Integrated hydraulic–hydrogeochemical assessment of flooded deep mine voids by test pumping at the Deerplay (Lancashire) and Frances (Fife) Collieries

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Abstract: To provide the basis for the design of two Coal Authority mine water management schemes, IMC Consulting Engineers (IMC) carried out step-drawdown pumping tests at the Deerplay (Lancashire) and Frances (Fife) abandoned collieries in the summer of 2000. Supplementary hydrochemical investigations were funded by NERC and undertaken by the University of Newcastle and Queen's University Belfast (QUB).

The results of the step-drawdown tests can only be interpreted by invoking a substantial component of turbulent flow in large open voids. Overall, the Deerplay system behaves in a manner analogous to natural aquifers, lending itself to modelling (using VSS-NET) to obtain effective hydraulic parameters that may be applicable in similar systems of flooded bord-and-pillar workings elsewhere.

The hydrochemical results for both sites showed some similarities, for example there was evidence of depth stratification of water quality in both cases, but also contrasts. For instance, although the total iron in the mine water pumped from the Deerplay Colliery rose gradually to a plateau at around 30 mg l^{-1}, the water remained net-alkaline throughout the test. By contrast, not only did the total iron in the Frances waters rise in abrupt steps to as much as 600 mg l^{-1}, but the water also switched from being net-alkaline at the beginning of the test to become strongly net-acidic by the end.

Mine abandonment often causes water pollution through the release of acidity and metals to receiving water courses. Pollutant loadings decline following the 'first flush' from the workings, although they can persist at ecologically damaging levels for many centuries (Younger 1997).

Frances Colliery (NT 309938) was abandoned in 1995, the closure of this colliery marked the end of dewatering in the East Fife Coalfield (see Fig. 1 for location map). Since 1995, groundwater has been recovering through a complex of multiple coal seams (Fig. 2b) formerly worked by Frances and adjoining collieries (Fig. 2a). Coal was exploited at Frances via older shallow bord-and-pillar workings and deeper more recent longwall workings. At Frances, test pumping took place from the mine shaft itself. The shaft is elliptical in section with a with a long-axis diameter of 6.86 m and a short-axis diameter of 3.05 m. The response to the test pumping was monitored by dataloggers placed in peripheral shafts and boreholes (Fig. 2a). The purpose of the test pumping by IMC Consulting Engineers (IMC) was to investigate how groundwater recovery could eventually be controlled by pumping and treating mine water in a designated site rather than letting the water recover naturally and treating mine water discharges as they emerge.

Coal mining in the North East Lancashire Coalfield was first recorded in the late thirteenth century. Nineteen seams within the Lower Carboniferous Coal Measures were exploited. The seams were thin, generally having a mined coal thickness of less than 1.5 m (Williamson 1999). Deerplay Colliery (SD 810267) (Fig. 1) was abandoned in the 1960s, since when a long-established polluting ferruginous discharge has impacted Black Clough and its receiving water course – the River Calder (Fig. 3a). The workings comprise a relatively simple system of bord-and-pillar workings in one major seam (the Lower Mountain Seam) (see Fig. 3a). Minor workings in other seams are largely above the water table. IMC drilled an abstraction borehole (Fig. 3b shows the log section of the Deerplay borehole) to intersect a roadway within the Deerplay workings. The location of the peripheral boreholes used to measure the response to the drawdown induced by test pumping is shown in Fig. 3a. The purpose of the subsequent test pumping was to abstract mine

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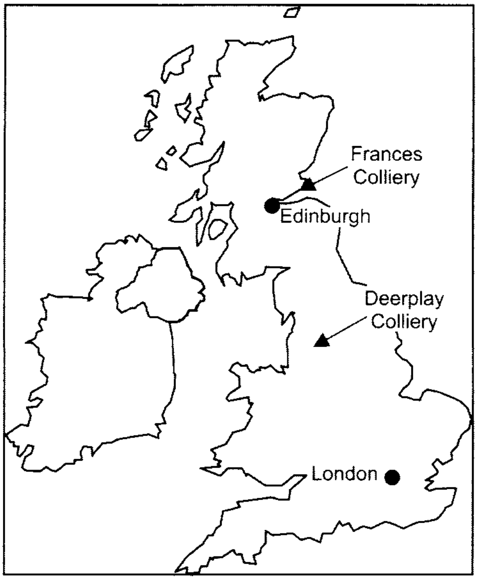


Fig. 1. Map showing the location of the Deerplay and Frances collieries.

water at a sufficient rate to intercept and, hence, stop the discharge entering the Black Clough.

Sampling and data collection

Automatic weather stations (AWS) were installed at both sites in order to record temperature, humidity, net solar radiation, rainfall, and wind speed and direction during the test period and the subsequent recovery phase. The weather data were then used for the hydrogeological modelling described later. When the test pumping began, samples were taken frequently over the first few days (i.e. every hour) but reduced after a few days to daily sampling for metals and weekly for a full analysis (i.e. metals and major cations and anions). Samples were also collected for isotope analysis by Queen's University Belfast (QUB). In the field, measurements of pH, reduction–oxidation poterhal (Eh), temperature and conductivity were taken using a Camlab Ultrameter, and alkalinity was measured using a Hach (HACH AL-DT) digital titrator with the range 0–4000 mg l^{-1} calcium carbonate.

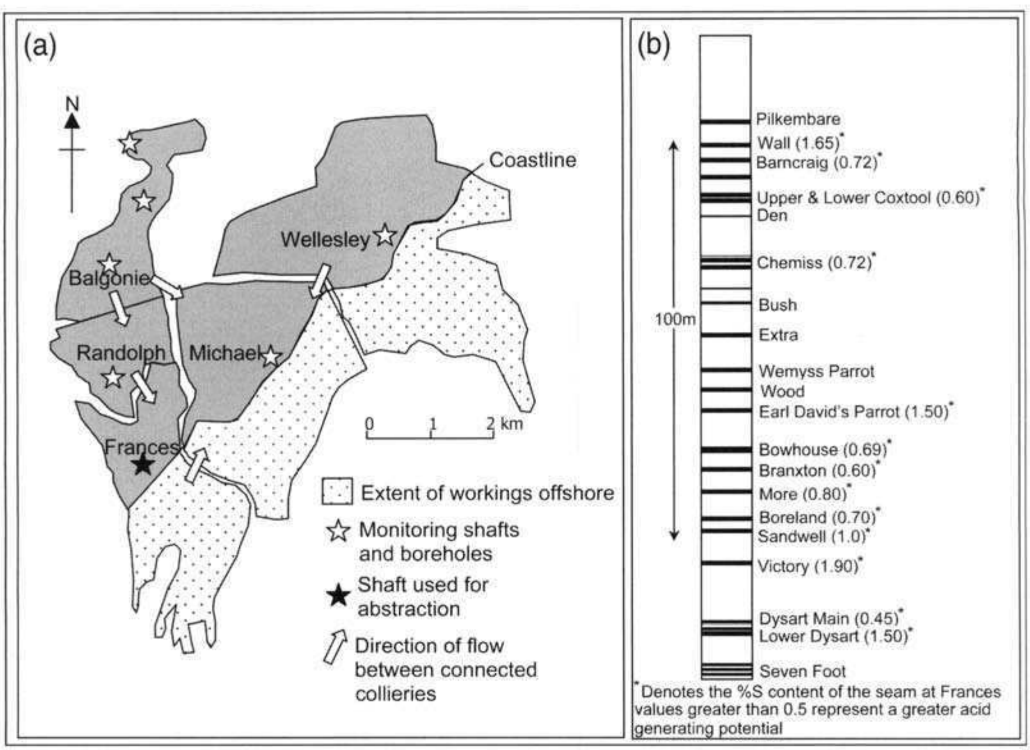


Fig. 2. (**a**) Schematic diagram showing how Frances Colliery is connected with adjacent collieries (after Sherwood 1997). (**b**) Generalized section showing the sequence of numerous coal seams throughout the East Fife Coalfield (after Knox 1954).

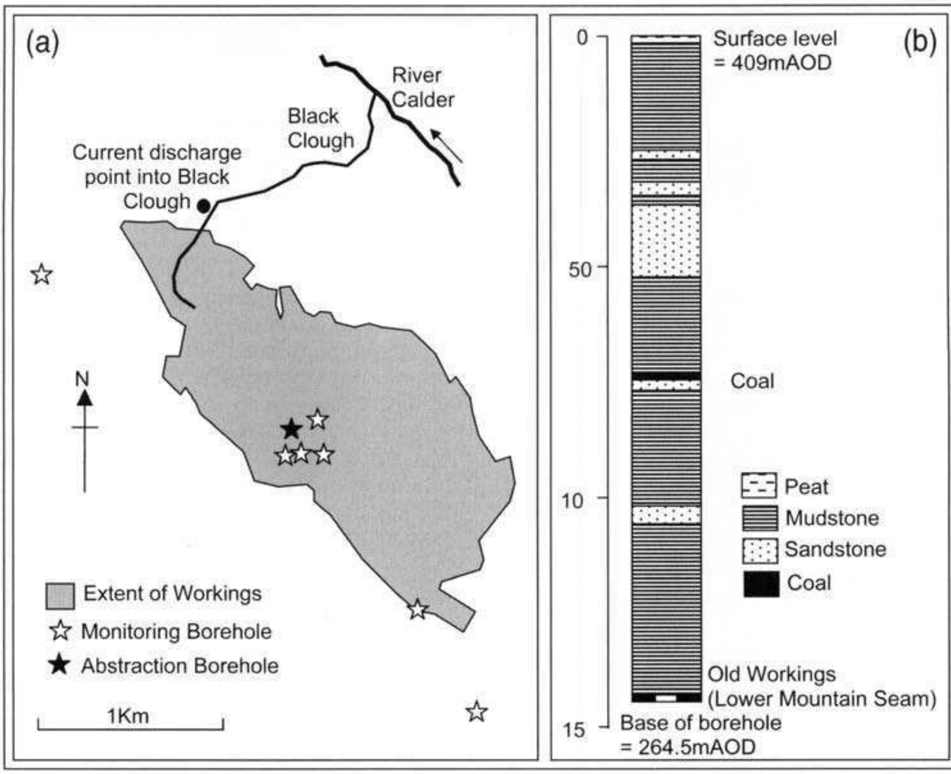


Fig. 3. (**a**) Schematic diagram showing the Deerplay Colliery workings and the site of the Black Clough discharge. (**b**) Log section of the abstraction borehole, which was driven to intercept a roadway within the Deerplay workings.

Dissolved oxygen was measured when a YSI 95 DO meter was available. In the laboratory, samples were analysed for major ions (calcium, sodium, magnesium and potassium) and major anions (sulphate and chloride) using a Dx-100 ion chromatograph. Dissolved silica was measured using a Hach colorimeter, and metals (iron, aluminium and manganese) were analysed by atomic absorption on a Unicam 929 AA spectrometer. Water level data were collected from peripheral boreholes and shafts by IMC Consulting Engineers, using a combination of manual dips and dataloggers.

Hydrogeological results

Stepped test pumping at Deerplay ran for 10 weeks, pumping at discharges rates (Q) of 7.25–30 l s^{-1} (see Table 1). The total drawdown (s in the following calculations) at Deerplay was around 20 m, and the gravity discharge was successfully intercepted and ceased flowing after one week of pumping. The stepped test at Frances took place over a six week period at rates of 38–76 l s^{-1} (see Table 2). During this time water levels were lowered by around 3 m. Figure 4a and b were achieved by plotting discharge (Q)

Table 1. *Summary of the test pumping data gained from Deerplay Colliery*

Step	Q (m^3 day^{-1})	Period	Water level (m aOD)	s/Q	% laminar flow
1	626.4	10/07 13.00–17/07 13.00	333.29–332.12	0.001485	53
2	1296	17/07 13.00–31/07 13.00	332.12–329.72	0.001937	35
3	1900.8	31/07 13.00–14/08 12.00	329.72–327.52	0.003346	27
4	2635.2	14/08 12.00–18/09 13.00	327.52–311.56	0.003639	21

Table 2. *Summary of the test pumping data gained from Frances Colliery*

Step	Q ($m^3 day^{-1}$)	Period	Water level (m aOD)	s/Q	% laminar flow
1	3283.2	07/08 11.00–04/09 16.30	−54.235 to −55.449	0.00037	18
2	5616	04/09 16.30–19/09 11.15	−56.449 to −55.377	0.000381	11
3	6566.4	19/09 11.15–24/09 14.00	−55.377 to −56.733	0.00038	10

against the specific capacity (s/Q), and can be used to estimate the predominant flow regime (i.e. laminar or turbulent) within both systems. Hydrological evidence suggests that when the large, open voids within flooded collieries are pumped, turbulent flow becomes the dominant flow regime at increasing discharge rates and the amount of laminar flow decreases. The evidence for the existence of turbulent flow when pumping water from areas containing mined voids was highlighted as follows. When the equation of the line from the graphs in Fig. 4a and b are known, it is possible to calculate a very rough approximation of the percentage of laminar flow (L_p) using the slope (C) and the y-intercept (B) in equation (1) (Driscoll 1987):

$$L_p = \frac{BQ}{BQ + CQ^2} \times 100. \qquad (1)$$

The rough percentage of laminar flow at Deerplay decreased from 50 to 20% over the course of the test (i.e. turbulent flow increased from 50 to 80% over the same period) (Table 1). A more accurate assessment of the amount of turbulent flow occurring at the end of the Deerplay test is provided in the modelling section. A rough calculation of the percentage of laminar flow present in the system at Frances indicates that there is a large component of turbulent flow. This increases as the mined voids are pumped at higher discharge rates until, at the end of the test, over 90% of the flow is estimated as being turbulent (Table 2).

The second piece of evidence for the presence of a turbulent flow regime comes from the calculation of Reynolds numbers (Re) (Driscoll 1987). For Frances, a detailed section of the shaft was available and it was possible to calculate Re for the four submerged roadways using equation (2):

$$Re = \frac{\rho d v}{\eta} \qquad (2)$$

where ρ is the fluid density, d is the pipe diameter (or roadway diameter in this case), v is the flow velocity (calculated from Q and the cross-sectional area of the roadway) and η is the viscosity (in this case the viscosity of water was used, $1.14 \times 10^{-5}\ m^2\ s^{-1}$).

In general, turbulent flow begins to occur at a Re value exceeding 10. Table 3 shows that the Reynolds numbers gained for the Frances Colliery roadways greatly exceeds the value of 10 and, therefore, turbulent flow must be significant within these roadways. The presence of a dominant turbulent flow regime may have

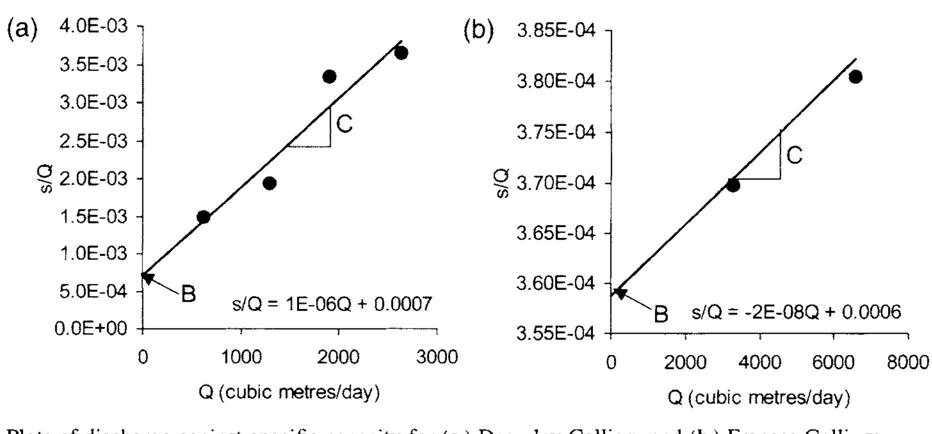


Fig. 4. Plots of discharge against specific capacity for (**a**) Deerplay Colliery and (**b**) Frances Colliery.

Table 3. *Calculation of Reynolds numbers (Re) for each of the submerged insets at Frances Colliery*

Inset name	Inset depth (m aOD)	*Re*
Lower Sandwell	66.96	350
Lower Dysart	140.11	190
Lethemwell	221.89	242
Pit Bottom	233.35	242

long-term implications for the efficiency with which the large open voids can be pumped.

Hydrogeological modelling

The complex hydrogeology of abandoned mines has been investigated under previous research that used physically based and lumped hydrological models to simulate groundwater flow in both the laminar and turbulent flow regimes (Younger & Adams 1999; Adams & Younger 2001). The VSS-NET model was developed as a new component of the physically based SHETRAN hydrological modelling system (Ewen *et al.* 2000), adding the capability of simulating turbulent subsurface flow in three dimensions (3D). This component links the VSS (*v*ariably *s*aturated *s*ubsurface) laminar flow component with the NET pipe network simulator. The mine workings are discretized as a system of conduits (representing the open roadways and shafts of abandoned mines) routed through heterogeneous, variably saturated porous media representing the surrounding rock (both intact rock and rock that has fractured in response to the mining below). The conduit network is shown in Fig. 5. The network was drawn using the US EPA's EPANET™ software. Deerplay Mine was deemed a suitable mine for a further application of VSS-NET because of the areal extent of the underground mine workings, the availability of detailed 1:2500 mine plans and the relative simplicity of the layout underground of the (mostly single seam) workings. The Frances system was deemed too complex for this type of modelling.

The principal aims of the hydrological simulations of flow in the Deerplay workings during the case study were:

- to assess the importance of turbulent flow in the hydrogeological response of the mine before, during and after test pumping;
- to reproduce by simulation the observed drawdown at the three deep boreholes into the Lower Mountain Mine (LMM) Seam

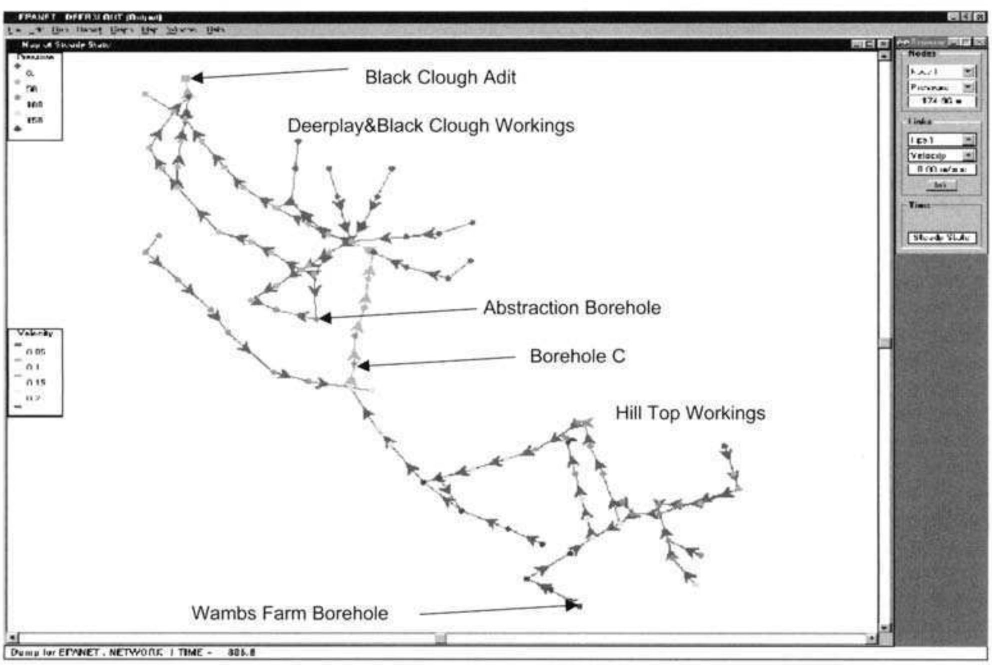
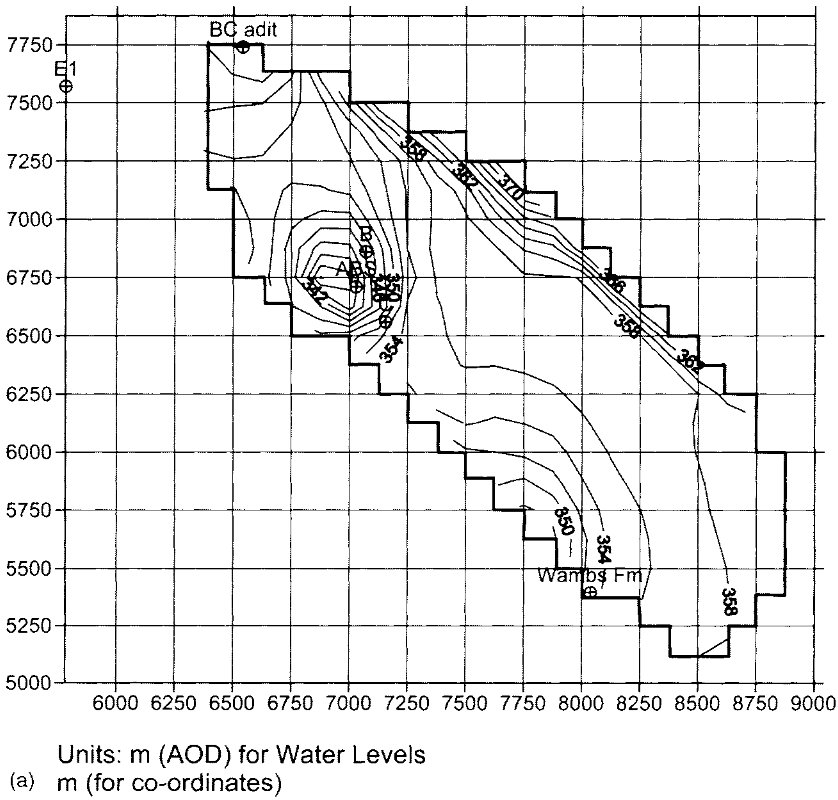


Fig. 5. Schematic diagram showing the conduit network for Deerplay Colliery.

(Wambs Farm, Abstraction and C) in the model (these boreholes are indicated in Fig. 5);

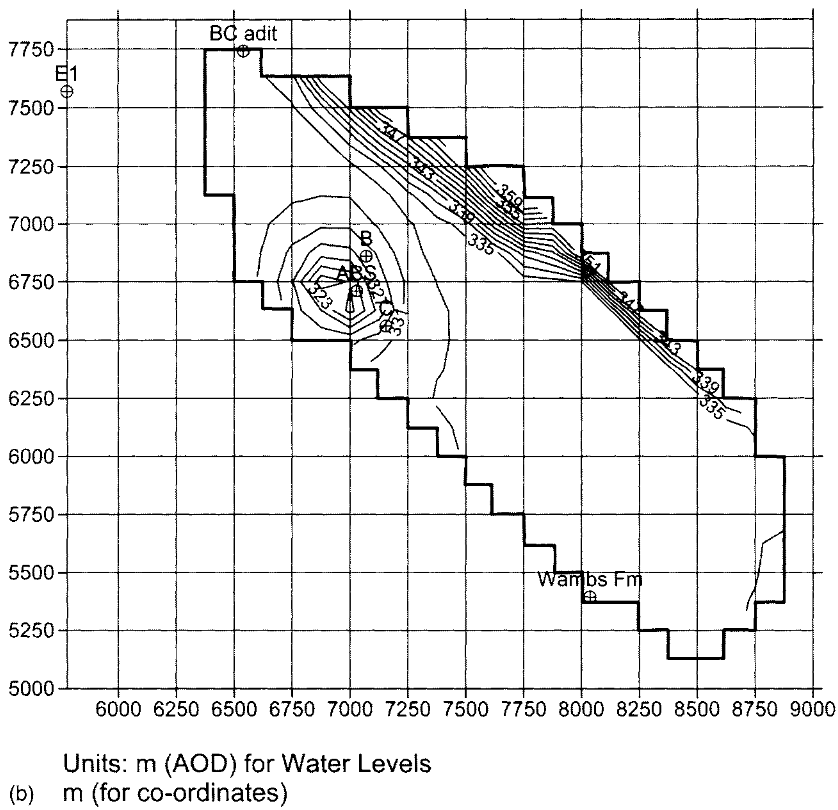
- to reproduce by simulation a discharge from the Black Clough adit of the correct order of magnitude. The model was also expected to concur with the field observations that pumping from Deerplay Abstraction borehole caused the discharge to cease flowing;
- to allow the relative contributions of turbulent and laminar to the pumped mine water to be quantified (for comparison with the analysis in the previous section).

The Deerplay hydrological simulations were run after a SHETRAN conceptual model was set up. The model domain comprised 202 125 × 125 m finite-difference elements, derived from the national grid (see Fig. 6 for illustration). The boundary of the model domain was determined from the 1:2500 mine plans of Deerplay and Hill Top collieries. The model domain was extended on the northern and northeastern side of the mines to the seam outcrop. Abandoned collieries to the west and south were considered to be unconnected to the modelled workings (IMC Consultant Engineers 2000). The base of the LMM Seam was considered to be the base of groundwater circulation, i.e. the impermeable lower boundary. The elevation of the LMM Seam was obtained from the mine plans. The strata between the LMM Seam and the ground surface was divided into two layers, a high-conductivity layer representing goaf and an upper layer extending to the ground surface representing the fractured, mixed Coal Measures strata above the goaf. The thickness of the goaf layer was estimated to be 4 times the LMM Seam thickness (1.2 m on average) (Younger & Adams 1999). Where the LMM Seam was not mined, the lower layer (effectively the unmined coal) was assigned a low hydraulic conductivity. The Upper Mountain Mine (UMM) Seam was also worked



(a)

Fig. 6. (**a**) Contour plot of modelled groundwater levels without conduits. (**b**) Contour plot of modelled groundwater levels with conduits.



(b)

Fig. 6. (*continued*).

separately from the Black Clough adit, and a layer representing the goaf was included wherever workings were indicated on the mine plans. High-conductivity values were also assigned to grid squares where the mine plans indicated that either or both seams had been opencasted (surface mined). In the southern and eastern Deerplay workings the UMM and LMM seams combine to form the Union Seam, here the workings become single seam.

Initial conditions were obtained by running the model with steady-state recharge until groundwater levels were constant. The steady-state recharge value was calculated from an estimated average discharge from Black Clough adit of $16.5\,\mathrm{l\,s^{-1}}$ (based on the field measurements of discharge made before test pumping). Meteorological data collected by the weather stations installed on site were used to calculate recharge into the mine using equation (3), which accounted for both rapid infiltration through the opencasted LMM and UMM Seam outcrops and slower, delayed infiltration through the strata overlying the seams:

$$R = f_1 A_{SO} P_{ND} + f_2 A_{SM} (P_{NM}/D_i) \qquad (3)$$

where R is the daily recharge into the model (mm), f_1 is a constant representing the percentage of the daily net rainfall, P_{ND}, infiltrating into the mine through the seam outcrop due to opencast mining (1.0), A_{SO} is the Area of the LMM and UMM Seam outcrop in the model ($0.266\,\mathrm{km^2}$), f_2 is a constant representing the percentage of the monthly net rainfall, P_{NM}, infiltrating into the workings (the remainder is assumed to either recharge the drift aquifer or form surface runoff) (0.2), A_{SM} is the Area of the mine workings ($2.5\,\mathrm{km^2}$) and D_i is the number of days in month i.

Pumping fluxes were abstracted from the model using a well element located at the grid element corresponding to the abstraction borehole. Daily rainfall totals and pumping rates are shown in Fig. 7. The total area of the model domain was equal to $A_{SO} + A_{SM}$ + unworked areas, and was, in fact, $3.156\,\mathrm{km^2}$.

The daily and monthly net rainfall values were calculated from the daily time series of rainfall from the automatic weather station (AWS) and

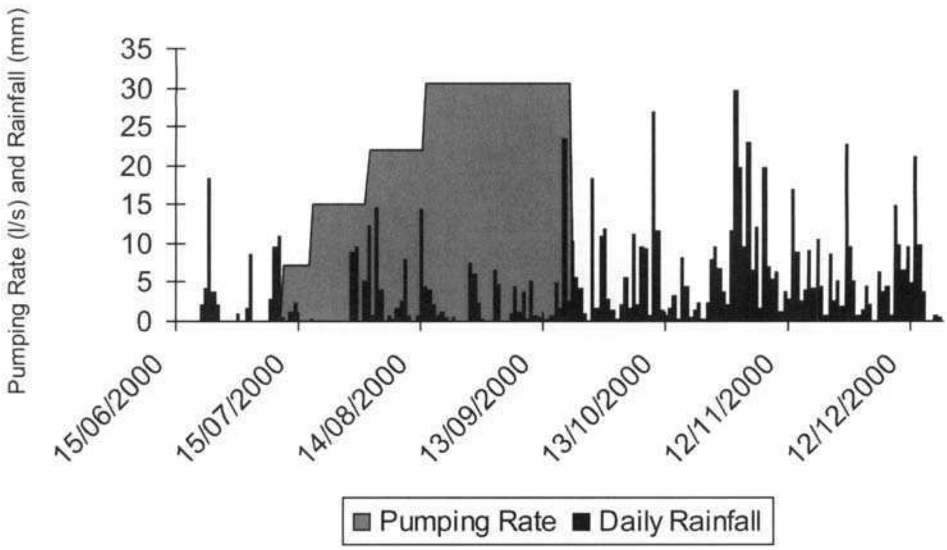


Fig. 7. Graph showing the pumping rate and daily rainfall.

monthly average potential evapotranspiration values were obtained from a national UK Meteorological Office database of potential evaporation supplied on a 40 km^2 grid (MORECS) (Thompson *et al.* 1981). The annual value for the grid square in the locality of the mines averaged over the period 1961–1990 was 558 mm year^{-1}. The AWS recorded daily rainfall for the period 15 June 2000–19 December 2000, which was also the SHETRAN simulation period. A time step of 4 h was used in the simulations, which proved to be stable. Minimal calibration was required in order to achieve the results described below.

Simulations were run using SHETRAN with and without the conduit network to determine the importance of turbulent flow during the test period. The conduit network simulated turbulent flow in the major roadways and the adits of the Deerplay and Hill Top workings (Fig. 5). The simulation without conduits only modelled laminar flow in the LMM Seam and the fractured strata above. This simulation failed to reproduce the observed drawdown at all three boreholes, and the spring representing the discharge did not dry up during pumping. Figure 6a shows a contour plot of water levels predicted by this simulation at the time of maximum drawdown in September 2000. It is clear that the cone of depression around the pumping borehole (A) does not extend to the workings draining towards the Black Clough (abbreviated to BC in Fig. 6) adit or Wambs Farm borehole (a small discharge was predicted to flow throughout the test at both locations). The predicted water levels during the pumping test were much higher than the observed water levels (for example, 354 m above ordnance datum (m aOD) at Wambs Farm compared to the observed water level of 328 m aOD on 18 September 2000).

The simulation with a conduit network reproduced the observed drawdown at the abstraction borehole within 1 m of the maximum value during the test (Fig. 8). The timing of the maximum drawdown was reproduced exactly. The observed drawdown at Borehole C was underpredicted by less than 3 m; but the model did not reproduce the observed drawdown at Wambs Farm (Fig. 8). Figure 6b shows a contour plot of water levels with the conduit network included. The groundwater flow direction was predicted to be towards the abstraction borehole (ABS). Furthermore, the absence of contours for a large region of the model area shows that the hydraulic gradient across the workings is very low due to the inclusion of the pipes. The steeper hydraulic gradient towards the NNE edge of the model is due to recharge flowing through the seam outcrop into the workings.

The simulation with a conduit network predicted that the discharge ceased flowing after around 54 days of simulation (7 August) and recommenced flowing after 96 days of simulation (approximately 16 h after pumping ceased). This matches the observed behaviour of the adit quite closely, although the modelled discharge recommences slightly early. The maximum discharge from the adit was predicted to be around 50 l s^{-1} after recovery in December 2000.

Analysis of the origin of the groundwater flow to the model element containing the abstraction

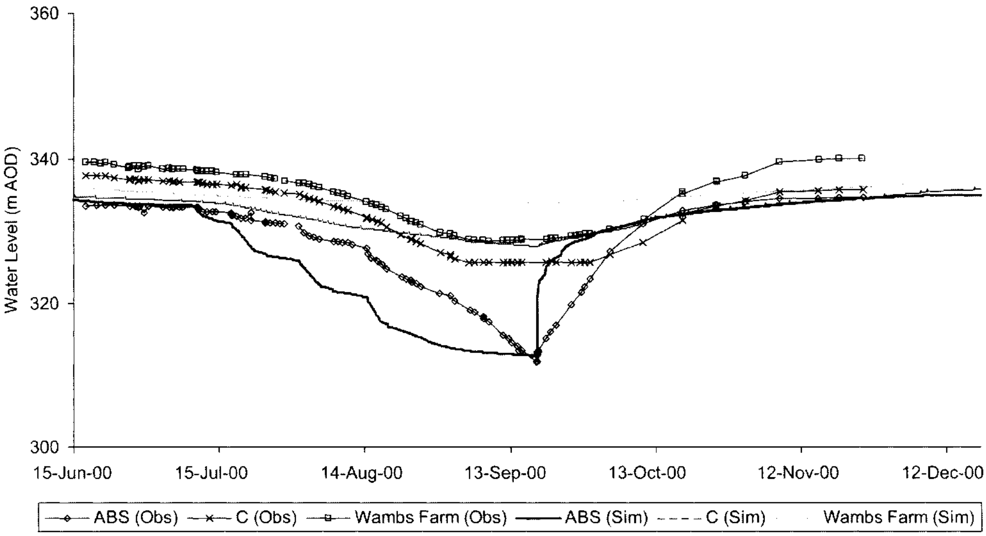


Fig. 8. Graph showing observed and modelled groundwater levels during the drawdown and recovery phase at Deerplay Colliery.

well (during pumping at the maximum rate in September) indicated that turbulent flow from the conduit network accounted for 17 l s^{-1} (56%) of the total flow.

Hydrogeochemistry

The Deerplay pumped mine waters remained net-alkaline (i.e. their alkalinity exceeded their acidity, as described by Younger 1995) throughout the course of the test, pH remained around 7 and alkalinity around 300 mg l^{-1}. The iron concentrations rose from 10 mg l^{-1} and levelled at 30 mg l^{-1} (Table 4).

The chemistry of the Frances pumped mine waters changed during the test (see Table 5). Initially, the waters were net-alkaline with an iron concentration of 6 mg l^{-1} and an alkalinity of around 400 mg l^{-1}, but after 24 h of pumping the

Table 4. *Summary of the pumped mine water quality at Deerplay Colliery (compared to the Black Clough discharge)*

Determinand	Initial	End	Black Clough
pH	6.96	7.0	6.9
Alkalinity (mg l^{-1} $CaCO_3$)	302	326	260
Conductivity (μS cm^{-1})	1189	1225	1200
Fe (mg l^{-1})	17	27	40
SO_4 (mg l^{-1})	213	355	370

Table 5. *Summary of the pumped mine water quality during the test pumping at Frances Colliery*

Determinand	Initial	1 day	End of test
pH	6.34	5.22	4.8
Alkalinity ($CaCO_3$)	437	75	0
Conductivity (μS cm^{-1})	5557	25 550	26 500
Fe (mg l^{-1})	6.5	406.7	596.6
Al (mg l^{-1})	B.D.	14.65	51.6
SO_4 (mg l^{-1})	4975	4223	6254

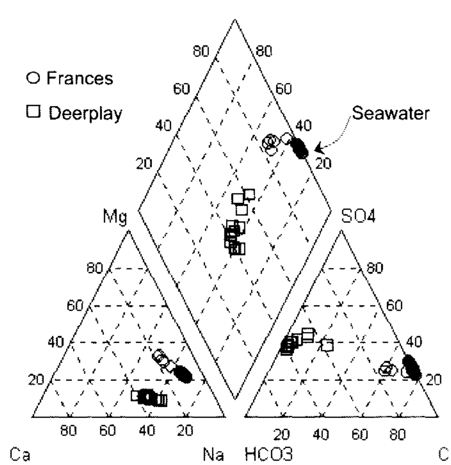


Fig. 9. Piper diagram plotting the pumped mine water chemistry at Frances and Deerplay Collieries.

quality deteriorated to 100 mg l^{-1} of iron and an alkalinity of around 40 mg l^{-1}. After a week of pumping, iron concentrations had risen to between 500 and 600 mg l^{-1}, and there was no alkalinity. There were also appreciable concentrations of aluminium (up to 50 mg l^{-1}) and manganese (up to 25 mg l^{-1}).

The chemistry of pumped mine waters from Frances and Deerplay Collieries are plotted on Piper diagrams (Fig. 9). The waters from Frances plotted in the sodium chloride field (Fig. 9) suggesting that there is a sea-water component (rather than a connate brine source) to the mine water (Younger *et al.* 1995; Younger 2001). The Deerplay pumped water plotted in the calcium bicarbonate field reflecting the carboniferous host geology (Fig. 9). The Black Clough discharge plotted nearer the calcium sulphate field, the sulphate probably sourced from pyrite decomposition.

Stratification within mine workings

The increase in iron concentrations over the duration of both tests can be attributed to stratification within the workings. Recovered (Deerplay) or slowly recovering (Frances) systems tend to stratify with better quality (mainly recharge) water remaining at the top of the system with poorer quality water beneath. As soon as these systems are disturbed by pumping (or by gravity discharge on completion of rebound) the turbu-

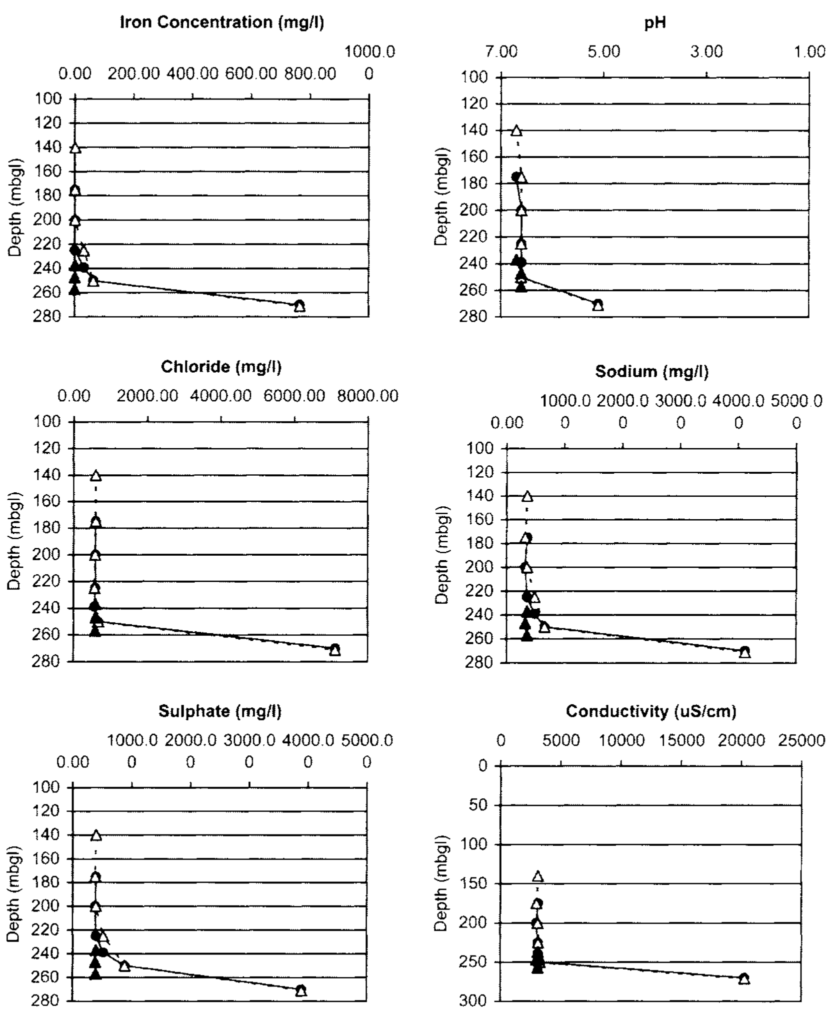


Fig. 10. Graphs showing stratification of various determinands in the Frances Shaft shortly after cessation of pumping (▲ = 12/12/95) and twice during the period of mine water recovery (● = 02/07/97; △ = 25/08/98).

lence induced causes mixing of the stratified water (Younger & La Pierre 2000).

Depth sampling carried out by IMC prior to the test pumping at the Frances Colliery showed that stratification was in existence in the shaft (Fig. 10). At Frances the top 200 m of the water column was of better quality (i.e. iron concentrations of less than 10 mg l^{-1}, pH of 7 and a conductivity of 3000 $\mu S\,cm^{-1}$). The deepest 70 m of the water column sampled contained the poorest quality water (i.e. iron concentrations greater than 500 mg l^{-1}, pH of around 5 and conductivity of 20 300 $\mu S\,cm^{-1}$). Often the position down a stratified shaft where water quality may change is marked by an inflow from a previously worked roadway or tunnel, and the change in quality at Frances represented a connection with the adjacent Randolph workings (via a high-sulphur seam mentioned below). An appreciation of stratification is important because whole treatment systems have often been designed following analysis of the better quality water, which are unable to cope with the poorer quality water that follows.

The following theory explains how stratification may build up within a system and how it may subsequently be lost (refer also to Fig. 11):

- The shaft fills up to the point just below an intersecting roadway. Stratification of the water column takes place. Poorer quality water is found at the bottom of the shaft and better quality water remains above.
- The water level rises steadily and the water reaches a connection. As the water flows along this route and fills the adjacent workings stratification is lost due to turbulent flow along the roadway causing mixing within the main water column
- As the water fills the adjacent workings, via the connection, a more stable rise in water level continues. Stratification may then redevelop.
- A pump is installed within the shaft, when pumping begins the initial water quality reflects that found at the top of the shaft and this quality remains until approximately one shaft volume has been cleared. By this time the turbulence induced by the act of pumping has caused mixing of all the water in the shaft and poor quality water is accessed, as at Frances Colliery.

The source of the poor quality water at Frances

Frances Colliery is directly connected with the adjacent Randolph and Michael collieries. Water transfer between the collieries (Fig. 2a) is known from datalogger information from surrounding shafts and boreholes. The poor quality water at Frances is due to the presence of high-sulphur coals associated with marine bands. The Dysart Main Seam provides the connection between Frances and the adjacent Randolph pit. Mining records show that Randolph discharged very low pH, iron-rich water whilst it was operational and it would seem very likely that this colliery provides the source of the poor quality water.

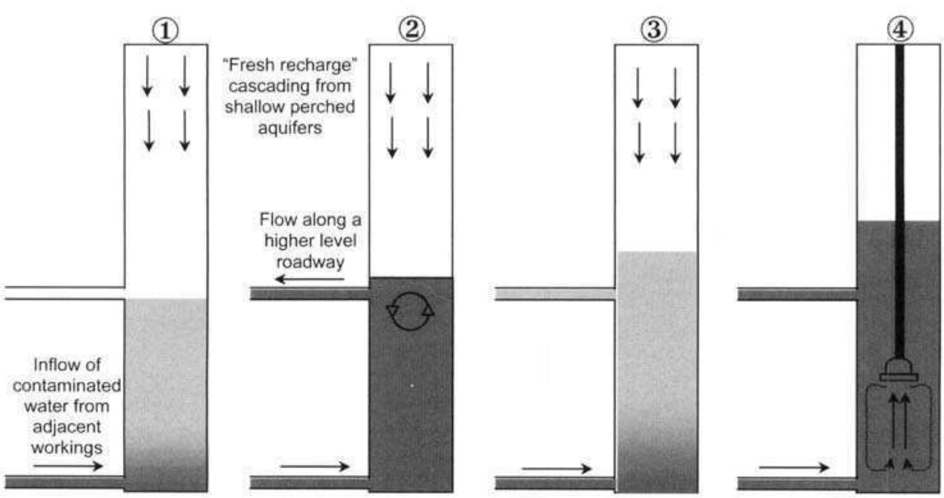


Fig. 11. Schematic diagram showing how stratification can build up within a system.

Conclusions

The behaviour of the Deerplay system was been successfully modelled with VSS-NET using a conduit-based model (which invokes a turbulent flow component). The model sucessfully reproduced the drawdown observed during the test and also managed to simulate the behaviour of the Black Clough discharge. These findings are supported by the data from the Frances and Deerplay step-drawdown test pumping, which was analysed by roughly calculating the percentage of laminar flow and also by calculating the Reynolds numbers as an indicator of the predominance of turbulent flow. These calculations show that there was a large component of turbulent flow occurring whilst both systems were pumped, due to the presence of large open voids within the workings.

Stratification is responsible for the changes in chemistry that occurred when both of these systems were pumped. Pumping a stratified system causes mixing of better and poorer quality water from the top and bottom of the shaft, respectively. The changes in chemistry that occurred at the Frances Colliery were rapid and unexpected, although previous depth sampling had shown the presence of contaminated water at depth. This exercise has outlined the importance of determining the extent of stratification within a system before designing any long-term treatment scheme.

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