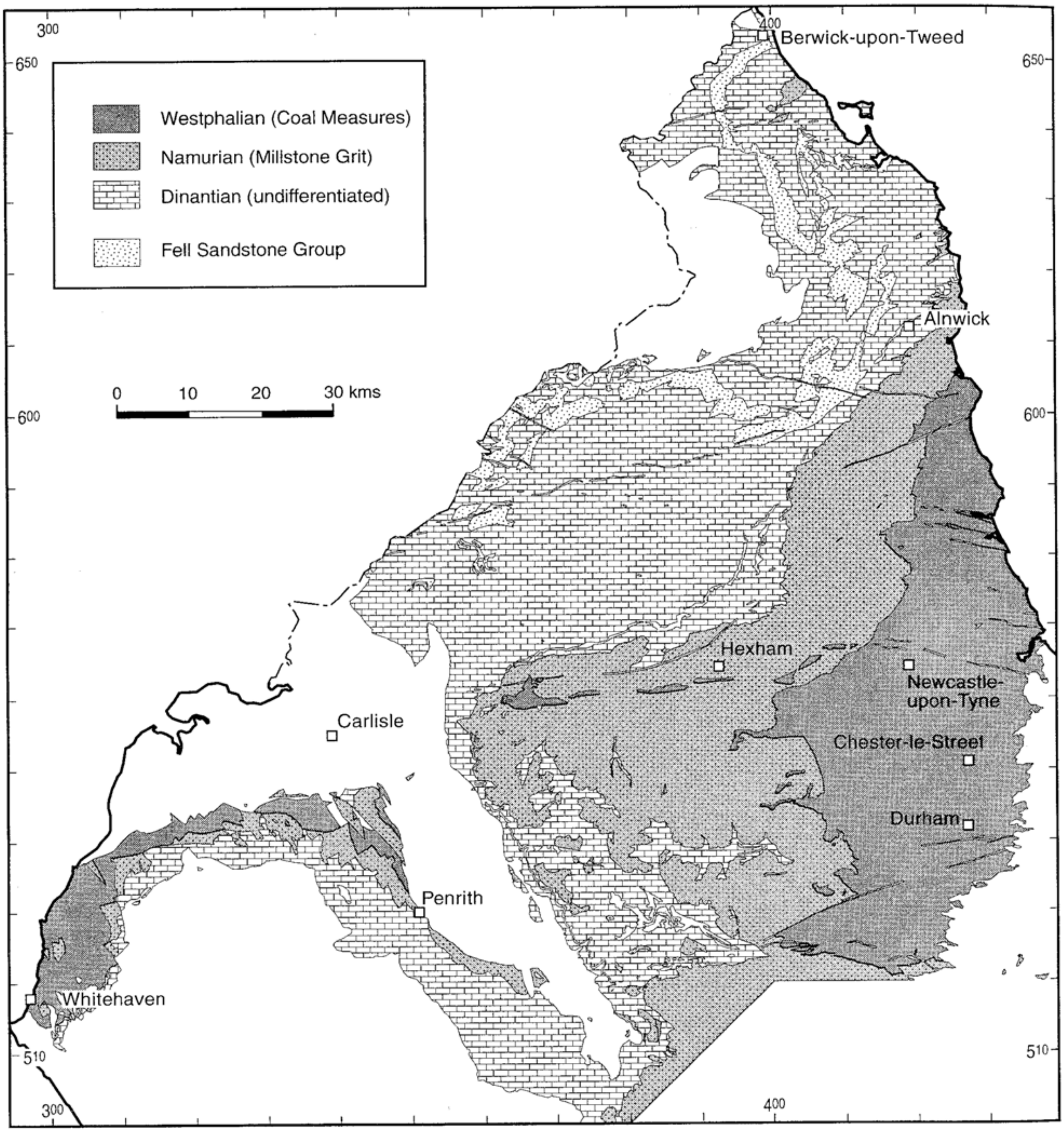

Figure 1. Distribution of Carboniferous outcrops relating to the hydrogeology of North-East England (after Jones et al. 2000)

In the Lower Carboniferous four groups can be earmarked, namely: Cementstone Group, the Fell Sandstone Group the Scremerston Coal Group and the Lower and Middle Limestone Group. Of these, the most important aquifer lies within the Fell Sandstone Group, which has been a source of water supply for over a century. Recent investigations confirmed that the Fell Sandstone Group is, in fact, seven separate aquifers effectively confined by thick, laterally persistent mudstones (Turner, Younger & Fordham, 1993). The Scremerston Coal Group acts as an aquitard while the Lower and Middle Limestone Group contains a number of thick permeable aquifers similar to the Fell Sandstones, in spite of their limited lateral extent (Younger 1991).

Within the Upper Carboniferous exists the Namurian (Upper Limestone Group and Longhoughton (Millstone Grit) Series and the Westphalian Coal Measures Group. The Namurian includes a number of multilayered sandstones and limestones made up of, effectively, separate aquifers with intervening mudstones and shale aquicludes/aquitards. The Westphalian Coal Measures Group forms a complex multi-layered minor aquifer, made up of argillaceous aquitards isolating the occasional thicker sandstone aquifer horizons. Coal Measures sandstones, due to their grain size distribution and degree of cementation, possess very little intergranular permeability. Groundwater movement is predominately through fractures in the sandstone. Mining-induced subsidence has, in certain places, created hydraulic continuity between layers. However, this extensive disruption has complicated the hydrogeology (Younger 1995). As the mine workings in the Durham Coalfield were interconnected, mining has caused an increase in bulk permeability (Minett et al. 1986). This has led to the creation of interconnected subsurface 'ponds' throughout the coalfield (Younger 1995). Associated with these 'ponds' is disparity of piezometric levels between individual ponds due to relatively impermeable seam barriers.

The Permian Magnesium Limestone constitutes the major aquifer in North-East of England and this covers about a quarter of the Durham Coalfield area, with the remainder being covered by Carboniferous Coal Measures. However, the aquifer properties are notoriously unpredictable (Allen et al. 1997). The Middle Permian Marl is, in effect, a 'leaky' aquitard and so a slight head difference is maintained between the Upper and Middle and/or Lower Magnesium Limestones.

The Quaternary formations play a considerable role with respect to recharge of the underlying aquifers. Deposits include: Blown Sands, Alluvium (predominately silt and sandy silts), dense lodgement tills and sequences of glacial sand and gravel. Where lodegement till is present (around coastal plains) recharge is minimal. However, the glacial sand and gravel sequences serve as perched aquifers or allow recharge to underlying aquifers. Unfortunately, no detailed hydrogeological analysis of the glacial sequences of the Durham area has taken place despite the importance of the Magnesium Limestone (Younger 1995).

RISING GROUNDWATER IN THE DURHAM COALFIELD

Mechanisms of groundwater rise

There are a number of key factors that can influence and alter groundwater levels across a region. Before any detailed evaluation of any changes or rise of groundwater in the Durham Coalfield is considered, it is necessary to briefly review the impact of these key factors. The key factors that can change groundwater levels and result in these levels rising are listed in Table 2. This table also includes a few key comments on their relative importance.

Table 2. Factors controlling groundwater rise

Factors	Comment	Reference
Change in precipitation	Direct influence on groundwater levels particularly after heavy rainfall events.	Yang et al. (2002)
River level change: flooding	Groundwater flow near large rivers is strongly influenced by transient river levels. Correlations have shown clear agreement between general and temporal groundwater levels	Forkel, Demny & Köngeter (1998)
Rising sea levels	Sea water level rise may cause seawater intrusion into groundwater aquifer. Tidal variations cause fluctuations of groundwater levels via cyclic compression of strata, reducing the storativity of the aquifer by forcing water out through joints.	Whitworth (2002)
Surface environment changes: (1) Urbanisation (2) Agriculture	(1) Common with many cities in the UK urbanisation has seen a cycle of abstraction rates exceeding recharge during industrial development causing a lowering of groundwater levels, followed by reduced abstraction and associated rising of groundwater levels, ultimately returning to historic levels. Leakage from water supply and sewer system can impact on groundwater levels. (2) Surface infiltration from agriculture irrigations schemes and impact of alien vegetation on groundwater levels.	Knipe et al. (1993) Jakoyljev el al. (2002) George (1990); Ruprecht & Schofield (1991); Cullen (2002)
Mining Activity: (1) Cessation of mine pumping (2) Changes to Hydrogeology	(1) Post closure groundwater levels rise as dewatering systems are terminated. Groundwater rebound occurs. (2) Mining activity permanently alters the subsurface hydrogeological conditions. Not only are interconnected voids created (pre-collapse) but fracturing, bedding separation, fracture porosity all change significantly altering permeability and groundwater flow regimes.	Henton (1981) Booth (2002); Straskraba et al. (1994)

Clearly, influences on groundwater can come from both external and internal (below ground level) sources. Of these it is clear that the most dramatic and rapid changes in the Durham Coalfield occur from mining activity and its subsequent cessation. In fact, trends in monthly precipitation in the Durham area over the last 30 years show only a very slight increase in levels. Thus, post closure will cause a direct elevation of groundwater levels as pumping activity is ceased. Whether these levels return to historic levels is unclear, primarily as groundwater flow regimes and general hydrogeological conditions are significantly different from the pre-mining condition.

There has been much research about groundwater rebound in abandoned mining areas. This includes assessments in South Yorkshire (Burke & Younger 2000), in Fife (Sherwood & Younger 1997), in South Nottinghamshire (Dumpleton et al. 2001), in Northumbria, North Nottingham, Durham, East Fife (Whitworth 2002), South Nottinghamshire (Robins, Dumpleton & Walker 2002), and predictive research in Durham (Younger 1993).

Groundwater rise in the Durham Coalfield region

Younger (1995) showed that, in general, over a 20 year period leading up to 1990, groundwater levels rose in the Durham Coalfield (Figure 2). During active deep mining, groundwater levels were maintained at a depth of around 150 m below ground level (Downing 1998). However, the majority of these deep dewatering pumps were turned off over a period starting from the 1950s and, as a result, groundwater levels rose. There is a clear correlation between cessation of deep pumping and groundwater level rise. These changes are due mainly to reductions in abstraction, particularly in the south-western part of the aquifer, with the cessation of dewatering in underlying coal workings in this area (Younger 1993). By comparison, some of the coastal boreholes were affected by subsurface seawater intrusion. However, Younger's work was based on data localised to certain areas where the Magnesian Limestone outcrops.

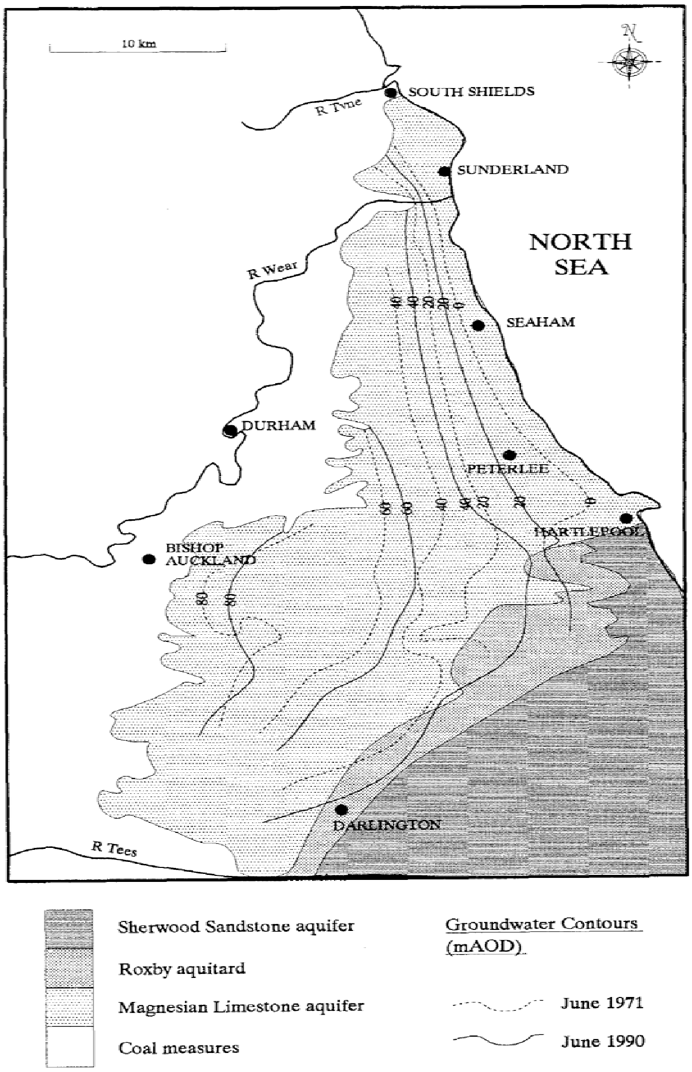

Figure 2. Hydrogeological Map of County Durham, showing selected groundwater contours for June 1971 and June 1990 (after Younger 1995)

Subsequent fuller data sets from the Coal Authority and the Environment Agency have allowed a more detailed and evenly distributed trend over the last 10 years (up to 2004) to be assessed (Figure 3). More that 30 data sites were used for each year from 1995 to 2004, giving a reasonable size and distribution geographically to the data used.

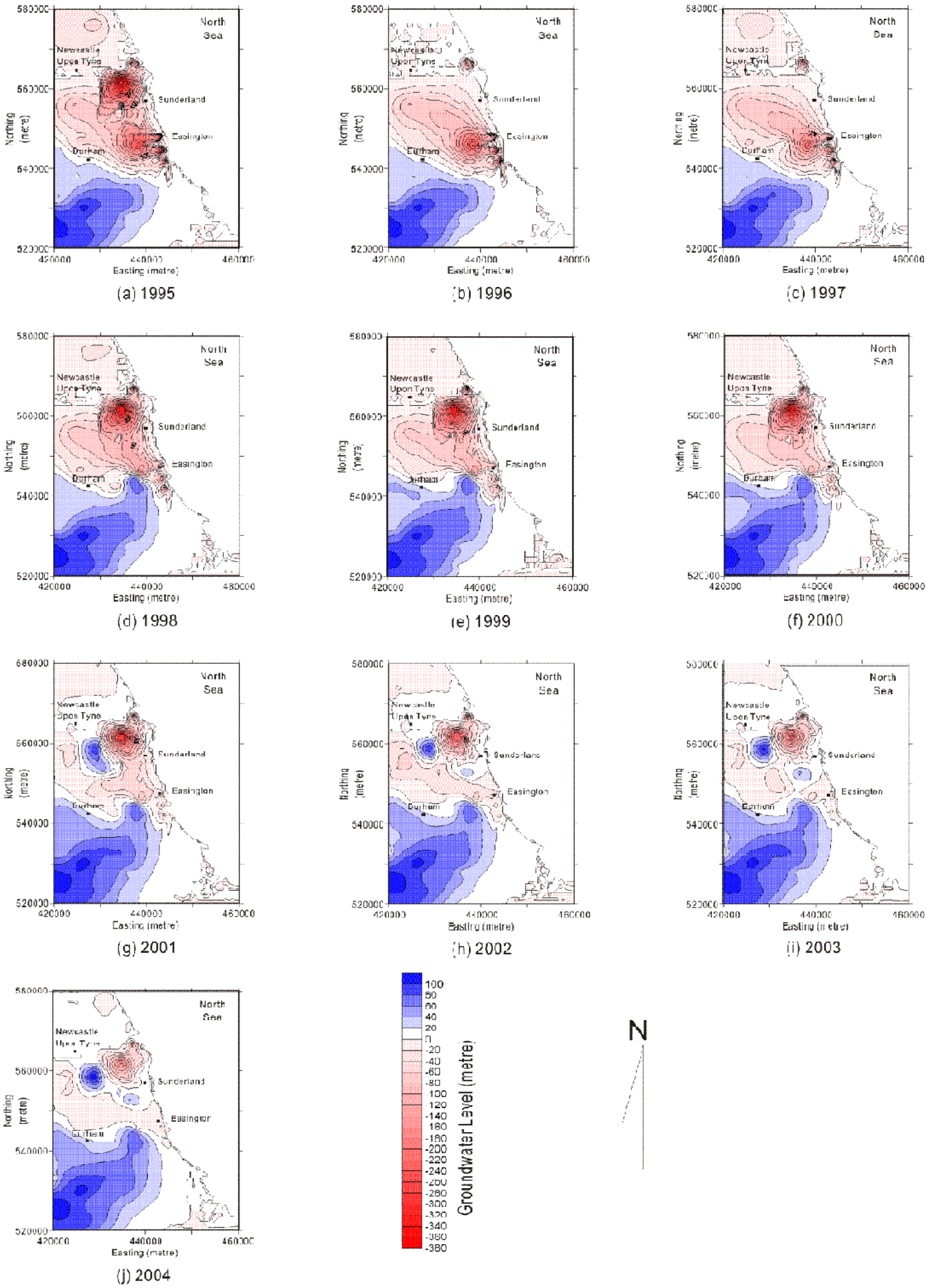

Figure 3. Groundwater levels in and around the Durham coalfield area for June 1995 and June 2004 (after Yu, Jefferson & Culshaw 2006a).

Data before 1995 are limited both in geographic distribution and number, and so the period from 1990 to 1994 has not been considered here. This is not considered problematical, as it is the overall trend that is important. To enable a direct correlation with data presented in the literature (notably Younger 1995), hydrogeological data corresponding to mid June have been taken. Additionally, this helps to reduce the impact of other external factors such as rainfall recharge, which is the lowest over the month of June, based on data supplied by the Environment Agency. This was consistent over a number of years and so was deemed to give an adequate benchmark for making annual comparisons.

The results from the data analysis show that the groundwater levels in the south-west of the region are generally stable over the period with a tendency for levels to start to reach longer term steady state positions further in a north and east direction (Figure 3). This is no surprise as most of the collieries in the south west were closed by the early 1970s. However, there is a clear trend of continued groundwater rising around coastal areas, in particular around Easington. In the period 2001 to 2004 these groundwater levels appear to be stabilising. This can be attributed to the relatively recent closure (early 1990s) of deep workings around these areas.

To assess how a complete cessation of pumping will influence groundwater level and ultimately the risk of geohazard development, a detailed numerical model was developed and assessed. A brief overview of this numerical model has been given in the following section. Further details can be found in (Yu 2006, Yu, Jefferson & Culshaw, 2006b).

Numerical simulation: future scenario

A numerical simulation has been undertaken to estimate groundwater rising after cessation of the present groundwater pumping. The numerical simulation has been undertaken with MODFLOW (McDonald & Harbaugh, 1988), a 3-dimensional groundwater assessment package that uses the finite difference method, results from which are shown in Figure 4.

The model was created using elevation data and geological information. The simulation was based on the worst-case scenario of all pumping having been turned off. Thus, this will allow an estimation of the maximum extend of change in groundwater levels across the Durham Coalfield. The model, therefore, was simulated under steady state conditions, corresponding to hydrogeological re-equilibration of groundwater levels post mining. It has been assumed that any geohazards that would develop as groundwater levels re-equilibrated would not occur immediately, but only after some time once levels had reached their maximum (worst case) extent. Examples justifying this assumption can be found in the literature, e.g. the delayed seismicity that resulted from fluid injection in the Rocky Mountains, which took at least one year to occur after injection had ceased (Ingebritsen & Sanford, 1998). In addition, it has been assumed that rainfall patterns will not change from historic levels. Again this seems reasonable in the shorter term, although changes of such patterns as a result of climate change will no doubt have an impact. However, there is a high degree of uncertainty about this and such changes will only act as an external influence on groundwater levels. Thus, overall, it seems reasonable to ignore the impact of climatic changes for the purposes of this study.

The results shown in Figure 4 clearly suggest that groundwater levels will not rise uniformly over the region. Some areas, particularly in the south and west, will experience a lowering of groundwater levels while others are predicted to see further elevation in levels. However, the simulation does show that for significant areas most of the potential for further rise in groundwater levels has been completed (indicated by the white areas in Figure 4). Where the blue and white patterned shading occurs in Figure 4., the simulation suggests that head difference between the simulated areas and outside the no flow boundary are similar. This may be influenced, in part, by the Kriging method of estimation used to assess differences across the boundary between known and unknown data points (see Yu 2006 for further details). The reddish area in Figure 4 shows areas that are vulnerable to groundwater rise after full cessation of pumping. Overall though, the numerical simulation shows groundwater levels at their final rebound conditions, if pumping was to fully cease. This is because the full time frame for this to occur has not been assessed here.

However, the decision to stop pumping should still be taken carefully in order to prevent dramatic rise in certain areas within specific geological strata. For instance, the simulation suggests that once complete cessation of pumping has taken place and total rebound has occurred, the area between Chester-le-Street and Durham would expect a head increase in the lower hydrogeological strata, particularly the Middle and Lower Coal Measures, Stainmore Group and Alston Group (Figure 4 b-e). Clearly, both recent and possible future worst-case scenario groundwater levels have implications for geohazards development and this will now be examined.

GEOHAZARDS CAUSED BY RISING GROUNDWATER

In the study of geohazards caused by rising groundwater in urban areas of the Middle East, George (1992) included damage to structures, damage to road and services, overloading of sewer system and treatment plants, salting and water logging of soils, and health hazards. More typical geohazards resulting from groundwater level rises can be considered to include landslides, ground subsidence, seismicity, gas emission, impacts on structures, mobilisation of pollutants and health hazards. An overview of these is given briefly in Table 3.

GEOHAZARDS CAUSED BY RISING GROUNDWATER IN DURHAM COALFIELD

Younger (1993) listed a number of environmental impacts, which may arise from water table rebound in County Durham, along with techniques for the mitigation of these effects. The possible environmental impacts included: the pollution of the River Wear and tributaries, the groundwater pollution in adjacent aquifers, the intersection of landfills/foundations/sewers/buried services by a rising water table, subsidence and surface gas emission. He chose the pollution of the River Wear as the most critical and certainly the most visible of all the potential impacts in his research.

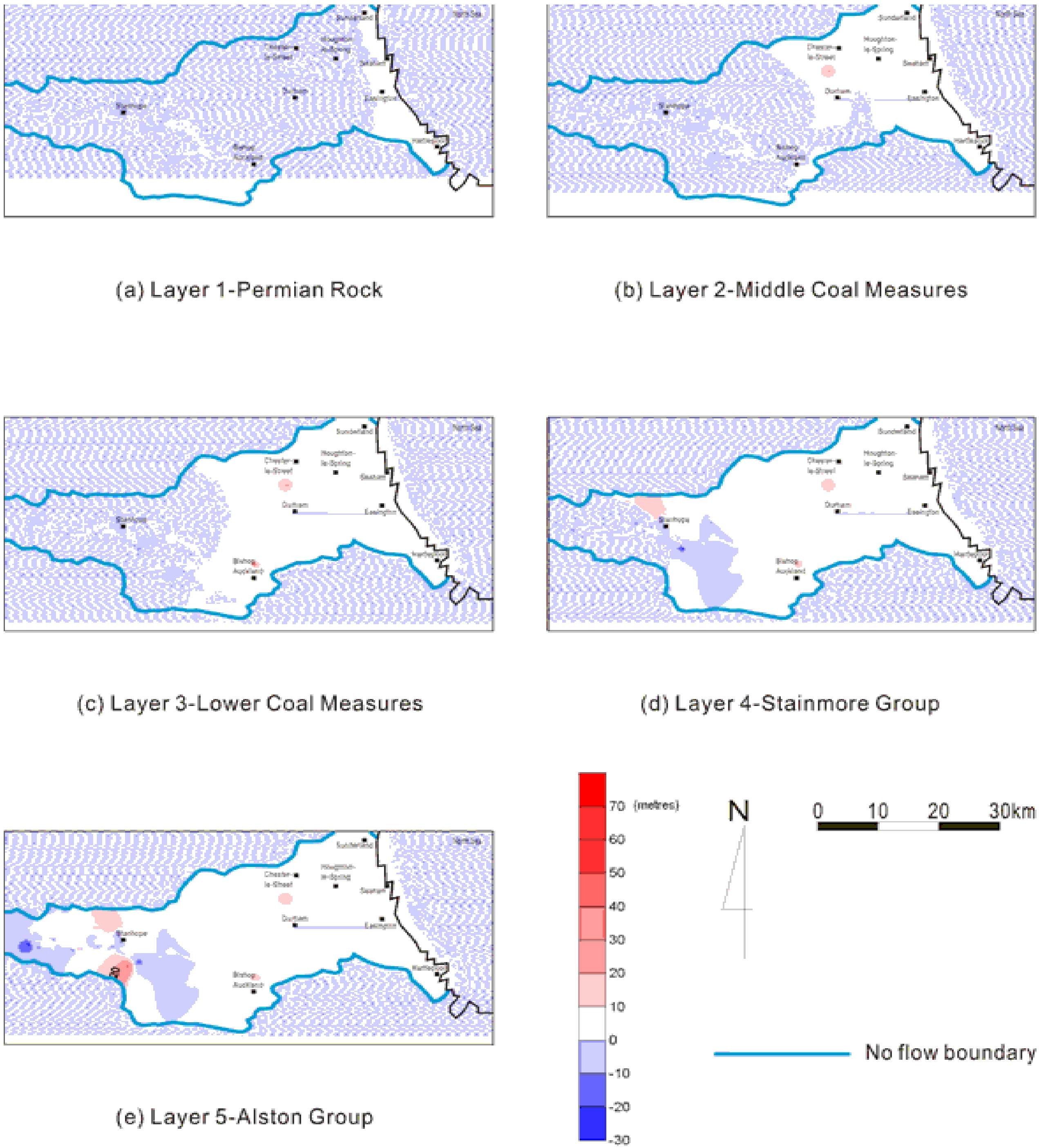

Figure 4. Hydrogeological simulation of groundwater head change after stopping groundwater pump in Durham Coalfield (Yu et al. 2006a)

With respect to Younger (1993), possible geohazards from rising groundwater in the Durham Coalfield would be ground subsidence, seismicity, gas emission, and river pollution. Among these, examples of seismicity induced geohazards can be found across County Durham, e.g. fissuring by fault reactivation found near Quarrington Hill. Associated with the geology of the Durham Coalfield are a number of features, which could be a source of geohazard development in this region. For example the Magnesian Limestone (Lower and Upper) contains a high frequency of fracturing and fissuring. Not only will these play an increasingly important role as groundwater levels rise to stabilised positions but could, in turn, present zones of weakness within the rock formations across the region. This will be further exacerbated as the nature hydrogeological barrier of the Coal Measures has now been substantially disturbed or removed. However, of the four geohazards listed above, fault reactivation (ground movement and seismicity) and gas emission present the major geotechnically-induced hazards to the built environment. This is not to say that river pollution is not important, just that its impact is more on water environmental quality and not specifically on geotechnical aspects of the built environment.

Table 3. Typical geohazards caused by rising groundwater

Geohazard	Comments	Reference
Landslides	It is well documented that rising groundwater levels promote landslides via elevation of pore water pressures.	Waltham (2002)
Ground subsidence	Collapse of old mine pillars and shafts can occur due to slaking of seat-earths, punching failure and loss of pillar strength. Water surges may induce/renew surface subsidence, which can be progressive or sudden over a wide area or concentrated along fault planes. Unknown shafts may also be revealed.	Gray & Bruhn (1984); Younger (1993)
Seismicity: earthquakes & fault reactivation	As groundwater levels rise, water may penetrate faults/joints, reduce strength and reactivate the fault.	Smith & Colls (1996)
Gas emission	As groundwater rises, trapped gases are pushed upwards and can escape via faults, joints and old mine entrances. Of particularly concern is 'blackdamp' as carbon dioxide rich – oxygen deficient air, which can often remain undetected, particularly in a domestic situation.	Younger (1993); Smith & Colls (1996); Robinson (2000)
Impact on structures	Structural damage can occurs with rising groundwater, particularly deep basements or shallow foundations. Principal causes of damage include: chemical attack, settlement/heave and mechanical damage due to erosion and hydrostatic forces.	Morris et al. (2003); George (1992)
Mobilisation of pollutants	As the water table rises pollutants may be mobilised causing new contamination problems. Salt levels can rise changing the groundwater chemistry.	George (1992); Cullen (2002)
Health hazards	In extreme cases, where groundwater levels reach the surface, septic tanks may fail releasing pathogens, etc.	Morris et al. (2003)

Fault reactivation

There have been a number of explanations offered for the observation of fault reactivation occurrence (or fissuring) in the Durham Coalfield. Wigham (2000) attributed fissuring to spatial variations of coal extraction causing differential mine subsidence in the Middle Coal Measures, resulting from Magnesian Limestone block rotation towards the free edge. However, according to Whittaker & Reddish (1989), in deep mines such subsidence is complete in 5 years. The events reported by Wigham (2000) were deep but occurred some time after the 5 year period. Thus, it is unlikely that the fissuring here was due to differential mine subsidence. Young & Culshaw (2001) suggested that fissuring in the Durham Coalfield comes from continuing mine subsidence resulting from a combined set of effects including pillar failure. Certainly such pillar failures would be expected as groundwater levels increase due to a reduction in pillar strength as pore water pressures increase. An example of this has been demonstrated by Ingebritsen & Sanford (1998) when investigating failure of fluid saturated rocks from the Rocky Mountains. In addition, such elevation of fluid pressures in the bedrock would also be expected to weaken already existing faults and fissures and so promote further subsidence as groundwater levels rise.

There is some evidence that such events are starting to be observed. Fissure opened across the A690 road in the Houghton-le-Spring area in 2000 and again in 2003 (Young & Culshaw 2001, Young 2003). Given the predicted groundwater rise discussed in this paper, it seems likely that further surface movements will occur. Thus, it seems reasonable to suggest that further groundwater induced fault reactivation will generate further ground subsidence in the future, especially if full cessation of pumping occurs and levels are allowed to complete their rebound. By assessment of fault direction and likely strength properties it has been possible to estimate the likely over stress risk ratio of the fault in the Houghton-le-Spring area. Over stress ratio is defined as an estimated shear stress acting on the fault divided by estimated shear strength across the fault, with values greater than 1 indicating a potentially unstable condition. Results from this analysis showed how the over stress ratio in the Houghton-le-Spring area is presently around 1.07 and if full cessation of pumping were to take place this would increase to 1.17 (see Yu, Jefferson & Culshaw 2006c for further details). Thus, the risk of increased subsidence being observed potentially will increase significantly.

Gas Emission

The unconformity between the Middle Coal Measures and the Permian strata can act as a collection zone for mine gas (Wigham 2000). Fissures formed by fault reactivation would generate pathways for emissions as groundwater levels rise; thus gas emission is a potential geohazard that occur directly as groundwater levels change. Two gases that are of concern are methane and blackdamp (a carbon dioxide rich air). Of these carbon dioxide is potentially more dangerous as it is present just above the water table and is often undetected. In the past, there have been a number of reported cases of methane and blackdamp emissions around the Newcastle-upon-Tyne/Washington area. However, most of the groundwater levels in this area have stabilised and no significant elevation of ground water is expected. Thus, further gas emissions are unlikely to increase significantly as a direct result groundwater level change in this area. However, placed on the observed recent groundwater level rises and future simulated changes, it is likely that areas around Sunderland and Seaham are at increased risk.

CONCLUSIONS

The Durham Coalfield region has been a major location of coal extraction for many centuries. Associated with this was deep mine workings, which necessitated deep groundwater pumping. Following closure of these mine workings pumping has been turned off and as a results groundwater level rising has been observed. Previous studies suffered from a relatively small data pool, but with more data across the region becoming available a more detailed picture of the recent groundwater level history has been obtainable. This shows a strong correlation between closure patterns and groundwater rise. A numerical simulation of a future scenario after full cessation of pumping has taken place, taking account of the heterogeneity and associated hydrogeological changes created by deep mine workings. From this it has been possible to assess likely final groundwater rebound levels. This simulation showed that levels will not rise uniformly but will vary across the region with significant head differences seem in the lower strata. In addition, a lowering may occur particularly in the south and west of the regions as levels equilibrate, with rising levels most notice in the Chester-le-Street and Durham City area.

Associated with this groundwater level rise are a number of geohazards. Specific geohazards that affect the built environment directly include fault reactivation and gas emissions. Recent events around Houghton-le-Spring are attributable to fault reactivation and a detailed assessments of the fault in this area suggest that changes in over stress ratio with groundwater rising can explain this event. This suggests that there is an increased risk of further ground subsidence from fault reactivation in the region. In addition, as groundwater levels rise, surface gas emissions increase as witnessed by observations where mine closures and pumping termination took place earlier. Two key gases associated with groundwater rise are methane and 'backdamp' (carbon dioxide rich/oxygen poor air). Of these blackdamp offers potentially the greater hazard as it is often undetected particular in the domestic setting, being present just above the groundwater surface.

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