Mine water rebound in South Nottinghamshire: risk evaluation using 3-D visualization and predictive modelling

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Abstract

Progressive abandonment of the South Nottinghamshire Coalfield raises concerns over the security of the Permo–Triassic Sherwood Sandstone aquifer which overlies the concealed part of the coalfield. A 3-D digital visualization package has been used to assemble and display the complex and diverse data-sets of relevance. Predictive scenarios have been run from these data using the University of Newcastle program GRAM (Groundwater Rebound in Abandoned Mineworkings). The work comprised three phases: (i) confirmation of the geological framework for the so-called 'Pond 3' area (southernmost part of the coalfield) and establishment of a water balance along with an outline groundwater flow path system for the Coal Measures and adjacent strata; (ii) the collation of detailed geometric information on the spatial distribution of discrete geological layers that are considered to have hydrogeological significance, the distribution of mineworkings within key horizons, and the locations of boreholes, shafts and pumping stations (both in the Coal Measures and within overlying strata). Possible flooding configurations have been assessed geometrically to identify 'hot spots' where mine water discharge to surface may occur, and areas where the piezometric level of the rising mine water might promote upward fluxes into the Permo–Triassic Sherwood Sandstone aquifer. In addition, critical areas where coal has been worked close to the base of the Permian and where hydraulic continuity may occur between the Sherwood Sandstone and Coal Measures have been identified; (iii) the GRAM model used data held in the 3-D visualization package VULCAN to define discrete 'ponds' within the coalfield. Recharge to the system allows each pond to fill until overflow pathways are reached, when the adjacent pond may start to fill. A variety of such scenarios have been completed and predictive data generated, which suggest that possible discharge to surface and into the Sherwood Sandstone might occur about 20 years after the end of dewatering.

Keywords: abandoned mines, acid mine drainage, aquifers, coal mines, models

Water from old mine workings rising to the ground surface has been a problem in the UK ever since the earliest coal and metalliferous mines were abandoned. Coal mining methods progressed from the shallow shaft and windlass 'bell pits' of the pre-industrial age to deeper, more systematic 'pillar and stall' extraction in the nineteenth and early twentieth centuries, and culminated in the modern, highly efficient fully mechanized longwall faces of today. Mining permanently alters the state of the ground as rock collapses above the extracted coal seams, causing subsidence and creating fractures which may extend right up to the surface from a depth of several hundred metres. The past 200 years of intensive mining has left a legacy of thousands of old shafts, hundreds of kilometres of old roadways and vast areas of broken strata.

Since all but the shallowest coal extraction has taken place below the natural water table, mining engineers have long had to cope with dewatering of the workings. Sometimes favourable topography has allowed the use of tunnels ('water gates' or 'soughs') to drain under gravity from the mine workings directly to the surface, but in the South Nottinghamshire Coalfield systematic pumping over the entire coalfield has been necessary to artificially lower the water table to deep levels.

Acid mine water drainage (AMD) is water that has become polluted through contact with mine workings. This is mostly groundwater which is either pumped up to surface, or eventually floods the voids once the last pump is switched off as the last working mine in the area is abandoned. Recharge via direct infiltration and lateral inflow of groundwater then effects a rise in water level at a rate determined by inflow rates, void geometry and void volume (Younger 1995). In South Nottinghamshire, there is a complex interconnection of roadways between collieries and between the thirty separate coal seams that have at times been mined. Handling the complex array of data necessary to predict when and where emergence at the surface may take place, and whether the Permo–Triassic sandstone aquifer which partially conceals the coalfield is at risk, is a major and somewhat daunting task.

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The hydrochemistry of AMD results from the dissolution of iron-rich minerals which are common in coal-bearing strata (Wood *et al.* 1999). Dewatering allows these weakly soluble minerals to oxidize to form soluble iron sulphate which in turn is taken into solution once dewatering ceases. The water is usually reduced with a significant COD, and is often acidic (sulphuric acid is a by-product of the solution process). On emergence into contact with the atmosphere, the AMD reacts further to precipitate ferric hydroxide, which is the insoluble ochreous deposit so often seen in streams around mining areas. Apart from damage to aquatic systems, AMD causes acid attack to Portland Cement in foundations, can leach metals from unlined landfill sites, and can create problems at sewage treatment works. Younger & Adams (1999) list the following current areas of concern, in order of frequency and environmental significance:

(1) Surface water pollution.
(2) Localized flooding of agricultural, industrial or residential areas.
(3) Loss of dilution for other pollutants in surface waters where former pumped discharges have ceased.
(4) Overloading and clogging of drains and sewers.
(5) Pollution of overlying aquifers by upward movement of mine water.
(6) Temporarily increased emissions of mine gases, driven ahead of rising mine water.
(7) Ground deformation due to renewed mining subsidence and reactivation of faults.
(8) Adverse effects on landfills—possible damage to lining, leakage of leachate, increased gas emissions.

All of the above have been observed in the UK in the last 30 years, with the exception of No. 8 (although some examples of this are now feared in the north of England).

The scale of the South Nottinghamshire Coalfield coupled with possible risk to the Permo–Triassic aquifer has led to a number of studies (e.g. Dumpleton *et al.* 1995; Wardell Armstrong 1997). Dumpleton *et al.* (1999) not only drew attention to the risks of wholesale coalfield abandonment but also illustrated the many potential hydraulic interconnections within the South Nottinghamshire Coalfield (Fig. 1). However, each of these studies was hampered by the magnitude of the coalfield area and the complexity of the underground systems and the geology. A new approach to handling and assimilating the vast and diverse range of data necessary to understand the hydraulics of this coalfield has now been tested and is based on 3-D visualization using the VULCAN 3-D computer modelling system (developed by the firm KRJA Maptek). The model developed using VULCAN incorporates the mine workings, geology and hydrogeology of the southern part of the Nottinghamshire Coalfield, including the areas between collieries and pumping stations still working in the late 1990s (Calverton, Annesley-Bentinck, Morton, 'A' Winning and Woodside; see Fig. 1) as well as the overlying Permo–Triassic rocks which contain important groundwater resources.

The key objectives of the study were:

(1) To construct a VULCAN 3-D model of the southern part of the South Nottinghamshire Coalfield.
(2) Use the 3-D model to determine potential mine water flowpaths in the event of coalfield closure and cessation of pumping.
(3) Identify areas at risk from future mine water pollution, including surface water courses and the Permo–Triassic aquifer.

The 3-D geological model of the Pond 3 area of the South Nottinghamshire Coalfield has been constructed in VULCAN using available mapping, borehole and other geological data. Mine abandonment plans were incorporated into the model through an intensive operation to digitize selected horizons using the Top Hard seam as the key horizon, the High Main seam as the upper and the Kilburn seam as the lower (Table 1). Not all the available data for the thirty or so intermediate seams were incorporated into the model. However, particular attention was paid to known critical areas, such as existing mine pumping stations and current and former mines which have been prone to water problems. Surface topography was constructed from Ordnance Survey digital contours and is accurate to about 1 m.

The VULCAN model enables simple flooding scenarios to be examined in order to see where mine water may emerge at surface, and it identifies where coal has been worked near to the base of the Permian in the concealed coalfield. In addition, it is apparent where public supply boreholes in the Permo–Triassic Sherwood Sandstone Group are located in areas where the hydraulic integrity of the sandstone is shown to be at risk from broken ground. Boreholes and shafts that penetrate the base of Permian and enter the Coal Measures, reportedly with an intact hydraulic seal, are also indicated on the model.

The second role for the VULCAN model is that it can be used as a data platform from which to run other models. For example, the Newcastle University GRAM (Groundwater Rebound in Abandoned Mineworkings) model (Sherwood & Younger 1997; Burke & Younger 2000) enables the complexity of the coalfield voids to be reduced to a series of interlinked 'ponds' each with a critical lip or overflow point. The VULCAN platform allows complex areas such as goaf (broken infill behind a collapsed longwall face) to be represented and determination of total void space to be made to parameterize the GRAM model, which can then used to obtain predictions of fill-up times and break outs under a

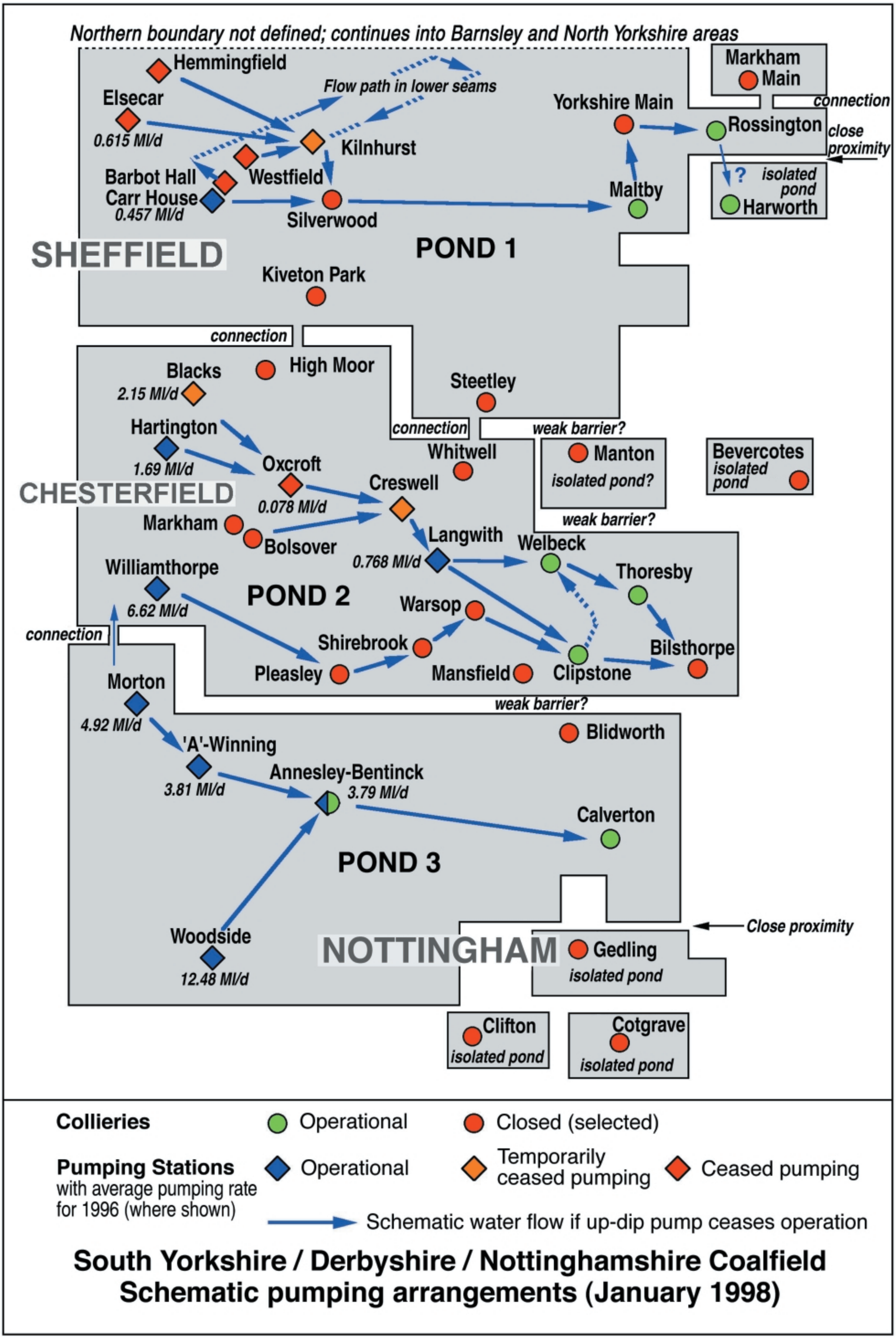

Fig. 1. Schematic flow and pumping in the South Yorkshire, Derbyshire and Nottinghamshire coalfields.

Table 1. *VULCAN key horizons*

Seam	Criteria	Rationalization of digitizing and input (NB: seam contours always input whever present)
High Main	Stratigraphically highest worked seam, extensively worked, digital coverage at Calverton and parts of neighbouring collieries.	Detailed goaf areas, main roadways, cross-measure drift intersections, pit-bottom layouts, shafts.
Abdy/Brinsley	Included as part of digital coverage at Calverton Colliery.	Detailed goaf areas and roadways at Calverton *only*. No other workings input.
High Hazles	Extensively worked, digital coverage at Calverton and parts of neighbouring collieries.	Approximate, generalized goaf areas and some main roadways only. More detailed at Calverton and Gedling collieries.
Top Hard	Very extensively worked, digital coverage at Calverton and parts of neighbouring collieries.	Detailed goaf areas, main roadways, cross-measure drift intersections, pit-bottom layouts, shafts.
Deep Hard	Extensively worked, mining layout often closely similar to overlying Deep Soft.	Approximate, generalized goaf areas, few roadways.
Blackshale	Very extensively worked.	Detailed goaf areas, main roadways, cross-measure drift intersections, pit-bottom layouts, shafts.
Kilburn	Stratigraphically lowest, extensively worked seam.	Approximate, generalized goaf areas, few roadways.

variety of different pumping scenarios given the constraints of the overall water balance for the coalfield.

Geological and hydrogeological constraints

The coal producing region to the east of the Pennines, which includes the Yorkshire, North Derbyshire and Nottinghamshire coalfields, has a regional dip eastwards from the Dinantian–Namurian anticlinal ridge of the Pennines. The dip of the strata takes the Coal Measures under the Permian and Triassic strata of the East Midlands shelf (Fig. 2). The Permo–Triassic sandstones are a major public water supply aquifer in this part of the country. The main dip of the coalfield to the east is interrupted by a number of NW to SE trending anticlines and synclines as well as normal faults which predominantly strike NW to SE and NE to SW (Duff 1992).

The South Nottinghamshire Coalfield lies to the south of the Hardstoft–Mansfield anticline, a prominent east to west/NW to SE structure that separates this coalfield from the Derbyshire and North Nottinghamshire coalfields to the north. The South Nottinghamshire Coalfield has been extensively worked since the eighteenth century, and the workings have moved progressively in an easterly direction, down dip and away from outcrop as the shallower seams were worked out. Pumping has maintained dewatered conditions for the deep pits. Once the few remaining pits close and pumps are switched off, iron-rich and possibly acidic mine waters are expected to flood the workings and ultimately to rebound to a level which may allow discharge to surface in the exposed coalfield (Fig. 3) and possibly also discharge to the overlying Permo–Triassic aquifer above the concealed coalfield. The risks of mine abandonment caused by the complex interconnecting layouts of abandoned and workings pits in this and adjoining areas was first recognized by Lemon (1989), and has been highlighted in the literature subsequently (e.g. Robins & Younger 1996; Burke & Younger 2000).

The Coal Measures Group forms a complex multilayered aquifer. The argillaceous strata comprising the majority of the sequence act as aquitards, isolating the occasional thicker sandstone horizons that form discrete aquifers. Coal Measures sandstones are generally fine-grained, very well cemented, extremely hard and dense and in consequence possess very little intergranular (primary) permeability or porosity. Groundwater storage and movement occurs predominantly within and through fractures in the sandstones.

The Carboniferous strata are extensively faulted. This may increase the secondary permeability in the faulted area, or the faults may act as hydraulic barriers to prevent groundwater flow between adjacent fault blocks. Local folding tends to open joints in anticlinal areas permitting water to infiltrate and migrate down bedding planes to accumulate in synclinal areas (Holliday 1986) so that collieries sited in synclinal areas are known to make more water than those sited on anticlines (Downing *et al.* 1970).

Even though the sandstone horizons generally contain discontinuities, Rae (1978) considered that they were

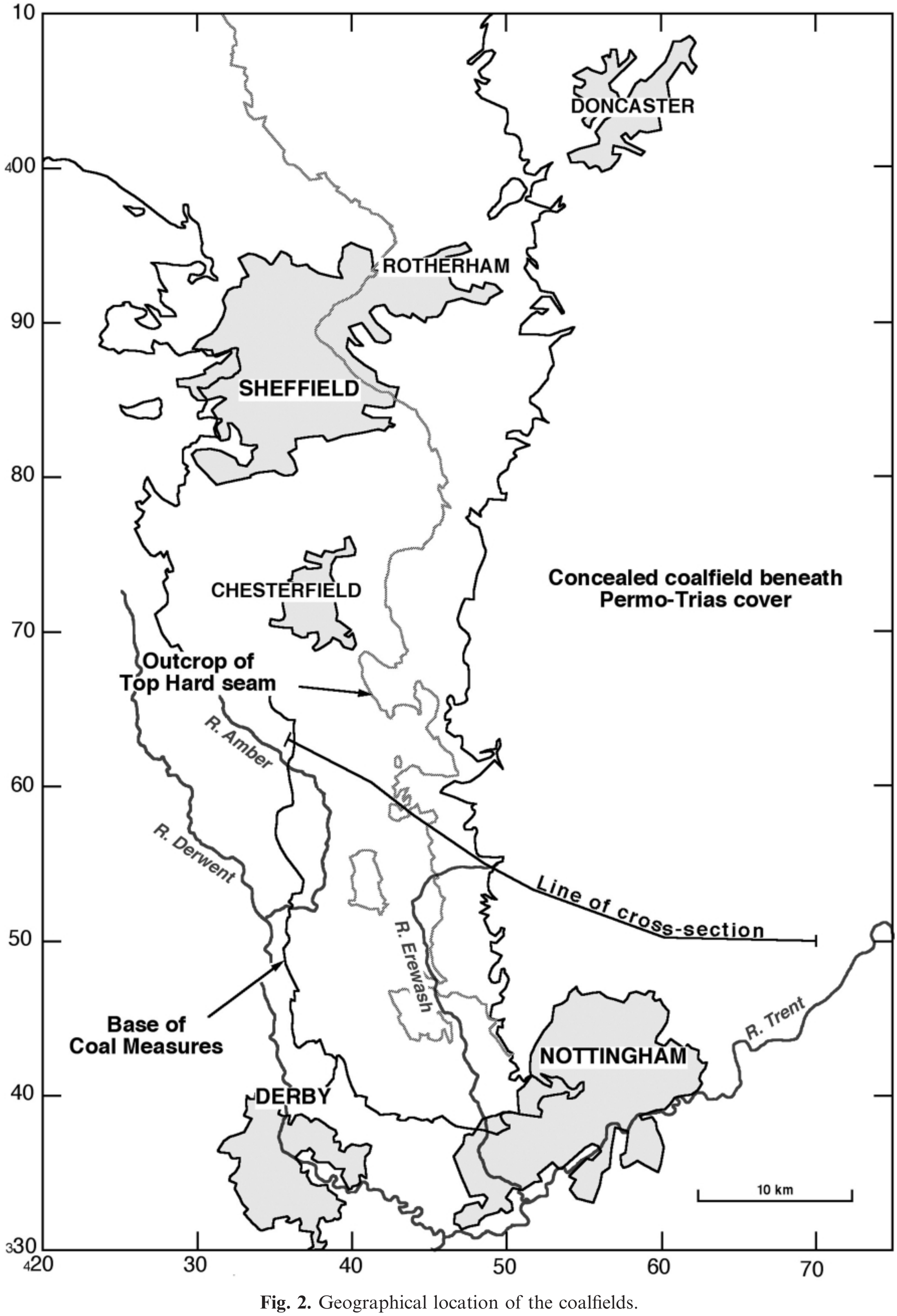

Fig. 2. Geographical location of the coalfields.

unlikely to contain significant amounts of groundwater at depths greater than 200 m due to pressure of overburden. Generally, the most easterly and deepest workings have experienced the least trouble from water ingress.

The removal of great quantities of coal and adjacent rock coupled with associated collapse and fracture of *in situ* strata has considerably altered the potential groundwater flow regime. The creation of open shafts

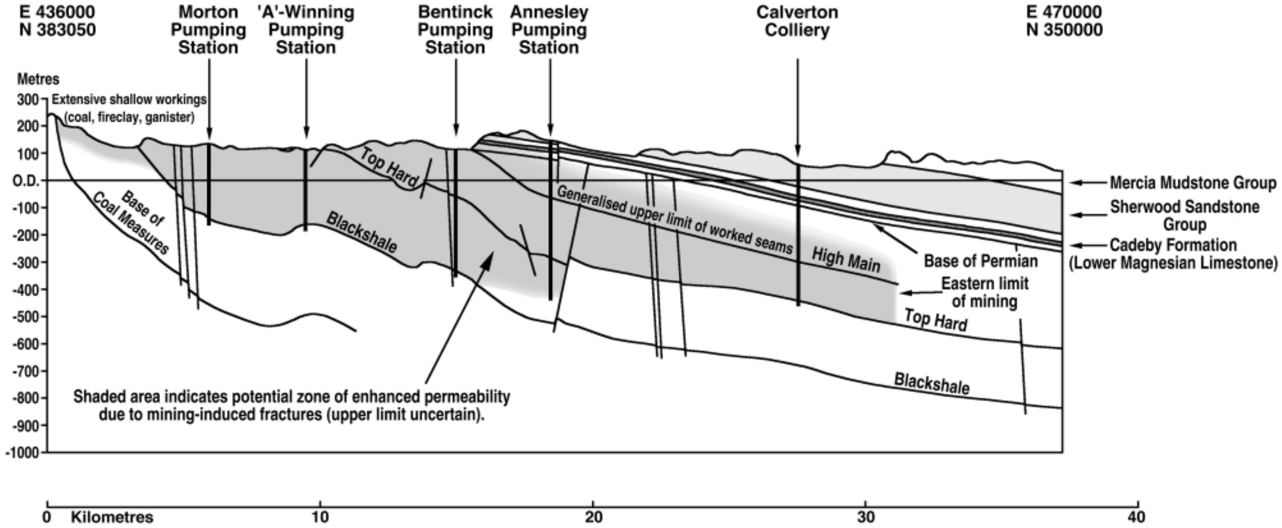

Fig. 3. Schematic cross section of the South Nottinghamshire Coalfield.

and roadways, together with collapsed goaf-filled workings, has created a complex pattern of undisturbed strata separated by the worked areas. Mine drainage soughs, or adits, continue to drain the Coal Measures long after the mines have been abandoned, and these have created hydraulic continuity between layers that were previously isolated and, in some places, between aquifer horizons and flooded disused workings. This modification of hydrogeological conditions has resulted in what has been described by Banks (1997) as an 'anthropogenically enhanced aquifer'.

The Top Hard seam in the centre of this sequence has been the most exploited. Many collieries have worked this seam to exhaustion, so that neighbouring collieries are often linked underground within this seam. Different collieries working from different directions also frequently connected seams together; cross-measure drift connections from one seam to another are also known to exist at many locations.

The Basal Breccias of the overlying Permian deposits comprise a mixture of breccias and sandstones, the result of continental weathering and subsequent deposition under fluviatile conditions. There is a marked variation in the lithologies of these deposits, with no breccias present at some locations, but up to 8 m recorded elsewhere (Charsley *et al.* 1990). Above the basal deposits is a lower mudstone facies, deposited under a fluviatile regime (formerly termed the Lower Permian Marl), and an upper carbonate facies sequence, deposited under marine conditions (formerly termed the Lower Magnesian Limestone). The uppermost Permian strata are the Lenton Sandstone Formation (formerly the Lower Mottled Sandstone) which represents a 30 m thick gradational transition from the mudstone facies to the arenaceous strata of the Sherwood Sandstone Group above. It is a fine- to medium-grained, poorly consolidated argillaceous unit with sporadic occurrences of angular pebbles.

The principal aquifer unit is the Sherwood Sandstone Group, which has a thickness of between 50 and 200 m. The thickness increases in an easterly direction down the stratigraphic dip, which has a gradient of about 1 in 50. The strata comprise friable, medium- to coarse-grained sandstones with abundant pebbles. At depth, the formation is commonly calcareous and has apparently undergone a number of stages of diagenesis.

The Carboniferous sequence lies in direct contact with the Permo–Triassic aquifer in the Nottingham area wherever the Permian formation is laterally discontinuous. Elsewhere, the Carboniferous sequence is isolated geologically and hydrogeologically from the aquifer by the Permian marls (Bishop & Rushton 1993).

Outline water balance

There are two major rivers which cross the outcrop of the southernmost third of the South Nottinghamshire Coalfield (known as the Pond 3 Coal Measures), these are the Amber and the Erewash, and both of which are augmented by mine water discharges. The River Amber has a catchment size of approximately 139 km^2 and is a tributary of the River Derwent. The Amber and Derwent meet a few kilometres to the north of Belper at SK 3451. The Amber flows in a southerly direction predominantly across Coal Measures blanketed by till. A gauging station is located at Wingfield Park [SK 376520] just before the river flows out of the outcrop area of the Coal Measures; the mean river flow is 1.38 $m^3\ s^{-1}$ (43.5 $Mm^3\ a^{-1}$). However, no contemporary gauging information is available for the Amber higher up the river with which to assess the contribution to flow as the river crosses the Coal Measures outcrop area.

The River Erewash has a catchment area of approximately 182 km^2, and rises in the vicinity of

Kirkby-in-Ashfield to the SW of Mansfield (approximate grid reference SK 4854). The river flows initially in a westerly direction across the Coal Measures outcrop before changing direction to flow southwards to the west of Nottingham. A gauging station is located at Sandiacre [SK 482364] approximately 2 km south of the outcrop area of the Coal Measures, where the mean river flow is 2.03 $m^3 s^{-1}$ (64 $Mm^3 a^{-1}$).

The effective precipitation over the Coal Measures outcrop is approximately 257 mm a^{-1}. The outcrop of the Coal Measures within Pond 3 is approximately 300 km^2. The proportion of different rock types within the Westphalian sequence has also been calculated from figures given by Frost & Smart (1979). They showed that sandstones and siltstones constitute up to 45% of the total sequence present, with coal deposits forming about 3.5%. Hence, this suggests that about 135 km^2 of the total Coal Measures outcrop is sandstones and siltstones.

Weighting the effective precipitation to outcrop area, 257 mm over an outcrop area of 300 km^2 of Coal Measures suggests a total effective precipitation volume of about 77 $Mm^3 a^{-1}$, of which only about 35 $Mm^3 a^{-1}$ falls over sandstone outcrop.

Surface infiltration properties of the Coal Measures suggest 30 to 40% of the available effective rainfall will infiltrate the sandstones, and only 5% will infiltrate the remainder of the Coal Measures (Saul 1936). The volume of recharge to the sandstones at 30 to 40% of 35 $Mm^3 a^{-1}$ is some 11 to 14 $Mm^3 a^{-1}$. Similarly, recharge to the rest of the strata in the Coal Measures is 42 $Mm^3 a^{-1}$ of which 5% is approximately 2 $Mm^3 a^{-1}$, which indicates a total volume of recharge to the Coal Measures of between 13–16 $Mm^3 a^{-1}$.

Outputs from the system include mine water discharges, where pumping from Pond 3 is approximately 25 Ml day^{-1}, equivalent to 9.1 $Mm^3 a^{-1}$ (as at January 1998). This quantity is the sum from four operational pumping stations at the western side of the coalfield: Annesley–Bentinck, Woodside, 'A' Winning and Morton. Of this quantity, 7.7 $Mm^3 a^{-1}$ is discharged into the Rivers Amber and Erewash (Annesley–Bentinck discharges the water into the River Trent). In addition, the licensed abstraction for the outcrop of the Coal Measures is of the order of 0.5 $Mm^3 a^{-1}$, although actual groundwater abstraction is likely to be less.

The basic input of water to the Coal Measures in Pond 3 is 13–16 $Mm^3 a^{-1}$, of which approximately 9 $Mm^3 a^{-1}$ is removed as pumped mine water discharge and 0.5 $Mm^3 a^{-1}$ as groundwater abstraction. The apparent net recharge to the Coal Measures is, therefore, 3.5 to 6.5 $Mm^3 a^{-1}$, which for the most part, discharges locally into the rivers as groundwater baseflow.

If the effective precipitation is of the order of 77 $Mm^3 a^{-1}$, but recharge is of the order of 13–16 $Mm^3 a^{-1}$, then approximately 61–64 $Mm^3 a^{-1}$ of the effective precipitation is available for run-off. This contributes about 60% of the river outflow quantity of approximately 107 $Mm^3 a^{-1}$. The remainder derives from baseflow, mine water pumping discharge, sewage outfall, leaking water mains and lateral components of flow into Pond 3. The influence of sewage discharges and mains leakages has not been considered further as it is unlikely to have a significant effect on the water balance given the unknown volume of lateral flow.

Constructing the VULCAN 3-D model for Pond 3

Two collieries were working during the construction of the model: Calverton (RJB Mining (UK) Ltd) and Annesley–Bentinck (Midlands Mining), although both of these ceased production during 1999. Mine plan data existed in digital format only for Calverton (including parts of the neighbouring abandoned mines Linby, Bestwood and Blidworth) and were kindly made available by RJB Mining. For all remaining collieries, mine plans were only available as paper prints at various scales. 1:5000 scale plans for Annesley–Bentinck were provided by Midlands Mining and copies of the 1:2500 scale abandonment plans of Gedling Colliery High Hazles seam were obtained from the Coal Authority Mining Records Office, Bretby, Burton-on-Trent.

The 1:10 560 scale 'seam plans' were the main source of mine plan data for the VULCAN model. These plans are held at the Mining Records Office, from where paper copies were obtained. Each plan generally consists of two 1:10 560 scale Ordnance Survey topographic quarter sheets arranged EW resulting in an areal coverage of 10 km EW by 5 km NS.

Mine workings are shown for each seam worked, having been redrawn and reduced from 1:2500, 2 chains to 1 inch, or other scale abandonment plans, or in the case of more modern workings, copied from the colliery surveyor's six-inch scale mine plan. The workings are somewhat simplified, depicting mine roadways as single lines, cross-measure drifts sometimes as double lines and goaf areas mostly shaded or ornamented. Complex roadway layouts, e.g. in pit-bottom areas, are necessarily simplified. Shafts are mostly shown as solid circular symbols. Near outcrop, any areas of opencast workings are usually indicated. In the urban areas, the heavy ornament and high density of topographic features often make it difficult to distinguish the mine workings.

Seam level information is generally shown by contours (values usually in feet above mining datum, i.e. 10 000 feet below Ordnance Datum). There are rarely any spot levels, an important point to consider if the start and end elevations of cross-measure drifts are required. Many areas of very old workings do not have any elevation information at all. Geological information is usually restricted to faults; the throw is often indicated, where known.

The seam plans may be considered to give a reasonably accurate summary of the mine workings, but omit fine detail, especially, as already noted, cross-measure drift intersections which may represent important intercolliery hydraulic connections. Only detailed scrutiny of the abandonment plans and surveyor's abandonment reports provides this degree of information. One important advantage of the 1:10 560 seam plans is the positioning of the mine workings with respect to the National Grid. Often, very old abandonment plans do not have any surface correlation features except field boundaries, buildings, roads or sometimes railways. While this may be sufficient to ultimately locate the workings, the procedure was too time-consuming for use during this investigation.

The 1:10 560 seam plans only show mine workings abandoned prior to 1987. In Pond 3, the only workings abandoned after this date were in the Gedling Colliery High Hazles seam. Paper prints of the 1:2500 scale abandonment plan were obtained from the Mining Records Office and incorporated into the model. These plans are based on the statutory Standard Mine Plans and are of the highest accuracy.

Table 2 lists all the seams which have been worked at one time or another in Pond 3 and for which 1:10 560 scale seam plans were obtained from the Mining Records Office. It became rapidly apparent that it would not be possible to incorporate all of these workings into the VULCAN model given available resources. Some degree of selection was, therefore, required to input as many of the most extensively worked seams as possible, whilst still achieving a reasonable representation of the mine workings in Pond 3, to facilitate preliminary GRAM modelling of possible future mine water rebound. The seams ultimately included in the VULCAN model are listed, with the selection criteria, in Table 1.

The mine workings on the selected seam plans were manually digitized and imported to VULCAN. Key features included were:

- goaf areas
- principal in-seam mine roadways linking goaf areas
- cross-measures drifts
- seam contours and spot levels, with appropriate elevation 'z' values.
- selected shafts and boreholes (where shown)

British Geological Survey (BGS) coal seam outcrop line work was also included and 'registered' (i.e. assigned 'z' values) on to the Ordnance Survey Digital Terrain Model (DTM).

From these data the 3-D model was constructed by an iterative process summarized as follows:

(1) Generate 3-D Delauney triangulation surface for coal seam from seam contours, spot levels, borehole/shaft intersections and outcrops.
(2) Register principal mine roadways and goaf polygons on to triangulation surface.
(3) Generate a sub-set ('relimited') triangulation contained within the goaf polygons.
(4) Register start and end points of cross-measures drifts on appropriate seam horizon.

User-interactive manipulation and rotation of the relimited triangulations allowed easy visualization and appreciation of the geometry of the mine workings. Values for surface area and volumes for the goaf areas were also rapidly obtained (parameters required for GRAM modelling).

Table 2. *Coal seams that have been worked in Pond 3 for which data are available*

High Main**
Wales
Swinton Pottery
Clowne (*Pond 2)
Main Bright (Foxearth, Meltonfield)**
Middle Bright (Two Foot, Sough)*
Low Bright (Furnace, Winter)*
Abdy/Brinsley*
High Hazles**
1st St Johns
2nd St Johns
Comb
Top Hard**
Dunsil*
1st Waterloo*
Waterloo Marker
2nd Waterloo*
3rd Waterloo
4th Waterloo
1st Ell
2nd Ell
Brown Rake*
Clay Cross Soft (Chavery) (**Pond 2)
Roof Soft
Top Soft
Deep Soft**
Deep Hard**
1st and 2nd Piper**
Hospital
Cockleshell
Tupton (Low Main)**
Threequarters*
Yard*
Blackshale**
Ashgate*
Mickley
Kilburn*
Alton

Seams marked * have been worked by deep mine methods to a greater or lesser extent; those marked ** are particularly extensive in Pond 3. The remaining seams are mainly too thin to have been worked by deep mine methods (except on a very local scale). Nearly all the seams have been exploited by opencast methods at or near outcrop. Ancient, unrecorded workings (e.g. bell pits) are indicated on the seam plans near the outcrops of some of the thicker seams.

The following Permo–Triassic surfaces were also incorporated into the VULCAN model:

- Base of the Mercia Mudstone Group (=top of Sherwood Sandstone Group)
- Base of the Sherwood Sandstone Group
- Top of Lower Magnesian Limestone
- Base of Lower Magnesian Limestone
- Base of Permian

These surfaces were generated as simple Delauney triangulations of borehole point and outcrop data held at the BGS.

Although surface positions of faults digitized from the 1:50 000 scale geological maps were registered on the DTM surface and were included in the VULCAN model, time constraints prevented any detailed 3-D modelling of faults. Triangulation surfaces in both coal seams and the Permo–Triassic horizons are thus continuous across faults and honour data points or seam contours on each side of the fault. This may be revealed by a temporary apparent change of dip of the surface affected. Fortunately, with a few exceptions, there are few faults with substantial throws in the study area. The northern boundary of Pond 3, situated adjacent to the steeply dipping southern limb of the Mansfield–Hardstoft anticline, is fault-bounded along much of its length. Workings in the Top Hard and the High Main seams frequently intersect or closely approach this fault. This is clearly visible in the VULCAN model and is shown in Fig. 4. The boundary between the Denby Hall–Woodside periclinal syncline (also known as the 'Shipley Basin') and the main portion of Pond 3 is a narrow but complex fault zone. This has been approximately modelled, though the current representation should not be regarded as anything other than a general indication of the structure.

Potential for mine water discharge

Mine plans of the area can yield information on the geological structure, supplementing detail obtained from large-scale geological maps. This can be used to predict the structural controls on directions of water flow within an area. Above the water table, mine waters flow down-dip, via roadways, goaf and collapsed zones and through other permeable stratigraphic units, e.g. jointed or fractured sandstones. Once a barrier is reached, such as a fault or intact pillar of coal, then the water level will pond, and levels rise up-dip until an overflow point is reached, such as a roadway connection to a neighbouring colliery or a discharge point at the surface. Therefore, the structural controls on the mined area are important as they may influence mine water flow in unanticipated directions, resulting in discharges in areas not thought to be at risk.

Mine plans and mine surveyors' abandonment reports were used to identify both inter-seam connections within each colliery and connections to neighbouring collieries and showed at an early stage that within Pond 3 there was a high degree of interconnectivity between collieries (Fig. 1). The VULCAN model not only effectively confirmed this but also clearly demonstrated the degree of vertical overlap or stacking of workings in different seams – a feature not always readily appreciated by visual inspection of the mine plans.

The model enabled the broad structure of Pond 3 to be evaluated, and the relationship and proximity of the mine workings to the base of the Permo–Triassic rocks over the entire area to be understood. The VULCAN model needs to be viewed interactively on the computer screen to be best appreciated; selected 'screen dumps' (Figs 4–6) are only partly effective in visualization. However, in summary, the following points may be noted:

(1) Pond 3 may be subdivided into two parts:
   (i) the Denby Hall–Woodside Sub-Pond and
   (ii) the remainder of Pond 3. The boundary between these two sub-ponds is a faulted anticlinal zone with the present-day topography at, or slightly below, the Deep Hard horizon (Fig. 5).

(2) Mine water levels in the Denby Hall–Woodside Pond are currently controlled by Woodside pumping station in the Deep Soft horizon.

(3) The VULCAN model shows the main part of Pond 3 to have a very broad synclinal structure, plunging to the east, with the Blidworth Colliery Top Hard workings representing the deepest area at 670 m below OD. It can be seen that if pumping were to cease at Morton, 'A' Winning and Annesley–Bentinck, all mine water would gravitate down-dip to this lowest point prior to commencement of final flooding and rebound of water levels.

(4) Examination of the surface topography DTM shows a critically low elevation area in the vicinity of Radford [SK 5498 4101] close to near-surface Top Hard workings and the old shafts of Radford and Newcastle collieries. This is thought to be the main potential surface discharge point in the event of complete mine water rebound. The former Chief Surveyor and Minerals Manager, RJB Mining (A. R. Barnes 1999, pers. comm.) corroborates this view, stating that the required mine water spillover elevation in Radford shaft for a surface discharge to occur is 41 m above OD. Figure 6 illustrates the extent of flooding in the Top Hard seam if mine water were to attain this controlling elevation.

The GRAM model

The GRAM model has been used to predict possible discharge points and time to discharge, based on data

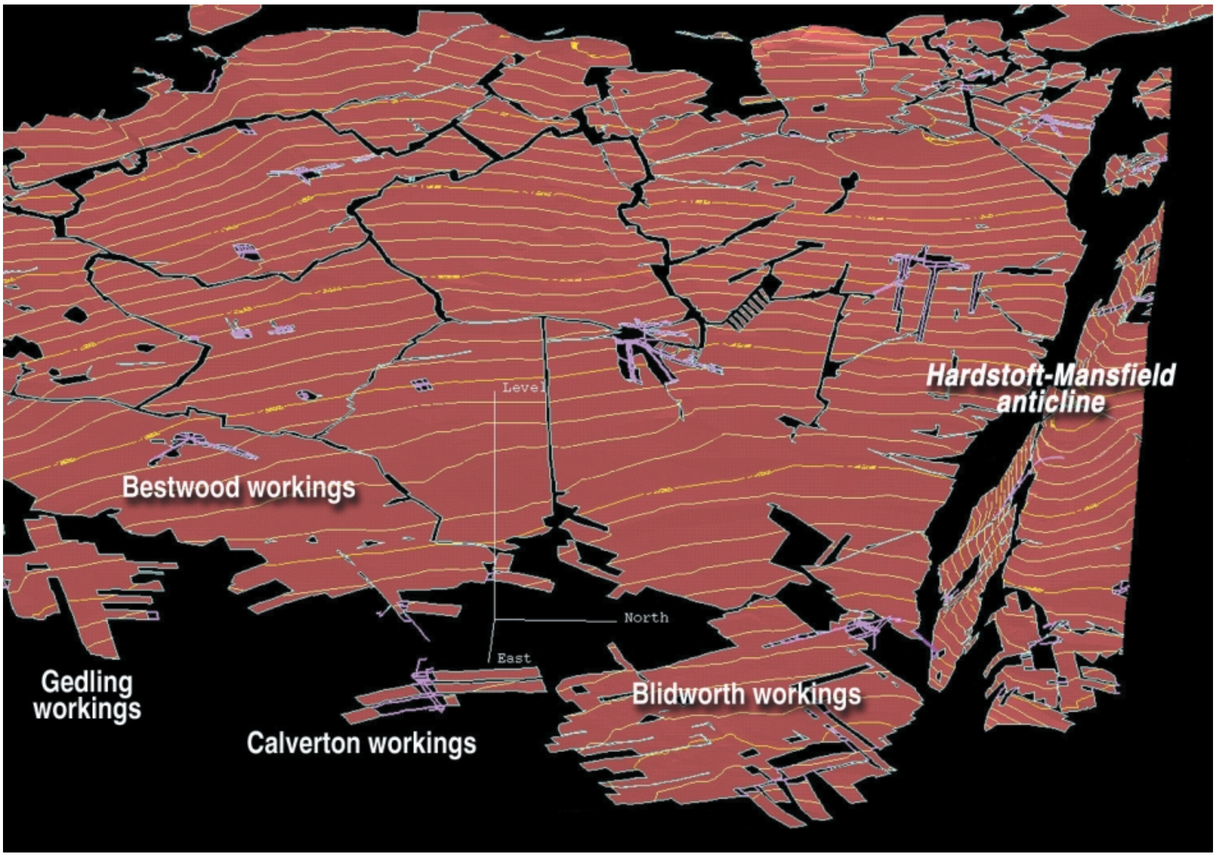

Fig. 4. Oblique view of Top Hard workings looking west, showing faulted boundary adjacent to Mansfield-Hardstoft anticline.

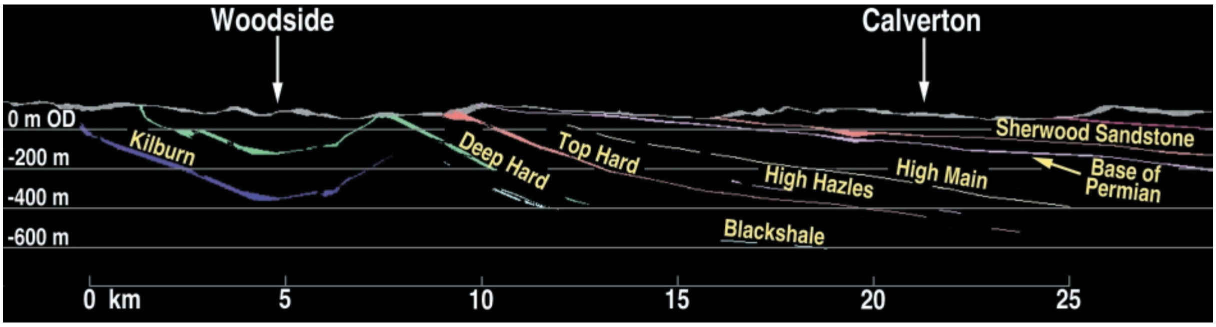

Fig. 5. Cross section—Woodside to Calverton showing Denby Hall–Woodside syncline.

held in the VULCAN 3-D model. GRAM builds on the conceptualization of a coalfield as a single pond, or a series of ponds connected by pipes (extracted seams/ roadways, inter-colliery connections). Isolated ponds are seen as those surrounded by intact barriers of un-worked strata. GRAM uses a mass balance approach, usually calculated over daily time-steps, allowing incremental changes in water level to be deduced. Certain assumptions have to be made before these calculations can be made:

- the water table is flat within each pond
- pipe flow equations are used to calculate pond overflow via interconnections
- mine water discharges to receiving water courses are calculated at the end of each time step
- ponds have vertical external boundaries.

Younger *et al.* (1995), Sherwood & Younger (1997) and Burke & Younger (2000) have described previous applications of GRAM in Scotland and Yorkshire. Due to the simple data requirements of GRAM (e.g. areal extent of colliery workings, pumping rates of individual collieries, rainfall inputs, approximate groundwater levels, number of pond inter-connections including depth and location, specific yield estimates and identification of areas vulnerable to surface discharges) it can be used effectively to predict areas likely to be affected by mine water rebound (Sherwood & Younger 1997). However, the model is very sensitive to storage parameter data (ratio of mined voids to total rock volume within individual ponds).

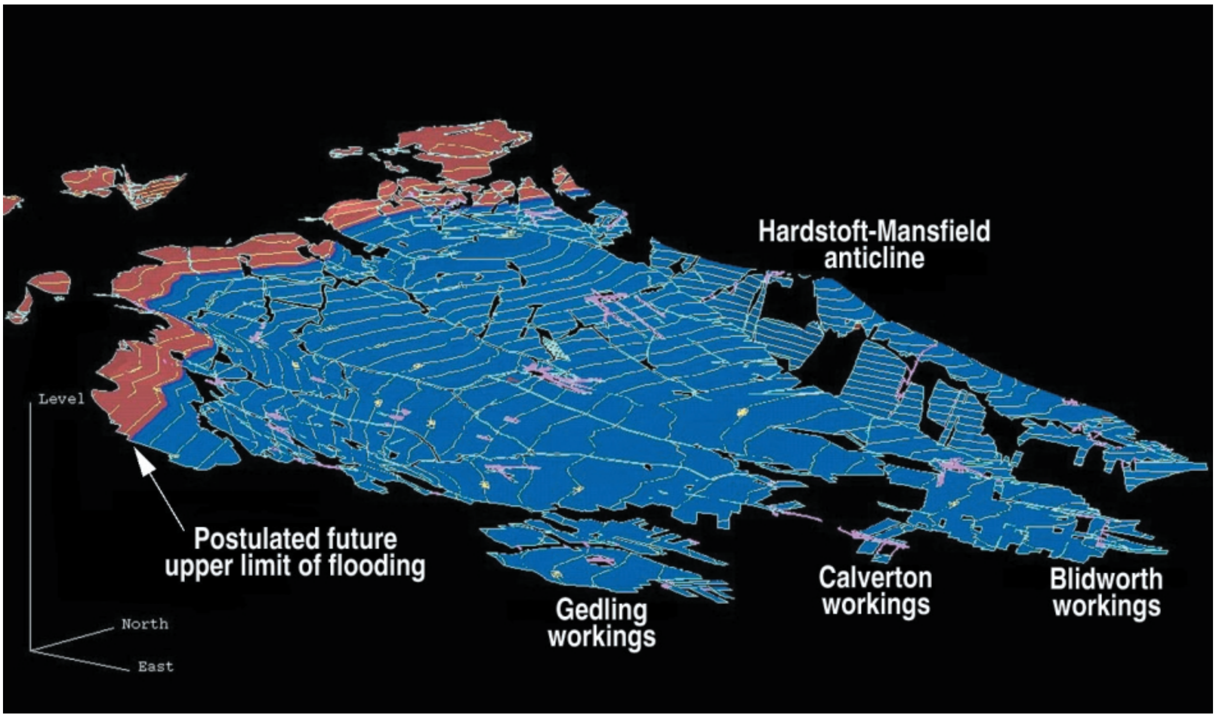

Fig. 6. Oblique view showing extent of flooding in the Top Hard seam if mine water were to attain an elevation of +41 m OD. Elevation.

Table 3. *GRAM modelling output*

Model type	Shut down pumps at*	Surface break out (years)
Model 1		
(1) Pond 3 as one pond	All	19–20
(2) Pond 3 as one pond	Annesley-Bentinck	>50
(3) Pond 3 as one pond	Woodside, 'A' Winning, Morton, Calverton	25
(4) Pond 3 as one pond	'A' Winning, Morton, Calverton	>50
(5) Pond 3 as one pond	'A' Winning, Morton, Annesley/Bentinck	37
(6) Pond 3 as one pond	Woodside, 'A' Winning, Morton, Annesley/Bentinck	19–20
Model 2		
(1) Pond 3 as two sub-ponds	All	52
(2) Pond 3 as two sub-ponds	Annesley-Bentinck	28
(3) Pond 3 as two sub-ponds	Woodside, 'A' Winning, Morton, Calverton	75
(4) Pond 3 as two sub-ponds	'A' Winning, Morton, Calverton	34–35
(5) Pond 3 as two sub-ponds	'A' Winning, Morton, Annesley/Bentinck	>75
(6) Pond 3 as two sub-ponds	Woodside, 'A' Winning, Morton, Annesley/Bentinck	>75

*Five pits/pumping stations were operating in mid-1999 (Annesley/Bentinck, Woodside, 'A' Winning, Morton and Calverton) although some closures had been announced.

The model depicts mine water rebound in Pond 3, and predicts areas where there is a high probability of mine water discharge. However, rebound depends on the cessation of the current Pond 3 pumping regime. Five pumping stations (Annesley–Bentinck, Woodside, 'A' Winning, Morton and Calverton) were operating at the time of the study to protect the remaining working pits. To investigate if it was feasible to operate a reduced number of pumping stations to control the mine water, six separate pumping scenarios were run (Table 3). The sensitivity of each pumping station depends on:

- the geological structure (mine water flow paths); and
- inter-colliery connections (spill-over points).

GRAM was run based on two different conceptual models of the Nottinghamshire Coalfield.

- Conceptual Model 1—the whole of Pond 3 modelled as a single pond.

- Conceptual Model 2—Pond 3 divided into two separate sub-ponds: the 'Main Pond' and the 'Denby Hall/Woodside Sub-Pond' (sometimes known as the 'Shipley Basin').

The six pumping scenarios were run based on these two conceptual models. Model 1 was run for a period of 50 years using 7-day time-steps. Model 2 was run similarly for a 75 year period. The longer modelling period allowed scenario 3 to be included. Each model was run with selected pumping stations shut down to show the time for mine water rebound to reach surface discharge elevations (Table 3). The results show that breakouts at surface are likely to occur from about twenty years onwards, but no single scenario can, as yet, be identified as an optimum management proposal.

Conclusions

The project has highlighted the benefit of using a 3-D visualization package to resolve a complex interrelated geometrical problem. The VULCAN package provides a platform to contain the data in a form that can readily be inspected to reveal emerging mine water hotspots at the ground surface as well as those areas where coal working has approached the base of the overlying Permo–Triassic sequence. Simple flooding experiments can be used to reveal the head of mine water that may be created beneath the base of the Permian. Locations of penetrating shafts and boreholes relative to critical areas in the base of the Permian are apparent from the model.

Not all the mine abandonment data were incorporated in the VULCAN model due to limited resources, but together with the GRAM model, it was possible to provide predictive synopses for a variety of different pumping regimes. Given the likely error range in some of the input data, notably the water balance, the degree of lumping necessary to create the model is acceptable. The runs have indicated that after cessation of pumping, the rising mine water will place selected areas of the Permo–Triassic aquifer at risk after about 20 years, when emergence at surface may also occur at specific locations.

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