A Strategy For Modeling Ground Water Rebound in Abandoned Deep Mine Systems

Adams, R. & Younger, P. L. (2001): A Strategy for Modeling Ground Water Rebound in Abandoned Deep Mine Systems. – Ground Water, 39: 249-261, 10 Abb.; Worthington.

by R. Adams[1,2], and P.L. Younger[1]

Abstract

Discharges of polluted water from abandoned mines are a major cause of degradation of water resources worldwide. Pollution arises after abandoned workings flood up to surface level, by the process termed ground water rebound. As flow in large, open mine voids is often turbulent, standard techniques for modeling ground water flow (which assume laminar flow) are inappropriate for predicting ground water rebound. More physically realistic models are therefore desirable, yet these are often expensive to apply to all but the smallest of systems. An overall strategy for ground water rebound modeling is proposed, with models of decreasing complexity applied as the temporal and spatial scales of the systems under analysis increase. For relatively modest systems (area < 200 km²), a physically based modeling approach has been developed, in which 3-D pipe networks (representing major mine roadways, etc.) are routed through a variably saturated, 3-D porous medium (representing the country rock). For systems extending more than 100 to 3000 km², a semidistributed model (GRAM) has been developed, which conceptualizes extensively interconnected volumes of workings as ponds, which are connected to other ponds only at discrete overflow points, such as major inter-mine roadways, through which flow can be efficiently modeled using the Prandtl-Nikuradse pipe-flow formulation. At the very largest scales, simple water-balance calculations are probably as useful as any other approach, and a variety of proprietary codes may be used for the purpose.

Mine Closures and Water Resources

Worldwide changes in the mining sector have led to the closure of many long-established deep mines (i.e., underground mines) in northern industrialized countries. During the 1980s and 1990s, coal mine closures have been particularly widespread in Belgium (Monjoie 1998), the United Kingdom (Younger 1993, 1995), the United States, Nova Scotia, Canada (Cain et al. 1994), France and Germany (Coldewey and Semrau 1994); further coal mine closures are forthcoming in Spain (González and Sáenz de Santamaría 1998) and Poland. Metals mines have shown a similar trend, with the closure of the last tin mine in Europe in 1998 (Younger 1998a), closure of zinc mines in France (Sadler 1998), uranium mines in Germany (Wolkersdorfer 1994) and Romania, various base-metal mines in Canada and fluorspar mines in the United Kingdom (Younger 1998b).

Following closure of a deep mine, cessation of dewatering generally results in ground water rebound (Henton 1981), as the mined voids and surrounding strata gradually flood up to the level of a decant point, via which the water will discharge either to a surface water course or an overlying aquifer. The most common decant points are man-made features such as shafts and drifts (inclined tunnels connecting the workings to the ground surface). Where the mined strata contained soluble sulphide minerals (which is the case for all types of mines just listed), this process of rebound can ultimately lead to surface discharges of water heavily contaminated with ecotoxic metals, which may also have a low pH (Banks et al. 1997). The ecological impacts of such discharges are often grave, including major fish-kills and persistent degradation of aquatic habitats (Jarvis and Younger 1997). The high degree of mineralization of many abandoned mine discharges may also render the receiving watercourses unsuitable as water resources (Younger and Harbourne 1995; Younger 1999), since conventional water treatment works do not include unit processes capable of significantly lowering the total dissolved solids content. For these reasons, there is growing concern over the threat posed to water resources by mine abandonment. Assessment of these risks is a multidisciplinary task, central to which is an ability to predict the timing, magnitude and location of polluting discharges resulting from ground water rebound in abandoned deep mine systems. This paper outlines a modeling strategy for this purpose.

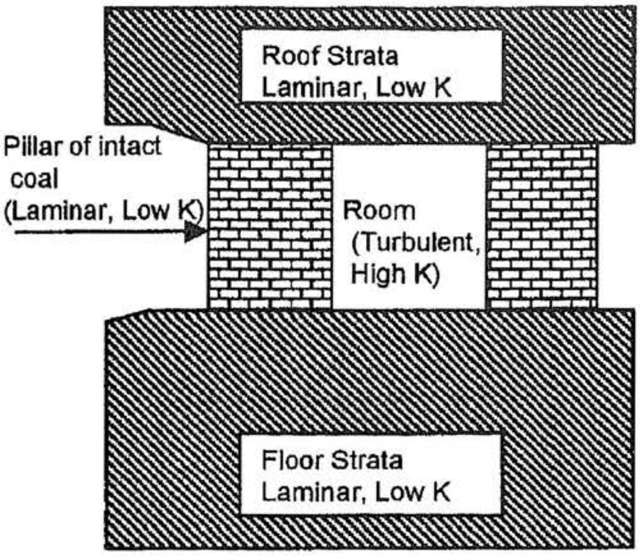
Mined Systems and Ground Water Models

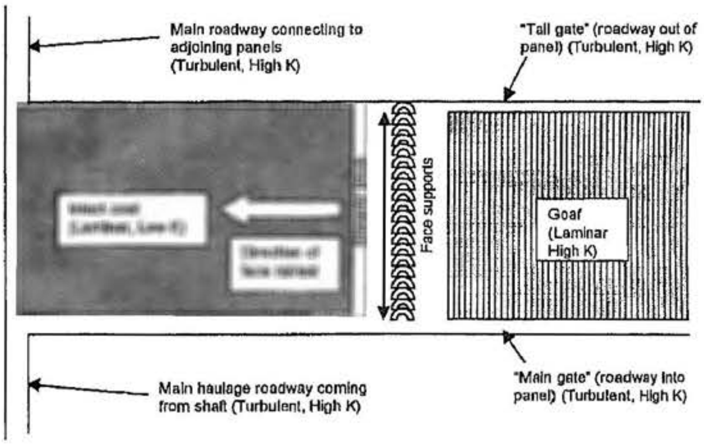
On first examination, it may seem that predicting ground water rebound in abandoned deep mines is simply an exercise in standard ground water modeling. However, there are a number of hydrological peculiarities of mined systems which are markedly nonstandard. Perhaps most important is the presence of large man-made voids of great lateral extent. Since the voids are dewatered during mining, their hydraulic properties under flooded conditions cannot

[1]Water Resource Systems Research Laboratory, Department of Civil Engineering, University of Newcastle, Newcastle upon Tyne NE1 7RU UK; +44 191 222 7113; +44 191 222 6669 (fax); r.adams@ncl.ac.uk

[2]Corresponding author

Received February 2000, accepted September 2000.





(c) Layout of a series of panels in relation to main haulage and shaft access.

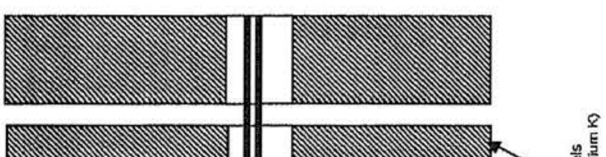


Figure 1. Conceptual diagrams of room and pillar (1a) and longwall (1b and 1c) deep mine workings, showing those portions of the workings and surrounding strata in which flow may be turbulent or laminar, and indicating the typical hydraulic conductivities (K) found in each zone.

be directly characterized in advance of rebound. Furthermore, flow through large open voids will often be turbulent during the rebound process (therefore with high velocities), violating the assumption of laminar ground water flow upon which conventional Darcian ground water flow models are based. While flow may well be laminar in the disturbed strata around the mine voids, the overall character of mined systems is one of extreme, but orderly, heterogeneity both in permeability and in dominant regime (i.e., turbulent or laminar). Figure 1 (a-c) shows a schematic representation of those portions of a mined volume of ground in which flow during rebound can be expected to be turbulent (i.e., open workings and major roadways) and those in the surrounding strata and goaf (collapsed material filling former worked voids) in which laminar, darcian flow can be anticipated, subject to hydraulic conductivities of low, medium and high values. Figure 1a shows a portion of room and pillar workings, this extraction method was prevalent in Europe before the Second World War. Figures 1b and 1c show a portion of a modern longwall mine in which a mechanized shearer is used to extract the coal from the seam.

Notwithstanding the nonstandard hydrology of abandoned deep mine systems, various modeling projects have been undertaken in which the various complications have simply been ignored, in order to allow the modelers to use pre-existing (often proprietary) conventional Darcian ground water flow codes. For instance, Toran and Bradbury (1988) used the well-known finite difference code MODFLOW (McDonald and Harbaugh 1988) to simulate piezometric drawdown (during mining) and subsequent recovery (after mine closure) for strata surrounding a lead-zinc mine. Despite their efforts being considered a qualified success, it proved impractical to apply the 3-D capabilities of MODFLOW to this system, mainly due to problems encountered in relation to spatial and temporal discretisation. Similarly, when Lancaster (1995) and Sherwood (1997) applied MODFLOW to two multiseam lowland coalfields in the United Kingdom, they found it was difficult to avoid non-convergence if all worked seams were modeled explicitly. Problems are particularly acute in faulted sequences, and where dips are steep. Definition of boundary conditions also proved particularly problematic for a case involving active rebound. This is because the numerical scheme used in MODFLOW demands the inclusion of a specified head condition on at least part of the domain perimeter, which is not very helpful in cases where the outermost boundary is dry at the start of the simulation.

A reading of the international literature reveals that little work has been done on modeling turbulent ground water flow in large open voids. Flow in soil macropores has been extensively studied (see McCoy et al. 1994, for a critical review). However, in natural macropores, the pore walls are sufficiently close to the centers of the pores that water-soil adhesion strongly influences hydraulic behavior. This is not the case in mine roadways of several meters diameter. Perhaps the closest natural analogs for these features are karst conduits. While work has been done on modeling flow in karst conduits routed through porous media, most studies to date have concerned hypothetical, single-fracture systems (Groves and Howard 1994; Howard and Groves, 1995; Hanna and Rajaram 1998), and have not attempted to model the dynamics of water table change in natural conduit networks. One exception is the recent work of a European consortium, who coupled a 2-D pipe-network solution to a single-layer MODFLOW model to simulate flow and transport in conduit systems typical of those which feed karst springs in Germany and the United Kingdom (Younger et al. 1997). The modified version of MODFLOW used in that study is limited in its applicability to mined systems, not by the conduit representation, but by the unwieldy discretisation process for the porous medium representation when analyzing multiple-depth mine workings.

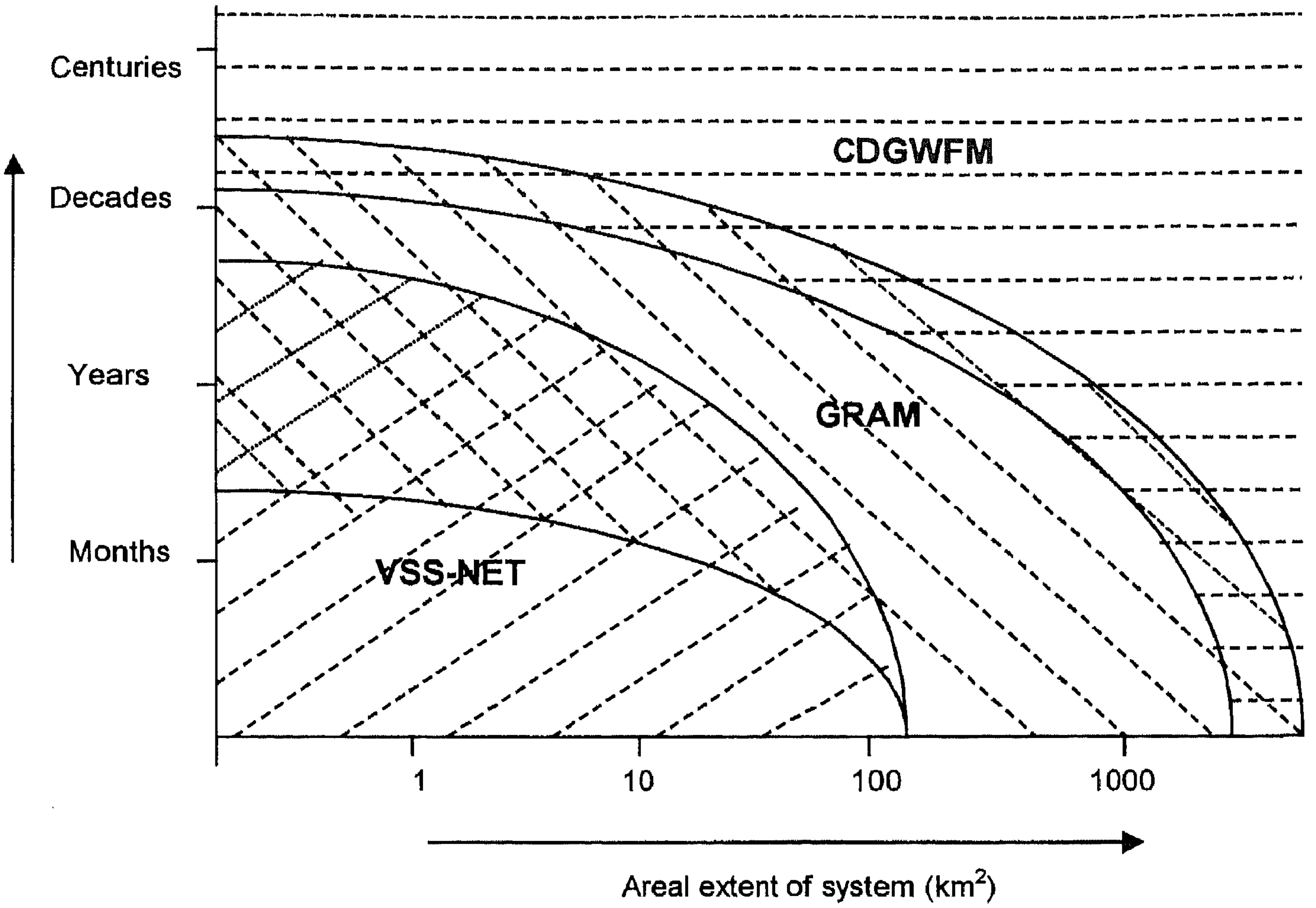


Figure 2. A schematic representation of the temporal and spatial scales over which different ground water rebound modeling techniques are most applicable. VSS-NET signifies a physically based, 3-D model of pipe networks routed through variably saturated porous media, as described in the section titled "Physically Based, Distributed Model for Detailed Analyses." GRAM signifies a semidistributed mass-balance model for systems of ponds as described in the section titled "Semidistributed Model for Large Systems" and CDGWFM stands for "conventional Darcian ground water flow model," or indeed for any code supporting a simple mass-balance calculation at the coarsest spatial and temporal resolution.

To meet the requirement for predictive hydrological models for abandoned deep mines, a new strategy is required, providing a modeling capability applicable across the wide range of scales encountered in real mine systems.

Outline of Strategy for Rebound Modeling

Deep mines vary in size from tiny operations underlying only a few hundred square meters of ground to regionally integrated, multiple-horizon workings which are interconnected over areas of several thousand km^2 (Younger 1993). Given that the smallest operations are least likely to yield large quantities of water, there is a natural tendency to focus model development on systems which extend over areas of 10s to 1000s of km^2. Experience also shows that the total simulation periods for rebound problems may vary from a few months for relatively small mine systems (e.g., the Wheal Jane mine in Cornwall, which took nine months to flood; Banks et al. 1997) to several decades for regionally interconnected coalfields (e.g., the Durham Coalfield, England; Younger 1993). Hence model domains for rebound problems can be expected to range over three orders of magnitude in both space and time. It would be unreasonable to expect that a single code might be developed which could be cost-effectively applied at all combinations of spatial and temporal scale. Rather, a selection of modeling tools, each appropriate over a different range of spatial and temporal scales, is the most logical development. Figure 2 illustrates the general relationship between system scale and model applicability for the modeling tools described in this paper. At the finest scales, it is sensible to use a physically based, fully 3-D model which explicitly accounts for conduit flow interspersed within a variably saturated porous medium. This specification matches up to the VSS-NET code described later. For systems much larger than 100 km^2, or for total simulation periods in excess of a few years, a complex code like VSS-NET begins to lose its cost-efficiency, as the burden of parameterization becomes too demanding. At these larger scales, a simpler code is called for, in which fine details are averaged and detail is retained only for structures which control regional interconnections. This specification matches up to the GRAM code described in the section titled "Semidistributed Model for Large Systems." At the greatest time and spatial scales, water balances over large time-steps dominate the hydrological behavior, and the specifics of the flow algorithm become almost irrelevant. Hence a conventional Darcian ground water flow model (e.g., MODFLOW), or indeed a simple spreadsheet mass-balance calculation, may be perfectly adequate.

The overall strategy for modeling ground water rebound in abandoned mines is to directly model turbulent flow processes on a spatially distributed basis when the model is operating at fine temporal and spatial resolution, and to move to more generalized, semidistributed approaches at coarser scales. Algorithmic details and examples of practical applications are presented in the following sections.

Physically Based, Distributed Model for Detailed Analyses

Model Formulation.

The following mathematical model is based on the conceptualization (shown schematically in Figure 1) that deep mines undergoing flooding are best regarded as systems of conduits (in which flow may well be turbulent) routed through heterogeneous, variably-saturated porous media representing the surrounding rock (both intact rock, and rock which has fractured in response to the mining nearby. There are a number of ways in which this conceptual model could be represented mathematically. For instance, a multiple-fracture system based on Navier-Stokes theory (Oron and Berkowitz 1998) is one option. In many natural aquifers, in which the conduits are irregular, planar fractures, this approach is probably most appropriate. In most mined systems, the major conduits are tube-like roadways, which are better represented as pipes rather than planar fractures. For this reason, the conduit representation selected here is that of a conventional pipe network.

A number of different representations of turbulent flow in a pipe network were tested for this application, including the Darcy-Weisbach formula and the Hazen-Williams formula. No great differences in the results produced by the different formulae were obtained for the range of parameters likely to be encountered in most mine water rebound problems, providing temperature and therefore fluid viscosity are constant. In general, for turbulent flow, the friction loss in a pipe, h_f (L) is related to the velocity by a nonlinear equation of the form

$$h_f = \alpha V_{ij}^n \tag{1}$$

where V_{ji} (LT^{-1}) is the velocity from node i to node j, α, n are coefficients which are obtained either from experimental work or empirical curve fitting. In the case of the widely used Darcy-Weisbach equation, n equals 2. Obviously, a large system of pipe elements meeting at numerous nodes define a complex 3-D network for which simultaneous solutions of potentials, and therefore flows, in all pipe elements must be sought. Such solutions require a numerical algorithm, which must be iterative in order to accommodate the nonlinearities in the equations. Probably the most computationally efficient and robust numerical scheme currently available for this problem is the Gradient Algorithm (Todini and Pilati 1989), which has been extensively tested in comparison with other methods (Salgado et al. 1989), and has been selected by the U.S. EPA for its own network analysis code "EPANET."

The three-dimensional pipe-network modeled using Equation 1 is routed (just as mine roadways are) through a variably saturated porous medium in which flow can be expected to be predominantly laminar, conforming to Darcy's law. Again, almost any 3-D variably saturated ground water flow code could have been used to represent the porous medium in the case of mine water rebound, as long as its mathematical basis is appropriate. For our purposes, the mathematical basis which we stipulate is that ground water movement can be described by the following partial differential equation:

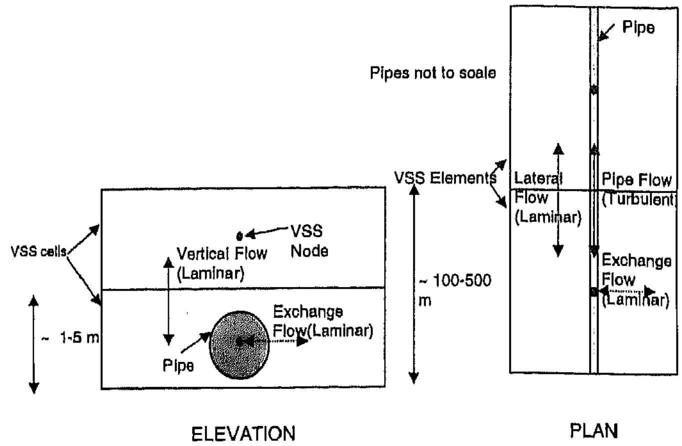


Figure 3. The assumed geometry of pipe network nodes and porous medium elements assumed in formulating the exchanges of water between pipes and porous media in the VSS-NET code.

$$\eta \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x}\left[K_x k_r \frac{\partial \psi}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_y k_r \frac{\partial \psi}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_z k_r \frac{\partial \psi}{\partial z}\right] + \frac{\partial (k_r K_z)}{\partial z} - q \tag{2}$$

where x, y, and z are Cartesian coordinates, t is time, ψ (L) is the pressure potential, K_x, K_y and K_z ($L.T^{-1}$) are components of the saturated hydraulic conductivity tensor and k_r the relative conductivity which defines the unsaturated hydraulic conductivities as a fraction of the saturated value, and is therefore a function of ψ; q is a specific volumetric flow rate ($L^3 \cdot T^{-1}$) out of the medium in the time δt, representing sources or sinks; η is the storage coefficient (dimensionless) defined as

$$\eta = \frac{\theta S_s}{n} + \frac{d\theta}{d\psi} \tag{3}$$

where θ is the volumetric moisture content (dimensionless), S_S is the specific storage (L^{-1}), and n is the porosity (dimensionless).

Equation 2 can be solved numerically by various schemes, of which finite element and finite difference formulations are the most popular. In this application, it proved most convenient to use a finite difference approach, both to simplify integration with the Gradient Algorithm solver for the pipe network equations, and to take advantage of an existing finite difference solution of Equation 3 which has been developed within a rigorous QA/QC environment. This solution forms part of the SHETRAN code, which is a physically based, spatially distributed catchment modeling system, comprising modules representing flow and transport (solute and sediment) in all of the terrestrial phases of the hydrological cycle (Ewen et al. 2000). The SHETRAN module which solves Equation 2 is named VSS (variably saturated subsurface). VSS solves for a new value of the pressure potential (ψ) at each time-step by means of an iterative finite difference scheme using rectangular column elements (Parkin 1996).

For the simulation of ground water rebound in abandoned

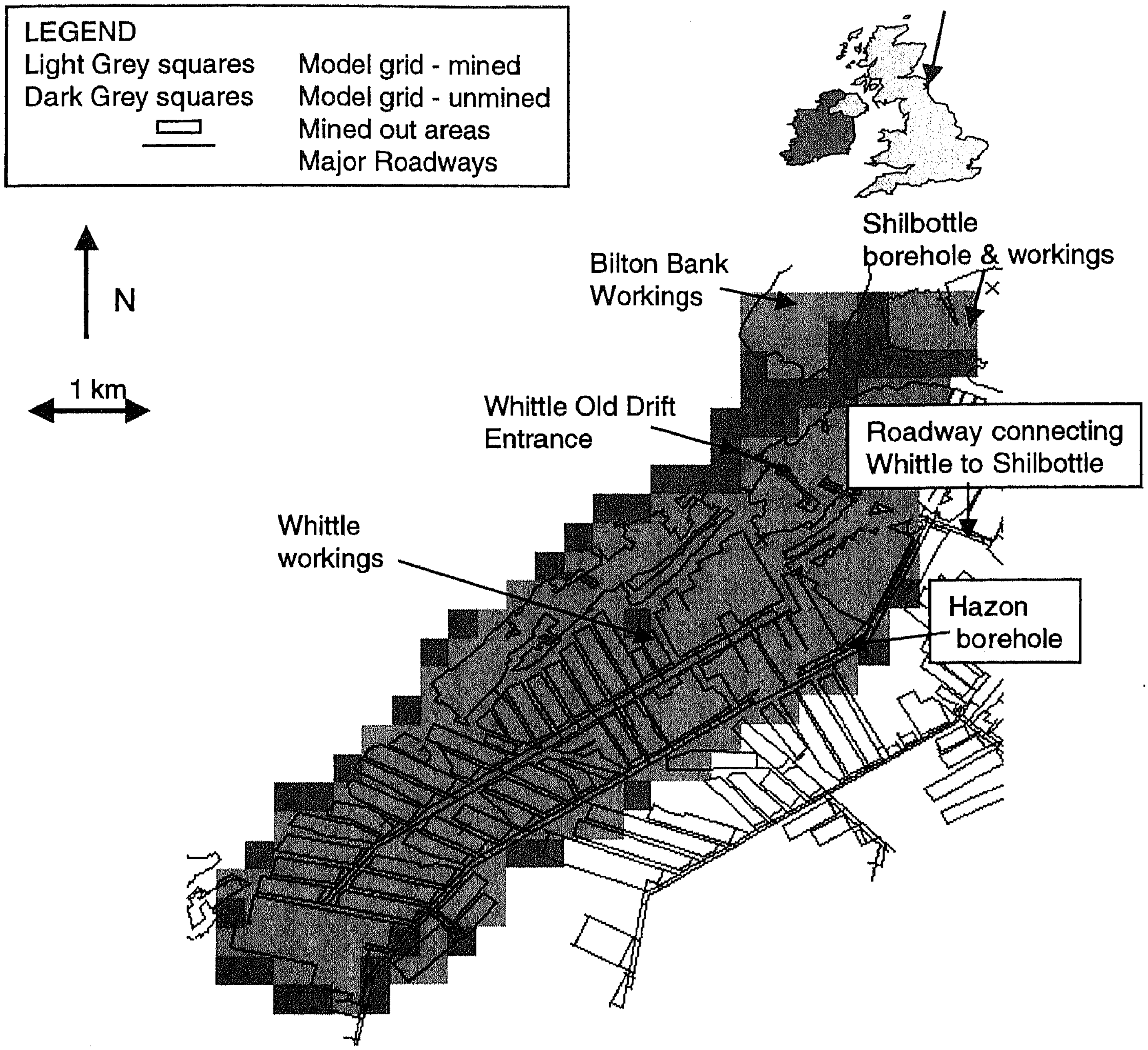


Figure 4. Location and plan of Whitttle and Shilbottle Collieries.

mines, it is necessary to couple the Gradient Algorithm solution for the pipe network with the finite difference solution of Equation 3. This is achieved by configuring the model grid such that the nodes of the pipe network are spatially coincident with the block-centered nodes of the porous medium grid in VSS. Figure 3 illustrates the geometry of the coupling. The overall time-step used in the coupled model is determined according to the accuracy requirements of the pipe network solution. Flows between each pipe element and its contiguous porous medium element are calculated at each time-step, assuming laminar flow in the porous medium, by a Darcian expression as follows:

$$Q_p^{n+1} = \beta_p \, k_r^n (z_p^n - \psi^n) \quad (4)$$

Where Q_p^{n+1} ($L^2 \cdot T^{-1}$) is the exchange flux at the current time-step between pipe and aquifer, β_p is the conductance ($L \cdot T^{-1}$), k_r^n (dimensionless) is the relative conductivity (< 1.0 if the column is unsaturated), z_p^n, (L) is the head at the pipe, and ψ^n (L) is the head at the column node, the superscripts n indicating the value at the previous time-step. After the exchange flows are calculated, the pipe network model is run to calculate a new set of z_p values over the current time-step. The VSS module then iterates for the heads in the aquifer at the current time-step including the source/sink term q in Equation 2, which has been adapted to incorporate the exchange between the porous medium and the conduits represented by Equation 4. An implicit procedure is employed which accounts for the change in the exchange flows as a result of the change in the aquifer heads. This procedure ensures the numerical stability of the coupled solutions. Different stability criteria apply in the VSS and NET modules. The overall coupled package is referred to hereafter as VSS-NET.

Application of VSS-NET to Real Mine Systems

To date, VSS-NET has been applied to three abandoned coalfields in the United Kingdom. Full details of these applications are

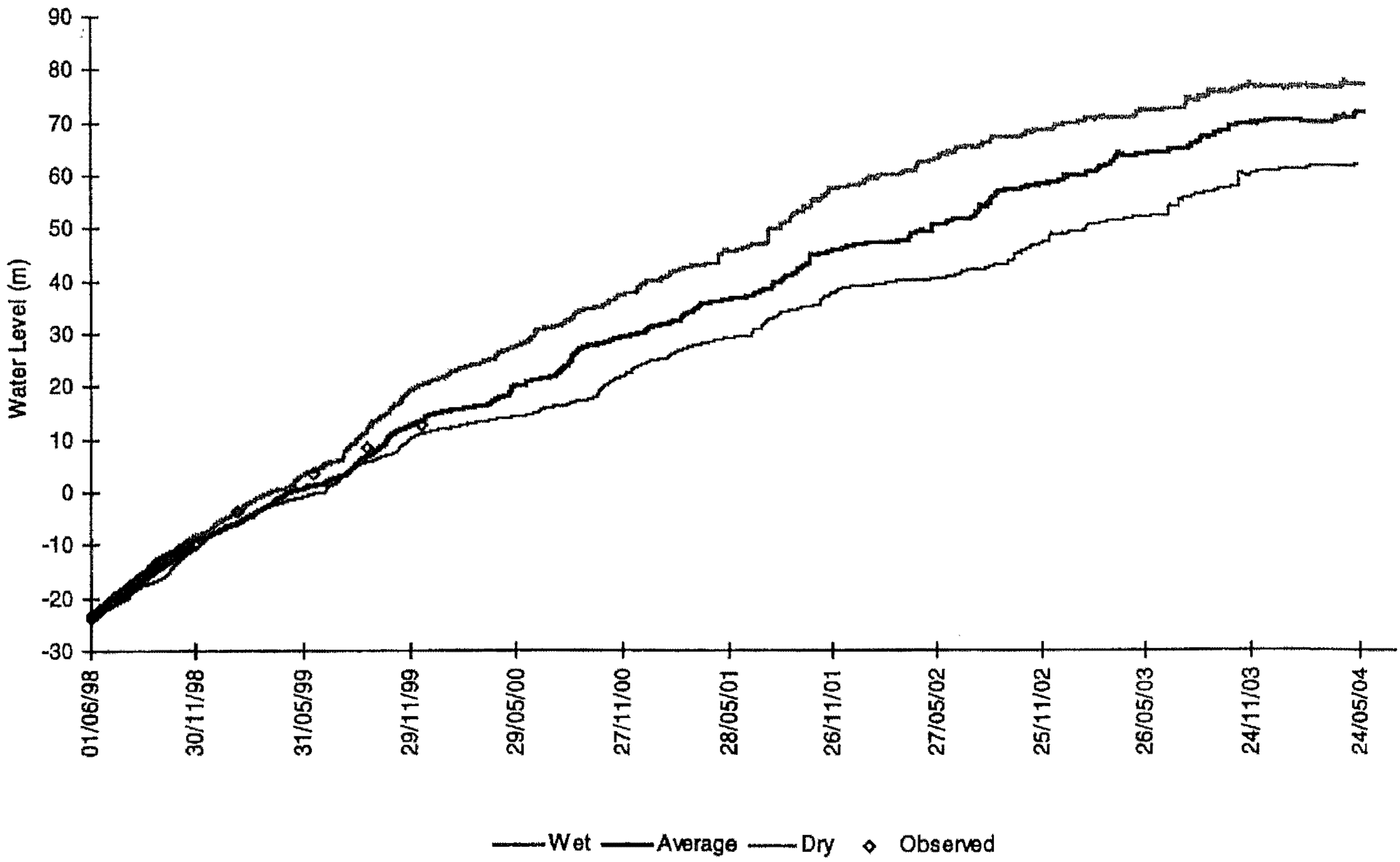


Figure 5. VSS-NET predictions of ground water rebound in the abandoned Whittle Colliery mine workings, Northumberland, England, assuming different recharge scenarios (wet, dry, and average), shown for the period June 1998 to June 2004, with observed data for 1998–1999 (crosses).

given by Younger and Adams (1999). The most extensive application so far has been to the Whittle and Shilbottle Collieries in Northumberland, England. These two collieries worked a single seam of coal which dips steadily eastward at about 8° to 10°. Shilbottle underlies an area of some 4 km^2, and Whittle an area of 28 km^2. The mines were interconnected by means of a single roadway driven in 1978, and in 1982 Shilbottle Colliery was abandoned. Figure 4 shows the location and configuration of the two collieries and the model grid, which comprised 250 m square finite-difference elements, (shown by the light and dark gray squares). Water formerly pumped from Shilbottle migrated through the connecting roadway, where it was intercepted by the Whittle dewatering pumps. Dewatering of Whittle Colliery ceased suddenly in April 1997 following bankruptcy of the mining company. Since then, water levels have been rising in the old workings, threatening to severely pollute a river of national conservation importance if they emerge unchecked at the surface. Since the mine system was well-mapped and some water level data were available, VSS-NET was used to obtain predictions of the timing of possible surface discharges from the mine by running simulations on a time-step of two hours. Two key points of uncertainty were examined using the model: whether an isolated area of old workings (known as Bilton Banks) northwest of Shilbottle were contributing water to Whittle; and the magnitude of recharge to the workings, and the degree to which the rate of rebound is sensitive to dry and wet years (1998 has been the wettest year on record in Northumberland). Recharge was calculated on a daily basis from the meteorological data (rainfall, potential evapotranspiration and soil moisture deficit) for the area of the mines.

Figure 5 shows three rebound curves obtained for the Whittle workings (for dry, wet, and average recharge conditions), with observed recovery data from the Hazon borehole (for location, see Figure 4) for comparison, for the time period June 1998 to June 2004. It is immediately apparent that the observed rebound (shown up to December 1999) is more consistent with the wet and average recharge rate scenarios than the dry scenario, bolstering confidence in the recharge estimation methods used. The modeled rebound curves are less linear than the observed curve, probably because the damping of the recharge flux in the unsaturated rock (sandstone, limestone, and shale) above the workings is not being represented in the model. VSS-NET also revealed that the existing rate of rebound in the Whittle workings cannot be explained without invoking lateral inflows from the old Bilton Bank workings. Running VSS-NET with and without a pipe network representing the major roadways produces a contrast in hydraulic gradients, with much steeper gradients when the pipe network is omitted, and Figures 6 (a and b) show respectively (with and without the pipe network) contour plots of water levels within the Whittle workings after six years of simulation. Boreholes recently drilled into the workings reveal low hydraulic gradients, consistent with the predictions of VSS-NET running with roadways represented as pipes. Further VSS-NET runs are underway for this site, as part of a pollution prevention strategy, which will include development of a pump-and-treat solution.

Semidistributed Model for Large Systems

Model Formulation

The VSS-NET code demands much computer storage and

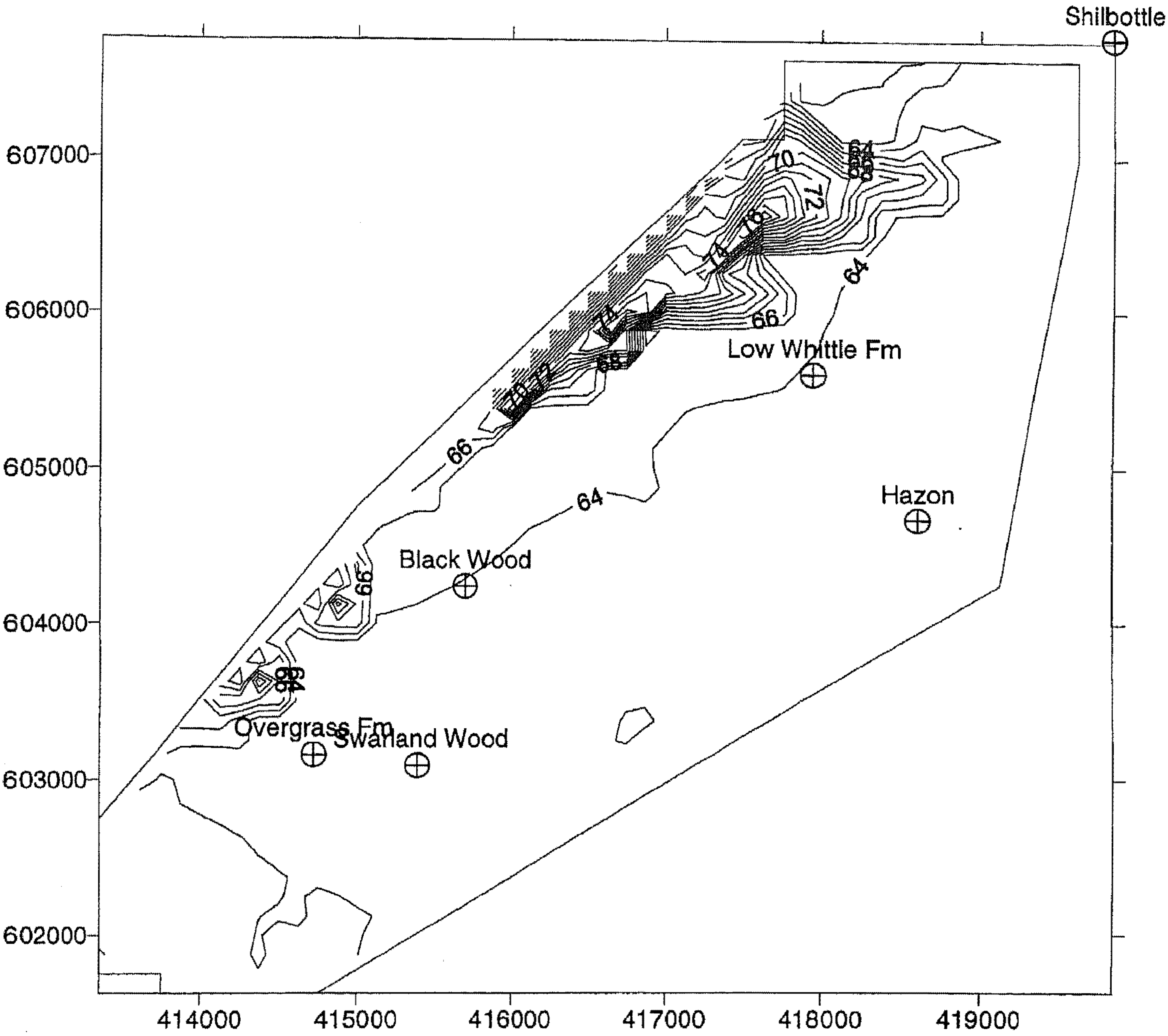


Figure 6a. Water levels in Whittle Colliery, June 2004, with a pipe network to represent major roadways in the mine.

patience in parameterization, and is therefore relatively costly to apply to mine systems any larger than a few tens of square kilometers. When one must analyze interconnected mine systems extending over hundreds of square kilometres (as in the Dysart-Leven Coalfield of Scotland; Younger et al. 1995) or even several thousand square kilometers (as in the Durham Coalfield of northern England [Younger 1993], the Silesian Coal Basins of Poland [Rogoz 1994], or the Ruhr Coalfield of Germany [Coldewey and Semrau 1994]), then a more modest mathematical representation becomes desirable, at least as the first step in system simulation. Typical features forming inter-mine overflow points include:

- Roadways (which, in Europe at least, were often driven between formerly separate mines during war time, to ensure security of egress in the event of bombing)
- An area in which two adjoining areas of workings effectively coalesce
- Old exploration boreholes
- Permeable geological features (e.g., the margins of a basaltic dyke, a limestone bed, or an open fault).

The concept of representing large areas of flooded mine workings as a pond of water has been adopted in this modeling approach. The extent of each pond can be determined by scrutiny of mine plans. Each pond encompasses the workings of numerous collieries, but each corresponds more or less to the take of the last major colliery to be worked in its vicinity. Experience has now established that similar systems of ponds can be defined in all major United Kingdom coalfields, and in the analogous coalfields of Germany and Poland. This compartmentalization of coalfields has its origins in the system of private ownership of mineral rights and/or mining leases, which dominated mining economics until the middle of the 20th century.

Figure 7 shows the concept of rebound in relation to ponds:

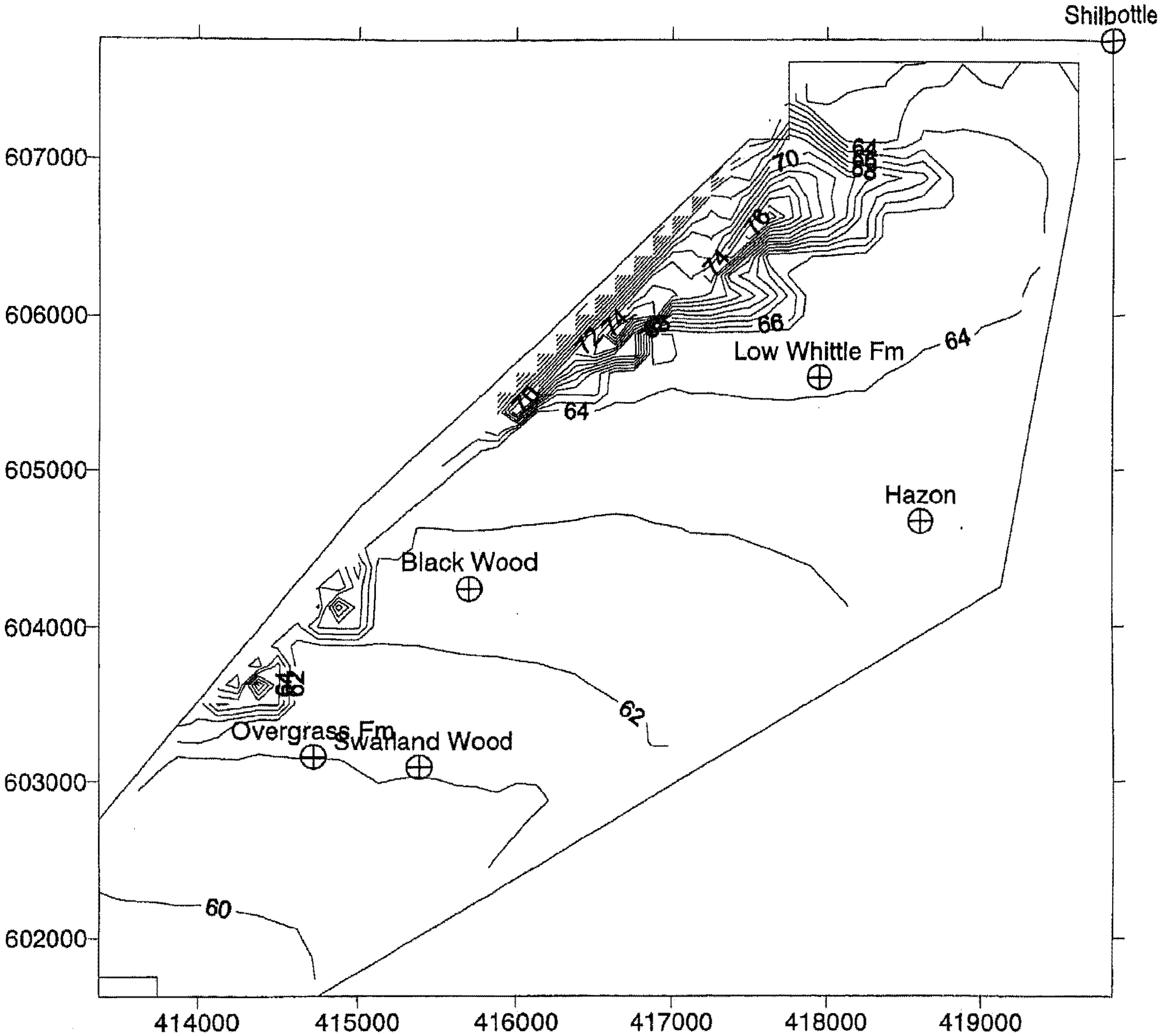


Figure 6b. Water levels in Whittle Colliery, June 2004, without a pipe network to represent major roadways in the mine.

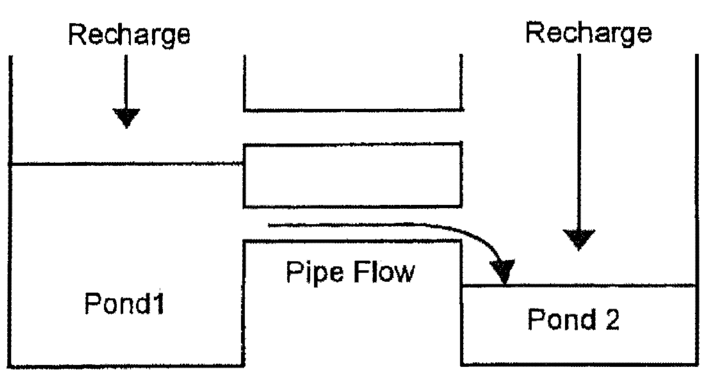


Figure 7. A sketch illustrating the concept of ponds and flow through overflow features as implemented in the GRAM code (after Sherwood 1997).

the water level in each pond will rise largely independently of all others until the invert of an overflow feature is reached, after which inter-pond transfers will occur, generally by turbulent flow in open voids. Once the water levels in two adjoining ponds are equal, levels in both will rise together. This type of behavior has been observed in a number of mining settings, and has prompted several independent groups of mining hydrogeologists to consider an appropriate from of mathematical representation. For instance, Younger and Sherwood (1993) proposed a "bespoke lumped-parameter model" to represent flooding of four ponds in the Durham Coalfield, England. A refined version of this model is presented later. Shortly thereafter, Rogoz (1994) proposed a similar model to predict rebound in the Upper Silesian Coal Basin, Poland. Subsequently, Gatzweiler et al. (1997) proposed a conceptually similar approach (which they termed "box modeling") to simulate ground water rebound in the deep uranium mines in eastern Germany.

Pond-based models of rebound in large systems are based on definition of mined volumes available for flooding, and on the calculation of water balances. In most of the models previously mentioned, this is achieved by solution of the following expression for a long series of short time-steps:

$$R - O - V_p = \Delta S \tag{5}$$

where

R = recharge during time-step (Δt) (= recharge rate $\times$ pond area (A) $\times$ Δt) (L^3)

O = inter-pond flow, during time-step (Δt) through overflow points (L^3); positive for flow leaving the pond, negative for flow entering it) and surface outflows

V_p = volume of water (if any) pumped from the pond during the time-step (L^3)

ΔS = change in volume of water stored in the pond during the time-step (L^3).

The change in water level (ΔL) in the pond over the time-step is related to ΔS by

$$\Delta L = \Delta S/(AS_y) \tag{6}$$

where S_y is the specific yield (dimensionless) of the pond at the relevant horizon.

Given that the level at the start of the time-step (L_{t-1}) is always known, then the water level at the end of each time-step (L_t) is given by

$$L_t = L_{t-1} + \Delta L \tag{7}$$

As in most water balance calculations, it is advisable to apply these equations only over short time-steps. Generally, a time-step of one day has been used without any problems.

Inter-pond transfers of water can be modeled in a number of ways, some of which are entirely arbitrary. Given that most inter-pond transfers occur via turbulent flow in large, open voids, it is perhaps most physically realistic to represent flow between ponds using formulae which describe turbulent flow in pipes, therefore the hydraulic conductivity of the mined strata is not required. In our study, we have used the Bernoulli equation, rearranged to represent head loss between two reservoirs connected by a pipe flowing full-bore:

$$H = \frac{0.5V^2}{2g} + \frac{V^2}{2g} + \frac{\lambda L V^2}{2gD} \tag{8}$$

Gross Head	Entry Loss	Velocity Head	Friction Head Loss

Using the Bernoulli equation in this form makes the implicit assumption that there is no free surface, which will clearly be untrue for short periods of time. In practice, this source of error is minimized by only allowing a pipe to function if the head in the upgradient pond is above the crown elevation of the pipe. However, the model can simulate inter-pond flow in either direction, so flow reversal due to backing-up of water in a pond can be represented. The diameter of the pipes in the model may be calculated from calibration, the calibrated diameter may be less than the actual diameter of the roadways connecting the mines. The model will adjust the diameter of the pipes so that they are always flowing full-bore. Of the components of gross head loss in Equation 8, only the friction head loss is of sufficient magnitude to materially affect flow rate in mining systems. Hence the entry loss and velocity head may be neglected with impunity, and Equation 8 rearranged to make the velocity of flow in the pipe (V) the subject, yielding an expression which converges on the well-known Darcy-Weisbach formula:

$$V = \sqrt{\frac{2g\Delta H}{\left(1.5 + \frac{\lambda L}{D}\right)}} \tag{9}$$

where

V = velocity of flow in the pipe ($L \cdot T^{-1}$)

ΔH = head difference between the ponds (L)

g = acceleration due to gravity ($L \cdot T^{-2}$)

D = pipe diameter (L)

L = pipe length (L)

λ = a non-dimensional coefficient which is a function of the roughness, diameter, and mean flow velocity of the pipe.

Evaluation of λ can be achieved by various means; the two most popular options being the Prandtl-Nikuradse Equation, which for rough turbulent flow is written

$$\frac{1}{\sqrt{\lambda}} = 2 \log \frac{3.7\,D}{k} \tag{10}$$

and the Colebrook-White formula:

$$\frac{1}{\sqrt{\lambda}} = -2 \log \left[\frac{k}{3.7\,D} + \frac{2.51}{Re\sqrt{\lambda}}\right] \tag{11}$$

where k is the surface roughness (L) and Re is the Reynolds number (dimensionless) (given by $Re = VD/\nu$, where ν is the kinematic viscosity ($L^2 \cdot T^{-1}$). The variation in kinematic viscosity is small for the ranges of pressure and temperature that occur in most ground water systems; hence it is convenient to consider it constant. The Reynolds number indicates whether the flow regime is laminar or turbulent, below 2000 laminar flow (and hence different equations) applies, between 2000 and 4000 is a transitional zone where the flow is unstable and no equation has been derived, above 4000 turbulent flow develops. Moreover, for large diameter pipes, the Reynolds number can exceed 10,000 and the second term in Equation 11 becomes insignificant, making the Prandtl-Nikuradse Equation more appropriate. Of these two formulations, the Prandtl-Nikuradse Equation is linear and therefore far less costly to use (in terms of computer run-time and storage) than the nonlinear Colebrook-White formula, which requires an iterative solution. Before settling on the Prandtl-Nikuradse Equation for this application, however, a lengthy comparative analysis was undertaken for pipe diameters and roughnesses relevant to mine water problems. It was found that errors in flow volume estimation introduced through selection of the Prandtl-Nikuradse formulation are of the order of zero to 0.001% of the total flow volume estimated using the more exact Colebrook-White Formula (Sherwood 1997). A full sensitivity analysis (Sherwood 1997) showed the model to be relatively insensitive to changes in the surface roughness of the pipe (k).

This mathematical formulation was coded in FORTRAN 77 (with a preprocessor written in Visual BASIC©) producing a package named GRAM (Groundwater Rebound in Abandoned Mineworkings). GRAM also includes refinements allowing for layering of specific yield within each pond in relation to areas of extensive

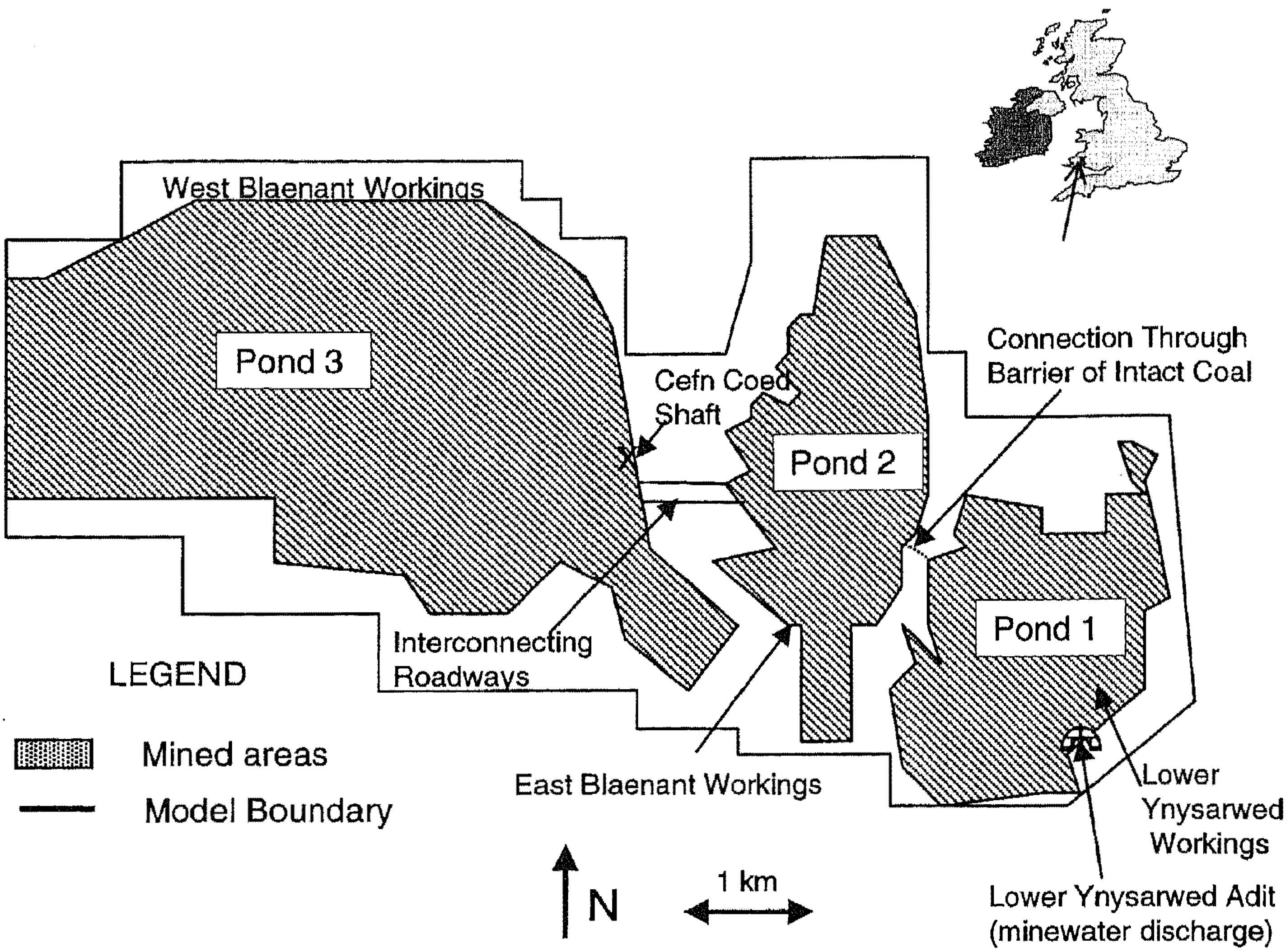


Figure 8. Location and plan of Blaenant and Ynysarwed Collieries.

working, some basic solute transport capabilities, and Monte Carlo simulation facilities. Further details of the algorithm are given by Sherwood and Younger (1997) and a full listing of the code with details of development and testing are provided by Sherwood (1997).

Application of GRAM to Real Mine Systems

The temporal and spatial scales over which we consider GRAM (and similar codes, such as those of Rogoz 1994 and Gatzweiler et al. 1997) to be applicable are indicated on Figure 2. To date, GRAM has been applied to seven abandoned mine systems as part of decision-making activities:

- Durham Coalfield, England (Sherwood and Younger 1994)
- Dysart-Leven Coalfield, Scotland (Younger et al. 1995 Sherwood and Younger 1997; Sherwood 1997)
- Rotherham district of the South Yorkshire Coalfield, England (Burke and Younger 2000)
- North Derbyshire/North Nottinghamshire Coalfield, England (Walker 1998)
- Blaenant-Ynysarwed Collieries, South Wales (Younger and Adams 1999)
- Whittle-Shilbottle Collieries, England (Younger and Adams 1999)
- Frazer's Grove Fluorspar Mines Complex, England (Younger, 1998b).

In all cases, GRAM produced predictions which have proven to be on the right order of magnitude for actual rebound subsequently observed. This means that the GRAM algorithm is a useful tool for predicting in outline the time-scales over which rebound will continue, therefore providing the basis for planning remedial action.

One example of a GRAM simulation is the Blaenant-Ynysarwed Collieries in the South Wales Coalfield, where cessation of dewatering led to flooding of two ponds in a single worked seam (the No 2 Rhondda Seam). Figure 8 shows the location and layout of the two collieries. The collieries were discretized into three GRAM ponds. The model was then run using a time-series of daily rainfall values from nearby gauges and recharge into the ponds was calculated using an annual average potential evapotranspiration, and a factor which partitions effective rainfall into either recharge or surface runoff. The correspondence between predicted and observed results, shown in Figure 9, which was obtained without fitting, illustrates, among other things, that the void volume estimates and recharge rate time-series derived for this system are highly credible.

Application of MODFLOW to a Real-Mine System

The laminar flow ground water model MODFLOW (McDonald and Harbaugh 1988) was applied to the Dysart-Leven Coalfield in eastern Scotland (Sherwood 1997). The generalized layout of the mines is shown in Figure 10. The aims of the simulations were to

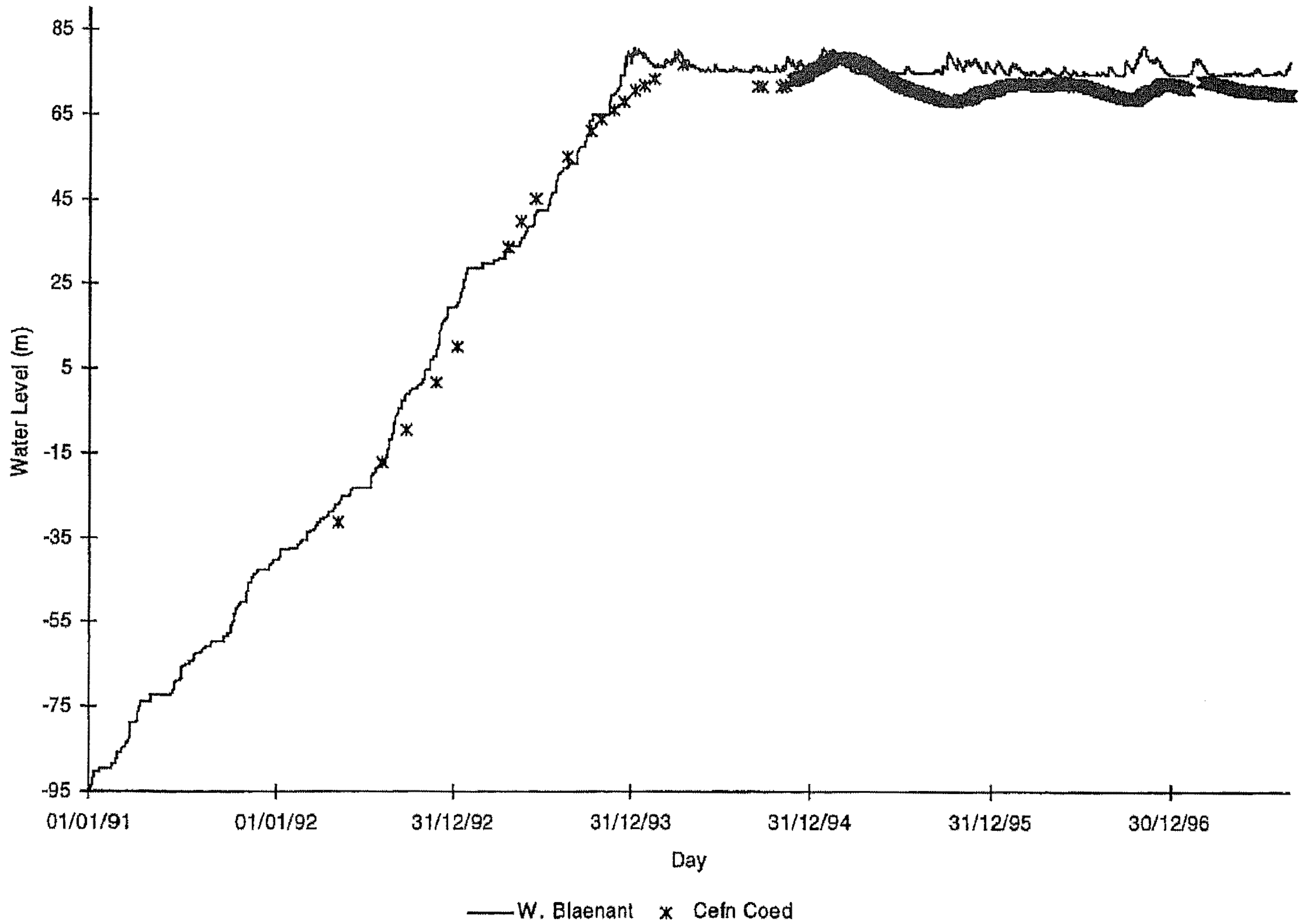


Figure 9. Ground water rebound in the Cefn Coed Colliery Shaft (Blaenant-Ynysarwed ponds system, South Wales): observed (crosses) and modeled (in West Blaenant pond) using GRAM, 1991 to 1997.

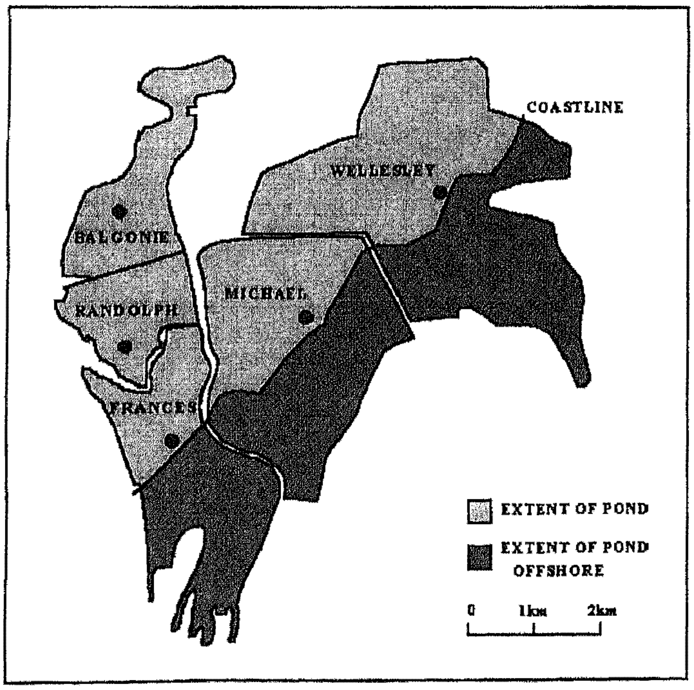


Figure 10. Diagram illustrating the occurrence of ponds within the deep-mined area of the Dysart-Leven Coalfield, Fife, Scotland (after Sherwood 1997).

develop firstly a steady-state model of the interconnected mines when mine water was being pumped out during mining. The coalfield was represented as an equivalent porous media (EPM) in MODFLOW; hence this model was of the type CDGWFM. The Block-Centred Flow Package 2 (BCF2) was used to simulate wetting of cells which was important in these simulations to ensure stability, however, convergence problems were encountered at cells containing abstraction wells. The model was calibrated against the observed water level in each mine during operation. However, the calibrated heads differed from the observed by 60 to 220 m even when the hydraulic conductivities were calibrated separately in each mine. At this point it was decided to abandon using MODFLOW to simulate the water levels in the mine during operation. MODFLOW has not, to our knowledge, been successfully applied to any other coalfield. However, as suggested above, it may be possible to use a laminar flow ground water model for a regional-scale water balance model.

Conclusions

In the preceding three sections, we have developed techniques for modeling ground water rebound in mine systems of increasing size and compared these techniques to the use of an existing ground water model. For relatively modest systems (area < 200 km^2), a physically based modeling approach is feasible. For instance, in the

VSS-NET program, 3-D pipe networks representing major mine roadways, etc., are routed through a variably saturated, 3-D porous medium (representing the country rock). For systems extending more than 100 to 3000 km^2, a semidistributed model (GRAM) has been developed, which conceptualizes extensively interconnected volumes of workings as ponds, which are connected to other ponds only at discrete overflow points (such as major inter-mine roadways) through which flow can be efficiently modeled using the Prandtl-Nikuradse pipe-flow formulation. At the very largest scales, it remains our contention that simple water-balance calculations are probably as useful as any other approach, and a variety of proprietary codes (including off-the-shelf ground water modeling packages) may be used for the purpose. Given that discharges of polluted water from abandoned mines are a major cause of degradation of water resources worldwide, the availability of a predictive strategy applicable across a range of scales is of clear benefit in the planning of pollution prevention strategies. These require the timing, location and magnitude of the polluting discharges to be accurately estimated by whichever modeling strategy is chosen.

While this paper has not dealt with the geochemical aspects of rebound prediction, it should be noted that these can be coupled to the flow calculations previously described. In most cases, it will be most efficient (and most consistent with generally limited data) to perform geochemical predictions of pollution severity and longevity as post-processing exercises, using a variety of predictive techniques (see Younger and Adams 1999 for further guidance).

Acknowledgments

The work described here was primarily funded by the Environment Agency (England and Wales) and Northumbrian Water Limited (a member of the Suez-Lyonnaise des Eaux Group) under the auspices of the R&D project "Improved Modeling of Abandoned Coalfields" (EA Contract No B04(95)2). Some of the development work for the GRAM model was funded by the Engineering and Physical Sciences Research Council.

References

Banks, D., P.L. Younger, R.T. Arnesen, E.R. Iversen, and S.D. Banks. 1997. Mine-water chemistry: The good, the bad and the ugly. *Environmental Geology* 32, no. 3: 157–174.

Burke, S.P., and P.L. Younger. 2000. Groundwater rebound in the South Yorkshire Coalfield: A first approximation using the GRAM model. *Quarterly Journal of Engineering Geology* 33, 149–160.

Cain, P., D.J. Forrester, and R. Cooper. 1994. Water inflows at Phalen Colliery in the Sydney Coalfield, and their relation to interaction of workings. In *Proceedings of the 5th International Minewater Congress*, Vol. 1, 83–95. Nottingham, U.K.: IMWA.

Coldewey, W.G., and L. Semrau. 1994. Mine water in the Ruhr area (Federal Republic of Germany). In *Proceedings of the 5th International Mine Water Congress*, Vol. 2, 613–629. Nottingham, U.K.: IMWA.

Ewen, J., G. Parkin, and P.E. O'Connell. 2000. SHETRAN: A coupled surface/subsurface modelling system for 3D water flow and sediment and contaminant transport in river basins. *ASCE Journal of Hydrologic Engineering* 5, no. 3: 250–258.

Gatzweiler, R., R. Hähne, M. Eckart, J. Meyer, and S. Snagovsky. 1997. Prognosis of the flooding of uranium mining sites in east Germany with the help of numerical box-modeling. In *Proceedings of the 6th International Mine Water Association Congress, "Minewater and the Environment,"* Vol. 1, 57–64. Ljubljana, Slovenia: IRGO and IMWA.

González, A., and J.A. Sáenz de Sanatamaría. 1998. La problemática del agua en minería subterránea activa y en proceszo de cierre de HUNOSA. In *Procedimientos de la Reunión Científico-Técnica Sobre el Agua en el Cierre de Minas*. Dpto de Explotación y Prospección de Minas, Escuela Superior de Ingenieros de Minas, Universidad de Oviedo, Asturias, España.

Groves, C.G., and A.D. Howard. 1994. Early development of karst systems, 1. Preferential flow path enlargement under laminar flow. *Water Resources Research* 30, 2837–2846.

Hanna, R.B., and H. Rajaram, 1998. Influence of aperture variability on dissolutional growth of fissures in karst formations. *Water Resources Research* 34, 2843–2853.

Henton, M.P. 1981. The problem of water table rebound after mining activity and its effects on ground and surface water quality. In *Quality of Groundwater*, ed. W. van Duijvenbooden, P. Glasbergen, and H. van Lelyveld, 111-116.

Howard, A.D., and C.G. Groves. 1995. Early development of karst systems, 2. Turbulent flow. *Water Resources Research* 31, 19–26.

Jarvis, A.P., and P.L. Younger. 1997. Dominating chemical factors in mine water induced impoverishment of the invertebrate fauna of two streams in the Durham Coalfield, United Kingdom. *Chemistry and Ecology* 13, 249–270.

Lancaster, D. 1995. Delineating the catchment area and flow system of a major polluted spring in County Durham. Unpublished M.Sc. thesis, Department of Civil Engineering, University of Newcastle, United Kingdom.

McCoy, E.L., C.W. Boast, R.C. Stehouwer, and E.J. Ladivko. 1994. Macropore hydraulics: Taking a sledgehammer to classical theory. In *Soil Processes and Water Quality*, ed. R. Lal and B.A. Stewart, 303–348. Boca Raton: CRC Press.

McDonald, M.G., and A.W. Harbaugh. 1988. A modular three-dimensional finite-difference ground-water flow model. United States Geological Survey, Techniques of Water Resources Investigations Report O6-A1.

Monjoie, A. 1998. Problemática general del agua en relación con el cierre de minas en Bélgica. In *Procedimientos de la Reunión Científico-Técnica Sobre el Agua en el Cierre de Minas*. Dpto de Explotación y Prospección de Minas, Escuela Superior de Ingenieros de Minas, Universidad de Oviedo, Asturias, España.

Oron, A.P., and B. Berkowitz. 1998. Flow in rock fractures: The local cubic law assumption re-examined. *Water Resources Research*, 34, 2811–2825.

Parkin, G. 1996. A three-dimensional variably-saturated subsurface modelling system for river basins. Ph.D. thesis, Department of Civil Engineering, University of Newcastle Upon Tyne, United Kingdom.

Rogoz, M. 1994. Computer simulation of the process of flooding up a group of mines. In *Proceedings of the 5th International Mine Water Congress*, Vol. 1, 369–377. Nottingham, U.K.: IMWA.

Sadler, P.J.K. 1998. Minewater remediation at a French zinc mine: Sources of acid mine drainage and contaminant flushing characteristics. In *Groundwater Contaminants and Their Migration*, ed. J. Mather, D. Banks, S. Dumpleton, and M. Fermor, 101–120. Geological Society Special Publication No 128. London: Geological Society.

Salgado, R., E. Todini, and P.E. O'Connell 1989. A comparison of the gradient method with some traditional methods for the analysis of water supply distribution networks. In *Computer Applications in Water Supply*, Vol 1: *Systems Analysis and Simulation*, 38–57.

Sherwood, J.M. 1997. Modelling minewater flow and quality changes after coalfield closure. Unpublished Ph.D. thesis, Department of Civil Engineering, University of Newcastle.

Sherwood, J.M., and P.L. Younger. 1994. Modelling groundwater rebound after coalfield closure: An example from County Durham, United Kingdom. In *Proceedings of the 5th International Mine Water Congress*, Vol. 2, 769–777.

Sherwood, J.M., and P.L. Younger. 1997. Modeling groundwater rebound after coalfield closure. In *Groundwater in the Urban Environment*, Vol. 1: *Problems, Processes and Management*, ed. P.J. Chilton et al., 165–170.

Todini, E., and S. Pilati. 1989. A gradient algorithm for the analysis of pipe networks. In *Computer Applications in Water Supply*, Vol. 1: *Systems Analysis and Simulation*, 1–20.

Toran, L., and K.R. Bradbury. 1988. Groundwater flow model of drawdown and recovery near an underground mine. *Ground Water* 26, 724–733.

Walker, J., 1998. The environmental effects of minewater discharge due to progressive abandonment of the North Derbyshire—North Nottinghamshire Coalfield. Unpublished M.Sc. thesis, University of Sheffield.

Wolkersdorfer, C. 1994. Changes in mine water hydrology during flooding of an abandoned uranium mine in the Erzegebirge, Saxonia, Germany. In *Proceedings of the 5th International Mine Water Congress*, Vol. 1, 43–55. Nottingham, U.K.: IMWA.

Younger, P.L. 1993. Possible environmental impact of the closure of two collieries in County Durham. *Journal of the Institution of Water and Environmental Management* 7, 521–531.

Younger, P.L. 1995. Minewater pollution in Britain: Past, present and future. *Mineral Planning* 65, 38–41.

Younger, P.L. 1998a. Adit hydrology in the long-term: Observations from the Pb-Zn mines of northern England. In *Proceedings of the International Mine Water Association Symposium on Mine Water and Environmental Impacts*, Vol. II, 347–356. Johannesburg, R.S.A.: IMWA.

Younger, P.L. 1998b. Environmental implications of the closure of Frazer's Grove fluorspar mine, County Durham. Report to the Environment Agency, Northumbria Area. Department of Civil Engineering, University of Newcastle.

Younger, P.L. 1999. Mine water pollution in Scotland: Nature, extent and preventative strategies. *Science of the Total Environment.* In press.

Younger, P.L., and R. Adams. 1999. Predicting mine water rebound. Environment Agency R&D Technical Report W179. Bristol, United Kingdom.

Younger, P.L., and K.J. Harbourne. 1995. To pump or not to pump: Cost-benefit analysis of future environmental management options for the abandoned Durham Coalfield. *Journal of the Chartered Institution of Water and Environmental Management* 9, no. 4: 405–415.

Younger, P.L., and J.M. Sherwood. 1993. The cost of decommissioning a coalfield: Potential environmental problems in County Durham. *Mineral Planning* 57, 26–29.

Younger, P.L., M.H. Barbour, and J.M. Sherwood. 1995. Predicting the consequences of ceasing pumping from the Frances and Michael Collieries, Fife. In *Proceedings of the Fifth National Hydrology Symposium*, ed. A.R. Black and R.C. Johnson, 2.25–2.33. Wallingford, U.K.: British Hydrological Society.

Younger, P.L., G. Teutsch, E. Custodio, T. Elliot, M. Sauter, M. Manzano, R. Liedl, T. Clemens, D. Hückinghaus, C.S. Tore, J. Lambán, and G. Cardoso da Silva. 1997. Groundwater resources and climate change effects—GRACE: Final report. EC Framework III Environment and Climate Programme, Project EV5V—CT94 - 0471.