SIMULATION OF GROUNDWATER REBOUND IN ABANDONED MINES USING A PHYSICALLY BASED MODELLING APPROACH

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ABSTRACT

The recent large-scale closure of most of the deep mines in the United Kingdom has lead to increased interest in predicting long term pollution problems. Extensive contamination of surface water and groundwater is expected as minewater emerges at the surface following groundwater rebound. Groundwater rebound will occur if the pumping of minewater from disused workings, which are often interconnected over a large area, is stopped. In order to predict the location, time of appearance and quality of uncontrolled minewater discharges, a physically based hydrological modelling system (SHETRAN) is being directly coupled with a pipe network model. SHETRAN can simulate groundwater flow and transport in subsurface zones of varying saturation. Existing groundwater models cannot simulate turbulent flow, which may develop in large conduits in mined systems such as roadways and open mined voids. Flows in these regions will be directly computed by the pipe network model. It is hoped that this modelling system, once fully tested and validated, will provide a powerful simulation tool for investigating scenarios where good data are available and accurate, precise predictions of minewater problems are required. The model will also be used to perform sensitivity analyses on alternative mine configurations and water level changes where there is uncertainty in the mine plans. A case study in the South Wales Coalfield is being used to validate the model, which will then be applied to a larger coalfield in North East England, where the cessation of pumping from abandoned mines is under consideration.

INTRODUCTION

Under the title "Improved Methods for Modelling Abandoned Coalfields", a research project has been undertaken to develop and test a new generic model for subsurface flow in abandoned coalfields. This project arose out of concern for the effects of future acid mine discharges from the North East England Coalfield on surface waters in the North East region. (Younger, 1993, Sherwood and Younger 1994), if pumping of water from abandoned workings in this coalfield is stopped. This paper describes the rationale for the adoption of an advanced physically based modelling system as the basis for a generic model for minewater rebound.

The generic model must be capable of simulating the time, location and volume of discharges of uncontrolled minewater, once the pumping of the mine workings has ceased. The model described below simulates water flow only but will be coupled with a geochemical component to simulate water quality.

THE HYDROGEOLOGY OF ABANDONED COALFIELDS

Figure 1 shows the hydrogeology, depicting the minewater flow regimes, found in abandoned coalfields during rebound. Mining methods shown are both "bord and pillar" and longwall. Both methods may leave some areas of intact coal as barriers and longwall workings also leave : (i) areas of goaf ; (ii) subsided or relaxed zones over worked panels (indicated by the dashed lines). Flow will be turbulent in open roadways, shafts and mined-out voids, and laminar in subsided or relaxed zones, goaf, barriers, and in intact strata.

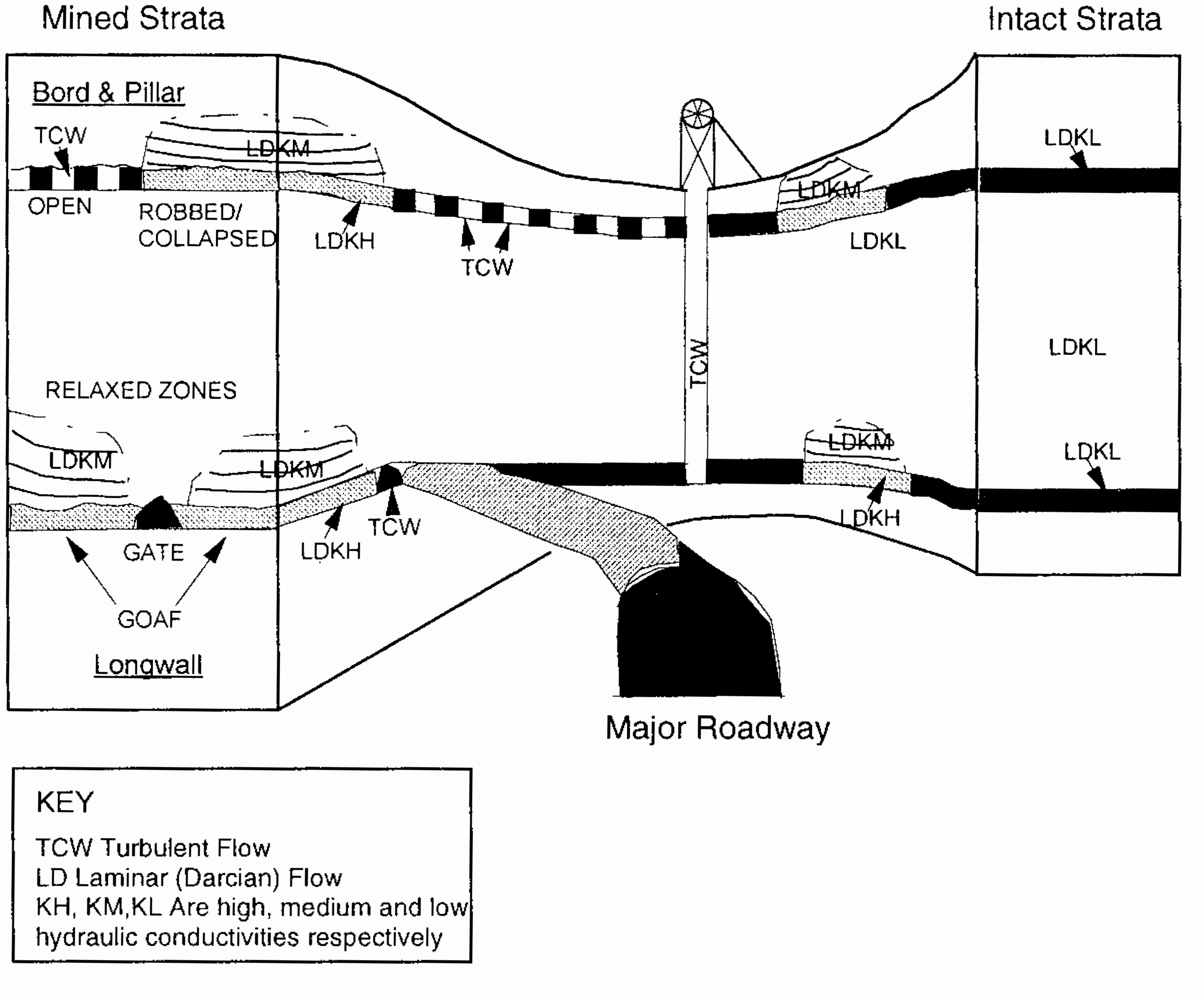

Figure 1: Generalised Conceptual Hydrogeological Model for an Abandoned Coalfield

Evidence for turbulent flow in abandoned workings has been observed in the response of shaft water levels after cessation of pumping at both the Dysart Leven coalfield in Scotland, (Younger et.al., 1995) and in the interconnected mines south of the Butterknowle fault in Co. Durham, England, (Lancaster, 1995). Plots from these coalfields of water level against time, during groundwater recovery, differ from the usual plots from pump tests which normally match the analytical solutions obtained assuming laminar flow in the aquifer. High concentrations of suspended solids have also been observed in water quality records from Frances and Michael Collieries in the Dysart Leven Coalfield as a result of erosion of the connections with Randolph Colliery, which indicate that turbulent flow developed between Randolph Colliery and Frances and Michael Collieries. Tracer tests in abandoned mineworkings have also indicated that turbulent flow can develop in open roadways. In a series of tracer tests in the Forest of Dean Coalfield, roadways above the regional water table were found to transmit water at velocities of up to 16 km/d (Aldous and Smart, 1988). Velocities this large in roadways of several metres in diameter clearly indicate turbulent flow, even below the water table where velocities were approaching 0.5 km/d. Figure 1. also shows the variation in hydraulic conductivity of mined and intact strata. The intact strata in the UK typically comprises Carboniferous sequences of sandstone, shale and coal, with different hydraulic conductivities, often overlain by Permian sands and limestones. The mathematical model being developed has to account for these differences in flow regimes and conductivities. The model will be verified and refined by application to an already abandoned coalfield for which a suitable data set exists. A suitable case study is the Ynysarwed - Blaenant colliery system (Younger 1995). Preliminary development and testing of the model is currently being undertaken.

MINEWATER MODELLING APPROACHES

Existing literature on the subject of minewater modelling was reviewed before commencing the conceptual model development. The review found a dearth of published literature on the subject of modelling groundwater rebound in coal mines which indicates that this research area is essentially a new development of groundwater modelling. No research into the modelling of turbulent flow in deep mine systems has been carried out to the author's knowledge, except by the team at Newcastle University. Applications of existing, conventional, usually two - dimensional, groundwater models have been made to abandoned mines with varying success (Toran and Bradbury 1988, Lancaster 1995, Paulino et.al. 1997). Finite element groundwater codes have been modified to estimate inflows into working mine systems in the UK (Fawcett et.al., 1984 & Lloyd et.al. 1991), and in the USA into working longwall mines (Girrens et.al. 1981), and abandoned mines, (Manula & Owili-Eger 1975 & Schubert 1978). The unusual characteristics of mined strata and data limitations appear to have restricted the success of these models. Few models have been capable of representing the heterogeneous and anisotropic characteristics of aquifers affected by mining. "Off-the-shelf" (MODFLOW) and specialist (MINEFLO) groundwater models are also used in the USA to simulate inflows to assess pumping requirements and also to predict acid mine drainage (Perry 1993). Lumped parameter models have been developed (Sherwood & Younger 1994, Rogoz 1994), to model abandoned coal mines, but no physically based models have yet been employed.

DEVELOPMENT OF THE GENERIC MODEL

Introduction to SHETRAN

A physically based methodology has been adopted for the modelling of abandoned mines after pumping has ceased. The advanced water flow and transport modelling system, SHETRAN has been selected for this purpose (Ewen 1995). SHETRAN is a physically based, spatially distributed catchment modelling system. A modular system of linked components has been adopted which allows contaminants and sediments to be modelled in conjunction with water flow.

For the modelling of 3-d groundwater flow in variably saturated porous media, the VSS (Variably Saturated Subsurface) component of SHETRAN, has been developed, (Parkin 1995). This component allows the modelling of complex geological structures by the model. The VSS component is fully coupled with the surface processes, so groundwater flows can be controlled by surface conditions and spatially varying recharge. Fig 2 depicts the physical processes and source/sink terms which can be simulated by the existing VSS component.

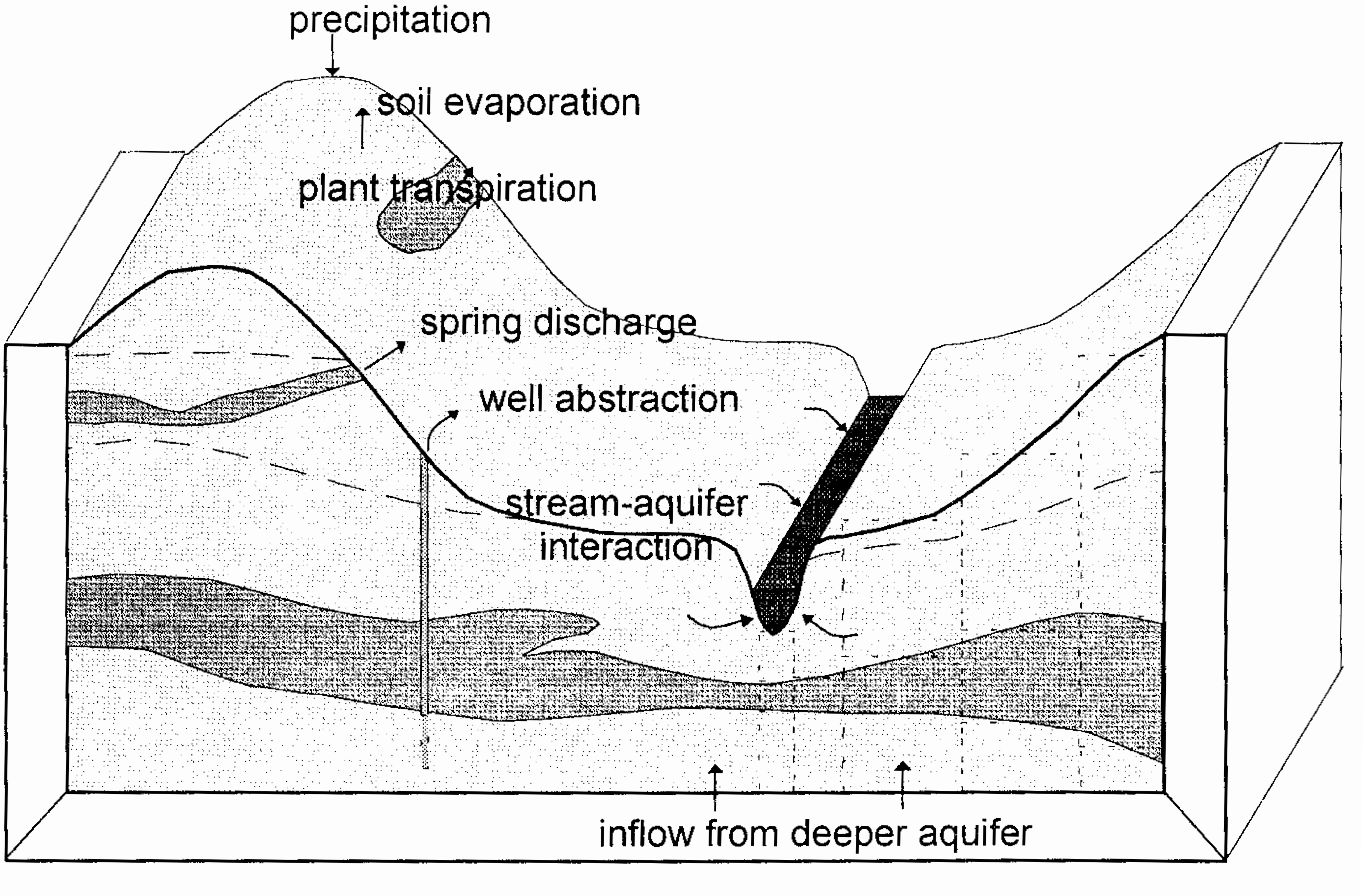

Figure 2: The Variably Saturated Subsurface (VSS) Component for SHETRAN

Application of the VSS component of SHETRAN to Abandoned Coalmines

In this application of SHETRAN, processes at the ground surface are not directly modelled, however the front-end of SHETRAN is utilised for the input of data and control of the simulations. The VSS component then obtains the catchment configuration, boundary conditions and source and sink terms (e.g. well abstraction flows), from the SHETRAN model. For minewater modelling, a time-varying recharge term is specified as the top flow boundary condition. The VSS component is capable of simulating the combination of saturated and unsaturated conditions found in abandoned coalfields. VSS discretises the aquifer into a series of laterally connected vertical columns (Fig 3a).

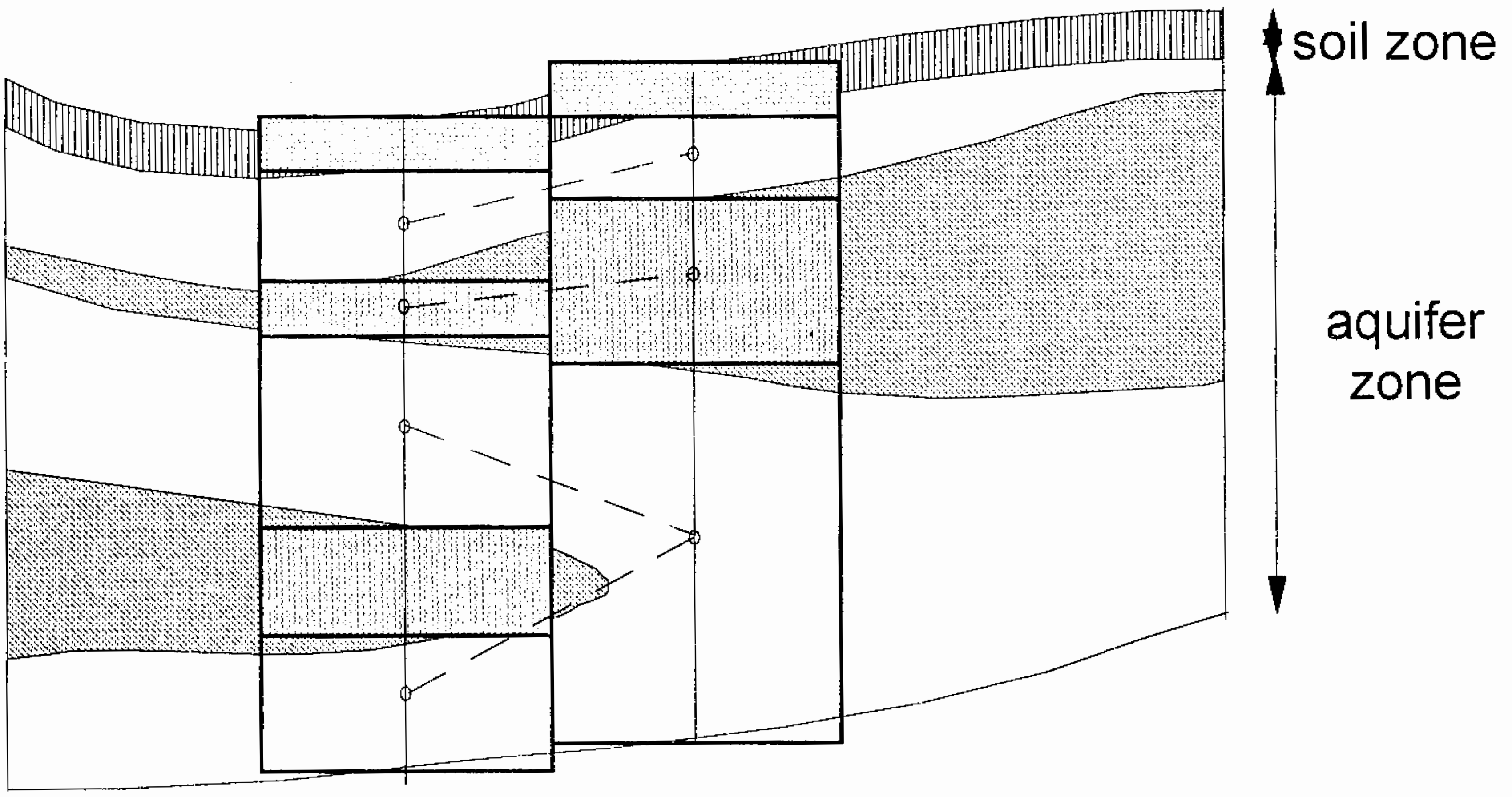

Figure 3a: Geological Layering and Connectivity in VSS

Each column comprises a series of computational cells which represent the heterogeneous nature of the aquifer. The modeller can select which cells are connected laterally in order to simulate sloping strata (Fig 3b).

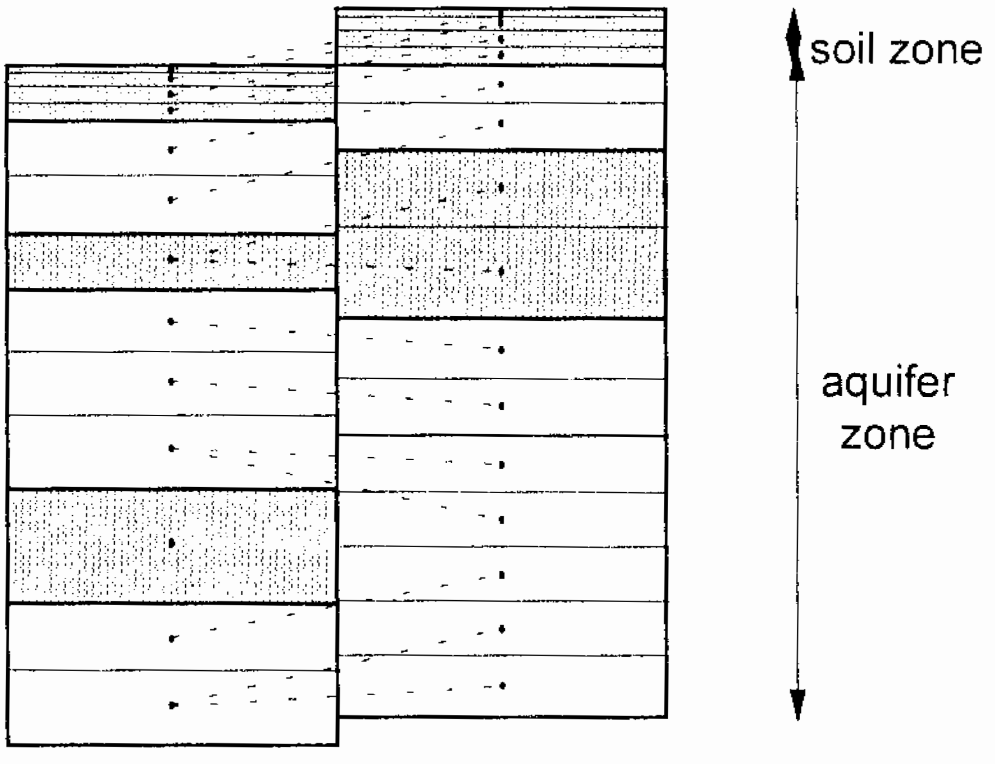

Figure 3b: VSS Computational Cell Definitions and Interconnections

The equation of three dimensional groundwater flow (1) which is employed by this model is based on the assumption of laminar flow and states that.

$$\eta\frac{\partial\psi}{\partial t}=\frac{\partial}{\partial x}\left[K_x k_r\frac{\partial y}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y k_r\frac{\partial y}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_z k_r\frac{\partial y}{\partial z}\right]+\frac{\partial(k_r K_z)}{\partial z}-q \qquad (1)$$

where x,y and z are Cartesian co-ordinates, q is a specific volumetric flow rate out of the medium representing sources or sinks, ψ pressure potential, K_x, K_y and K_z 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.

η is the *storage coefficient* defined by Eq. 2 as

$$\eta=\frac{\theta S_s}{n}+\frac{d\theta}{d\psi} \qquad (2)$$

Where, θ is the volumetric moisture content, S_S the specific storage, and n the porosity.
The model solves for a new value of the pressure potential ψ at each timestep using an iterative finite - difference matrix scheme.
Typically, SHETRAN has been used to simulate catchments of the order of tens of square metres (experimental plots) up to several hundred square kilometres (river basins). Grid squares are used to discretise the catchment, and squares of up to 1km by 1km have been used in previous simulations. For the simulation of abandoned coalmines, grid squares of the order of several hundred metres square will be used. There is no limit on the depth of the vertical columns, and for abandoned coalmines, depths of approaching 1000m may be necessary in some situations. A VSS computational cell will typically from be 1 to 20m in thickness.

Physically based modelling requires large quantities of hydrogelological data for the model parameters and validation. However, if good data sets are available, lengthy calibration of the parameters can usually be avoided. The other advantage of using of physically based parameters is that that the model can be used confidently to predict future scenarios of minewater emergence and discharge over a time scale of tens of years, incorporating if necessary stochastically generated rainfall data.

Overview of the Network Component

In regions where the flow regime is likely to be turbulent (non-Darcian), groundwater flow cannot be directly simulated by the existing VSS component. In order to simulate turbulent flow, a pipe network model has been adopted which will allow the larger flow pathways to be discretised by a series of interconnected conduits (pipes). This network model has been coupled to the VSS model in order to model the interactions between the aquifer (representing the intact strata) and these conduits in the mined out strata.

The solution of a pipe network, to calculate pressure heads and flow rates, requires a numerical algorithm, as the equations for turbulent flow are non-linear. In a pipe network, the pipes are joined together at *nodes* where sources and sinks are added into the network. One method referred to as the Gradient Algorithm (Todini & Pilati 1989), has been applied to several networks using a microcomputer program, for comparison with other methods, (Salgado et.al. 1989). For the simulation of turbulent flow in mined strata this method has been chosen as the most computationally efficient and robust numerical method currently available.

Flows in the pipes are calculated using either the Colebrook - White empirical pipe resistance formula in conjunction with the Darcy - Weisbach flow formula or the simpler, exponential Hazen - Williams formula (3).

$$q_{ji} = 0.27746 C_{ji} D_{ji}^{2.63} \left[\frac{h_i - h_j}{L_{ji}} \right]^{0.54} \qquad (3)$$

where q_{ji} is the flow from node i to node j, C_{ji} the Hazen - Williams flow coefficient for pipe ji, D_{ji} the pipe diameter and h_j, h_i the respective heads at nodes j and i.

The Hazen - Williams formula is generally preferred for most pipe analysis problems when pipes are operating in the turbulent zone. The Colebrook-White formula includes viscosity, which is temperature-dependent, so is applicable over a wider range of conditions.

Linking the Network Model with the VSS Component

The connections between the pipes in the network model with the columns in the VSS component are shown in figure 4.

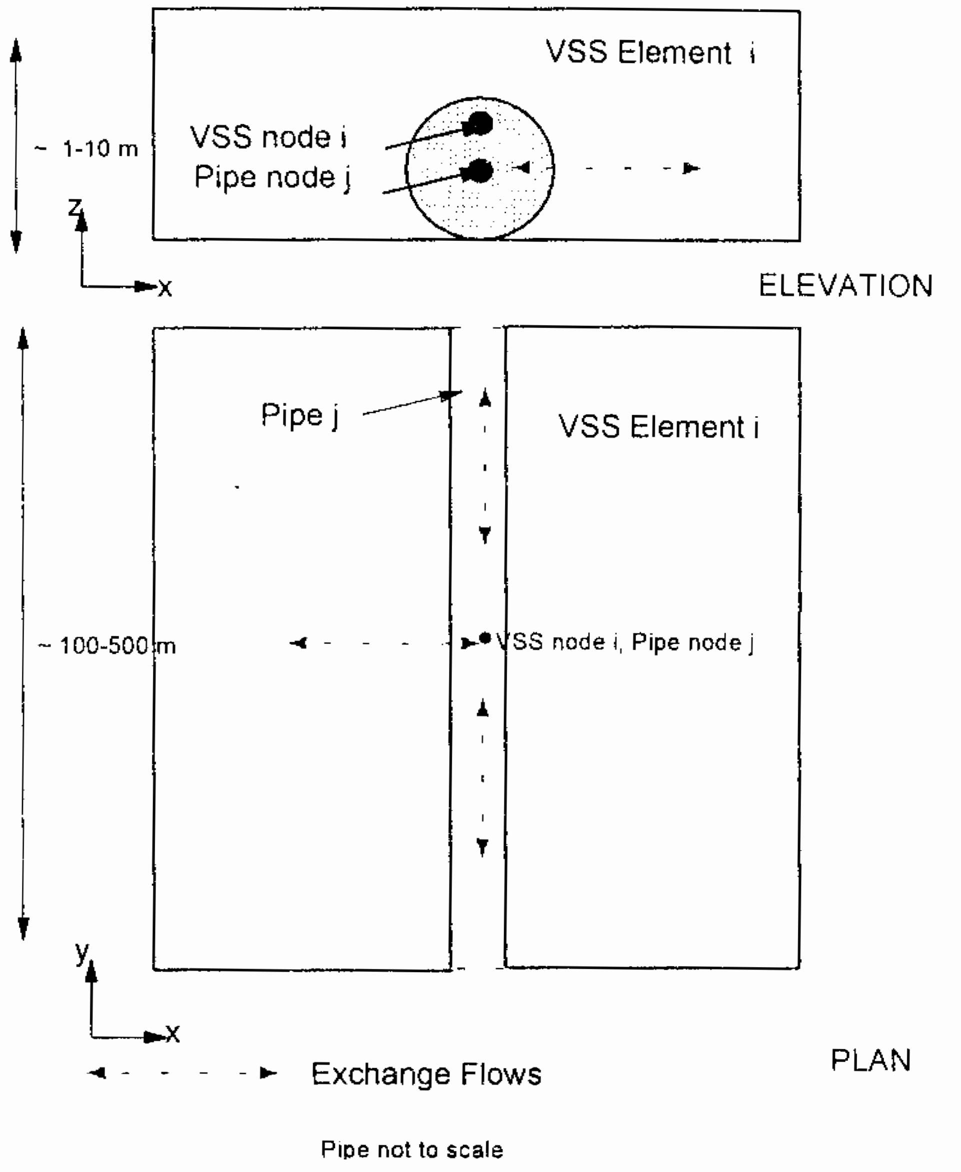

Figure 4: Configuration of Pipes and VSS Elements

Each pipe is connected to a cell in the vertical column and flows between the pipe and column are calculated at each model timestep, assuming Darcy's law applies, using the equation

$$Q_p^{n+1} = \beta_p k_r^n \left(z_p^n - \psi^n\right) \qquad (4)$$

Where Q_p^{n+1} is the exchange flow at the current timestep between pipe and aquifer, β_p is the conductance, k_r^n is the relative conductivity (< 1.0 if the column is unsaturated), z_p^n, the head at the pipe, and ψ^n the head at the column node, the superscripts n indicating the value at the previous timestep. After the exchange flows are calculated, the pipe network model is run to calculate a new set of z_p values over the current timestep. The VSS then iterates for the heads in the aquifer at the current timestep including the source / sink term q in equation (1) above, which has been adapted to incorporate the flow between the aquifer and the conduits represented by the network model. An inplicit procedure is employed which incorporates the change in the exchange flows as a result of the change in the aquifer heads. This procedure should ensure the numerical stability of the linked scheme.

CONCLUSIONS

The development of a generic conceptual model of an abandoned coalfield has been undertaken in order to improve the predictions of surface water pollution from uncontrolled minewater discharges, and perform sensitivity analyses, by simulating alternative mine configurations and water level changes, where there is uncertainty in the mine plans about open connections. A physically based approach has been adopted, and an existing modelling system, SHETRAN, has been enhanced to simulate turbulent flow in conduits or pipes. The pipe network model has been coupled with the Variably Saturated Subsurface (VSS) component of SHETRAN, which can simulate three dimensional flow in variably saturated porous media. The hydrogeology of abandoned coalfields often includes a complex mixture of unsaturated (dewatered) workings, saturated aquifers and high conductivity regions, making VSS an ideal choice. Data requirements are heavy however, and it is proposed that for case studies with scarce or poor hydrogeological data, and for screening different dewatering scenarios and/or configurations of abandoned mines that the model is used in conjunction with:

- simple manual calculations
- application of a simple semi-distributed model such as GRAM (Groundwater Rebound in Abandoned Mineworkings, a code already developed at the University of Newcastle; Younger et. al., 1995)

The generic model has not yet been fully tested and validated on an actual data set from an abandoned coalfield. A simple system of two linked coal mines, the Ynysarwed - Blaenant system in South Wales has been chosen for this task, and validation will commence shortly.

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