PREDICTING GROUNDWATER RECOVERY AFTER MINE CLOSURE

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ABSTRACT

Contamination by discharges from flooded mine workings and contaminated pit lakes is often amongst the main environmental concerns on mine closure which should be addressed in the mine closure plan. In addition to water quality issues, the rate of recovery, equilibrium water levels, discharge locations and discharge rates are key issues in planning the response. This paper focuses on these quantitative hydrological issues.

The rate of recovery is a key issue in mine closure planning, because if recovery is rapid, little time is available for preparation of mitigation schemes, such as mine water treatment, once the mine is closed. In such cases mine closure planning and implementation must rely on predictions of final discharge quality and rates, based on operational information. However in many cases mine water recovery is a slow process and in such cases designs can be based on actual measurements of the water quality and inflow rates during the recovery period. This enables more accurate prediction at a lower cost.

Mine inflows come from various sources which show different behaviour seasonally, in response to rainfall and through the minewater recovery period. Identification of these sources and the relative proportions of each contributing to mine inflows, dictates the methodologies used for prediction as well as the ability to extrapolate mine pumping and recovery data.

Prediction of recovery rate and related hydrologic issues is based on a conceptual model of the system geometry and hydraulics, which includes quantity and variability of flows from different sources, volume of mined void, regional hydrogeology and connection between workings and the surface. The model is required whether the prediction is based on simple water balance calculations or more sophisticated numerical modelling techniques. These considerations also apply to the assessment of equilibrium water level and final discharge rate. Various examples ranging from the Las Cruces copper project in Spain to closed collieries in Scotland are presented to illustrate the different types of system.

INTRODUCTION

Contamination of surface waters and groundwaters by discharges from flooded mine workings and contaminated pit lakes is often amongst the main environmental concerns on mine closure. This issue should be addressed in the mine closure plan and for new mining projects is generally considered at the feasibility study stage. In addition to water quality issues, the rate of recovery, equilibrium water levels, discharge locations and discharge rates are key issues in planning the response. This paper focuses on these quantitative hydrological issues.

For a modern mine, closure planning will typically involve the following stages:

- initial closure plan at feasibility study stage;
- interim up-dates during mine operation;
- final closure plan prior to ultimate closure;

- closure implementation at final closure;
- monitoring, passive care and close-out (SRK, 1999).

At each stage predictions of minewater recovery and its affects should be based on a sound conceptual model of the system geometry and hydraulics, encompassing quantity and variability of flows from different sources, volume of mined void, regional hydrogeology and connection between workings and the surface.

In terms of minewater recovery, the initial closure plan usually focuses on water quality, where the water will go after closure and the quantity of water which will either discharge or migrate into the groundwater system after flooding. The rate of recovery is often a secondary issue at this stage. Predictions are based on field geological and hydrogeological data and the mine plan. Predictions tend order of magnitude estimates, so that worst case closure costs can be assessed. However where post closure flooding is a major issue in the feasibility study, detailed groundwater flow modelling will form the basis of the predictions, which are intended to provide more reliable results.

Interim closure planning will usually only address flooding issues if operational data or findings suggest the situation is different from that predicted at feasibility stage. For example flows may be greater or water quality may be worse than predicted.

Whether or not interim closure planning has been undertaken, the final closure plan should be based on operational data through the life of the mine. Operational pumping data in particular will provide a full scale field model of the dewatering, on which to recalibrate models and update predictions. At closure it should also be possible to obtain a good indication of the volume of the mined void. This data will allow revision of predictions, and if necessary revision of the closure plan.

If minewater recovery is expected to be rapid, for example if equilibrium is reached within two years, and significant water quality impacts are anticipated, it is likely that closure implementation will involve implementation of a mitigation scheme, usually some form of water treatment. The designs will be based on predictions of discharge flow rate, location and quality from the final closure plan. Poor conceptualisation of the hydrogeology could lead to inappropriate design. Over-design will have cost implications, but these may be small compared to construction of plant at the wrong site or having to completely rebuild an under-designed scheme.

If minewater recovery is expected to be slow, closure implementation will involve making safe of mine openings and setting up of monitoring schemes. Final designs will be based on the monitoring data obtained during recovery.

In the case of rapid recovery where mitigation is constructed as part of the closure implementation, post closure monitoring tends to involve monitoring quantity and quality of discharges from the mine and/or treatment plant and groundwater quality and level monitoring to ensure the scheme is compliant. It may be necessary to continue this well after other closure issues are finalised and closed out.

Post closure monitoring may have to be continued for long periods of time to ensure that water quality has stabilised at acceptable levels or that a walk-away passive solution has been achieved. In many cases water quality is an ongoing problem which may require treatment for the foreseeable future.

SOURCES OF WATER TO MINES

Identifying and understanding sources of water to mineworkings is the key hydrogeological issue in predicting the recovery response and in selecting the prediction methodology. Sources of water include:

- lateral groundwater inflow;
- vertical groundwater inflow from overlying perched aquifers;
- direct rainfall (open pits only);
- surface water inflow;
- direct infiltration;
- inflow from adjacent workings.

These different sources of water to mineworkings are illustrated in Figure 1.

Lateral groundwater inflow

This occurs in all cases where mining occurs below the natural groundwater level, and therefore in most mining situations and refers to groundwater flow in the saturated zone towards the mined void and sumps. The flow may be radial such as to a well or linear as to a trench, depending on the relative geometries of the mine and aquifer system.

Groundwater inflow is dependent on head gradient and therefore changes as the mine floods. Seasonal variations can also be expected, but since the mine is likely to be deep compared to the range of seasonal groundwater level variation, the seasonal changes are generally negligible until the late stages of recovery. With flooding the hydraulic gradient towards the mine reduces and inflows decrease until equilibrium is reached. Equilibrium occurs when the minewater level reaches the lowest mine opening or the natural (pre-mining) groundwater level – whichever is lowest.

The discharge rate in systems dominated by lateral groundwater inflow is usually significantly less than the operational pumping rate, since the drawdown of the natural water table is much reduced at equilibrium compared to the operational condition.

Vertical groundwater inflow

This refers to inflow from aquifers above the mineworkings. The flow rate is proportional to the head in the aquifer and is not affected by the water level in the underlying mineworkings Therefore as recovery occurs vertical groundwater inflow will remain approximately constant, with variations related to seasonal changes in groundwater regime.

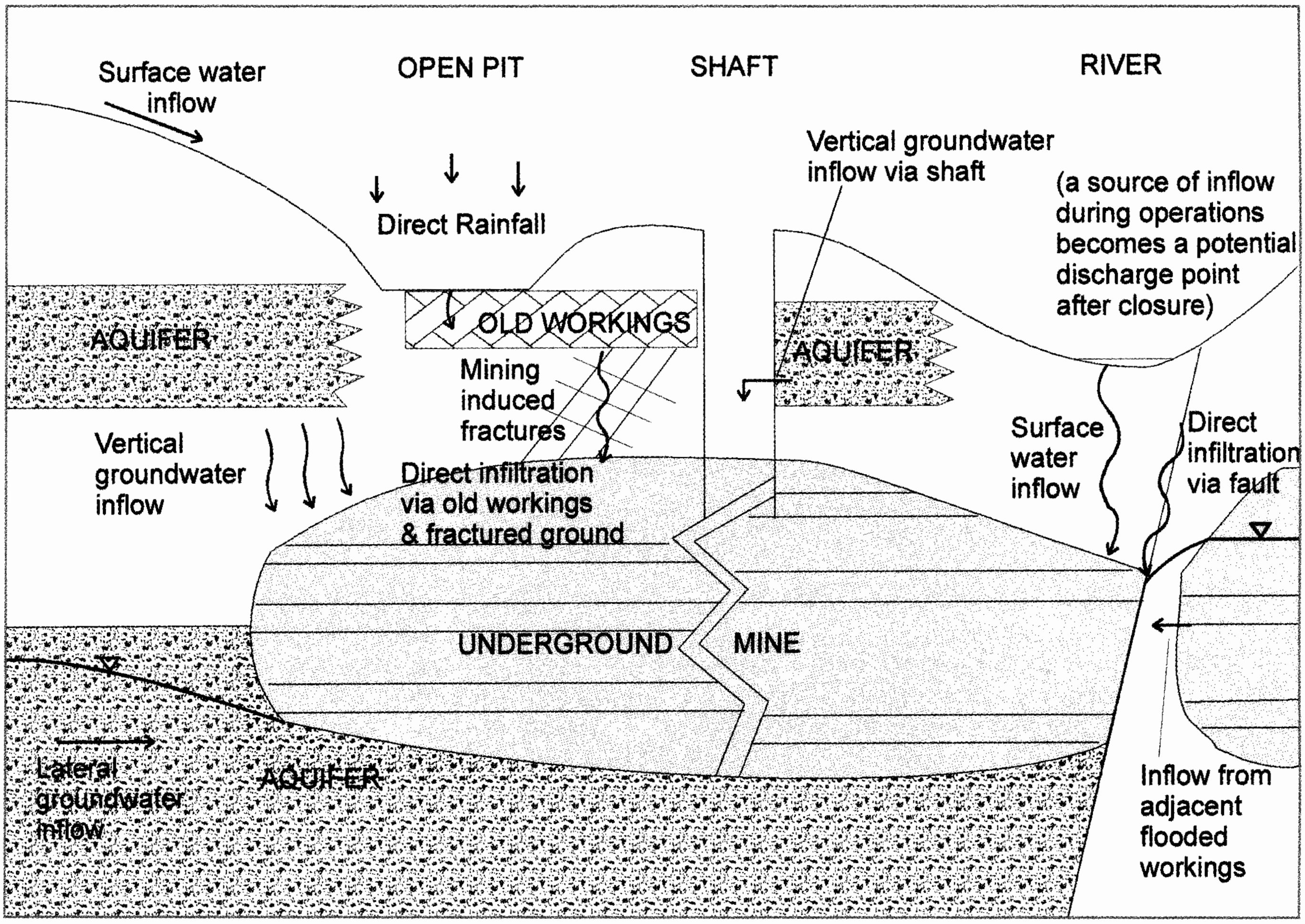

Figure 1. Schematic illustration of sources of minewater.

The minewater level may rise above the base of the overlying aquifer during recovery at which stage the inflow will behave as lateral groundwater inflow.

Direct rainfall

This is only a significant source in open pits subject to intense rainfall. The quantity is dependent on the area of the pit and the long term effective rainfall rate. Since rainfall rarely exceeds a few metres per year in any location, this is not usually a significant source of water during recovery.

Surface water inflow

Surface water inflow to open pits is usually minimised by construction of drainage channels on the pit perimeter, but in many cases the pit will have a catchment beyond the pit outline, either because drainage works are inadequate or because terrain makes capture of surface run-off unavoidable. For underground mines surface water entry can occur where stream channels are undermined and mining induced fractures provide conduits for leakage to the mine.

In each case the amount of inflow is dependent on the stage in the stream and is likely to vary in response to rainfall and seasonal factors, or be approximately constant. Surface water inflow will not usually be affected by changes in water level in the early stages of recovery, but later on the site of stream water loss may be subject to minewater discharge in the stream bed. This is dependent on the local topography and geometrical relations between sources of water and mineworkings.

Direct infiltration

This refers to water which infiltrates the ground and arrives directly in mineworkings without flowing as groundwater in the saturated zone. This differs from groundwater inflow in that it is not head dependent and tends to vary quite rapidly in response to rainfall. In deep mineworkings or where direct infiltration flows through workings for long distances before arriving in the mine sump or the flooded workings, the response to rainfall may be dampened and appear more like a groundwater response.

Mean annual inflows to workings tend to remain approximately constant throughout the recovery and where direct infiltration is the dominant water source discharges can be similar in magnitude to operational pumping rates.

Inflow from adjacent workings

This can include water derived from all the sources described above and can therefore produce different types of response through recovery. Typically connected workings will be either unsaturated and above the flooding workings, eg open pits or older shallow workings above deep underground workings; or flooded, but partially hydraulically isolated from the flooded workings. If they are adjacent to the mine and hydraulically connected, they can be considered the same mine.

Drainage through open pits and old workings at higher levels will show similar behaviour to direct infiltration, unless the higher workings are connected to perched aquifers, in which case there will also be an element of vertical groundwater flow.

Flow through adjacent flooded workings will be similar to vertical or lateral groundwater inflow depending on the relative elevations of the flow path and minewater level.

CONCEPTUAL MODEL DEVELOPMENT

In all cases predictions of minewater recovery should be based on sound conceptualisation of the hydrogeological system.

The first stage is to develop a geometrical model of the system, integrating geology, mine geometry and surface topography. Super-imposed on this will be the hydrogeological model which will identify the main aquifers or most likely water bearing zones, aquitards and barriers to groundwater flow, zones of natural groundwater recharge and discharge and model boundaries. It is also important to consider the potential effects of mining on the hydrogeological system, which are dependent on the engineering properties of the rock and the mining method.

Where no mining has occurred e.g. feasibility studies, quantitative hydrogeological information will be based on field testing programmes and water level monitoring in piezometers. Operational inflows to the mine are then calculated using analytical or numerical groundwater flow modelling. Groundwater flow modelling usually focuses on saturated groundwater flow, therefore the effects of different sources of water on inflow and recovery will often only be crudely estimated on the basis of the conceptual model.

For the final closure plan operational data and observations will be used to greatly enhance the conceptual model. These include:

- pumping data;
- response to rainfall and seasonal changes in inflow;
- changes in inflow through mine development;
- geological effects on inflow including lithological and structural controls;
- relationship between inflows and surface conditions, such as thickness of overburden and surface water courses;
- mined tonnages and volume of backfill.

In particular, these observations will enable the effects of inflows from different sources to be characterised and proportions of water from the various sources to be estimated. On the basis of this data it will be possible to estimate how minewater inflow will vary through recovery.

Where there is also the opportunity to monitor early recovery, the recovery curve generated (water level versus time) will provide further information on sources of water, volume of void effects and overall recovery rate, resulting in increased confidence in the conceptual model.

Test pumping during recovery may be used to establish the inflow rate at a particular elevation and also enables representative mixed minewater samples to be taken for chemical analysis and water quality determination. Such tests will greatly increase confidence in estimates of final discharge rates.

CASE STUDIES

The following case studies range from feasibility studies based on modelling prior to mine development to predictions made during the late stages of recovery through extrapolation. Four underground collieries and four metal mines are discussed. Predicted and observed water level recovery curves are shown in Figure 2.

Polkemmet colliery, Scotland, minewater recovery prediction

The Polkemmet colliery finally closed in December 1986 after partial flooding in 1984. The mine was the last in an interconnected system of mines to close. After closure, the workings began to flood and late in 1995 when the water level was measured in the Polkemmet shaft it had risen to within about 20 m of the lowest surface elevation in the mined area. SRK was appointed to predict the timing, location, quantity and quality of the anticipated minewater discharge.

The study included compilation of mine plans from the former inter-connected collieries and collation of information on geology, pumping and water levels into a simple conceptual model. The data led to the conclusion that the main source of water to the workings was recharge in the area where the mined seams outcrop ie direct infiltration, and that the Carboniferous Passage Group strata within which the seams occurred was not sufficiently permeable to affect recovery significantly by lateral groundwater flow.

The recovery was predicted on the basis of a number of simple assumptions:

- the initial rate of recovery measured in November 1995 – January 1996 was representative of winter inflow rates at the current volume of void;
- the summer inflow rate would be one third the winter rate due to reduced effective rainfall;
- the volume of void ratio would remain approximately constant at all elevations (since most of the seams were worked from the deep Polkemmet workings to the outcrop).

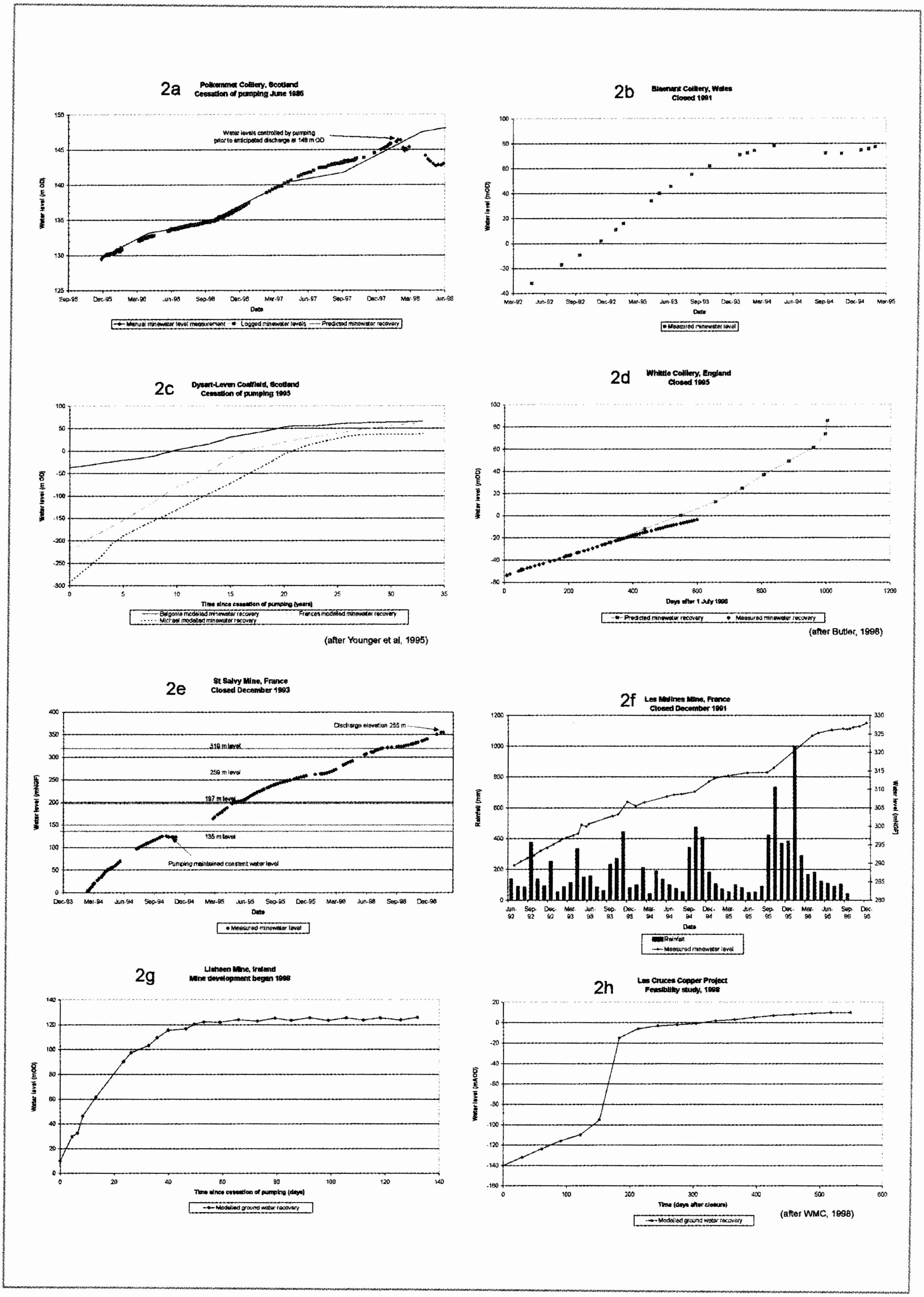

Figure 2. Minewater recovery case studies.

The predictions were intended to give an indication of the approximate timing of the discharge for planning purposes. In fact the prediction turned out to be more accurate than required. The actual and predicted recovery rates are plotted against time in Figure 2a. The recovery plot exhibits typical characteristics of a system dominated by direct infiltration, namely seasonal variation, but no overall change in recovery rate as minewater levels rise. The figure shows the very close correlation between predicted and actual rate of recovery. The prediction was accurate to within a few weeks over a period of over two years. The minewater was controlled through an emergency pump and treat scheme implemented in January – February 1998.

Blaenant colliery, Wales, minewater recovery monitoring

Blaenant colliery closed in 1993. The mine worked a single seam, the No.2 Rhondda in the Upper Coal Measures, but was connected to the Cefn Coed colliery which worked a number of seams in the Middle and Lower Coal Measures. The No. 2 Rhondda is overlain by a thick sandstone aquifer which yielded significant flows during mining. The Middle and Lower Coal Measures strata, by contrast are hosted by mudstones and siltstones of low permeability.

In 1994 SRK undertook a feasibility study into treatment the highly ferruginous and acidic discharge which had occurred via the adjacent Ynysarwed colliery following the closure of Blaenant. Groundwater recovery data, collected prior to the study was used for conceptual model development. The data are plotted in Figure 2b. The plot shows a near constant recovery rate until just before stabilisation (the occurrence of the discharge at Ynysarwed).

This type of response is likely to result from flooding of a large volume of void with gradual recovery of groundwater levels, and is analogous to drawdown or recovery in a large diameter well (Krusemann and De Ridder, 1994) where an initial straight line is followed by a Theis type response. The response is therefore controlled by lateral groundwater flow and a high volume of void.

Frances and Michael collieries, Scotland, minewater recovery prediction

Frances colliery was the last in the Dysart-Leven coalfield of Fife to close. The coalfield comprised a number of mines, principally Frances, Michael, Wellesley, Balgonie and Randolph collieries. This case study is based on work by Bullen Consultants (Younger, 1995) who undertook a study to predict the consequences of cessation of pumping at Frances colliery.

The conceptual model was based on mine plans, minewater pumping data, geological information, geochemistry and minewater level data. The mines can be conceptualised as five ponds with consistent internal water levels, but with limited connection between ponds at certain mined horizons only. The main sources of water to the mines were identified as recharge through the sea bed (vertical groundwater flow) and direct infiltration through mine openings. Lateral groundwater inflow was not considered to be a significant source.

Minewater recovery was modelled using the GRAM (Groundwater Rebound in Abandoned Mineworkings) code developed by Newcastle University (Younger et al, 1995). The model takes an average specific yield of mineworkings and collapsed mined strata rather than using estimated volume of mined void.

The model shows that cessation of pumping at Michael Colliery will result in recovery of the inter-connected system. Predictions of recovery from the model are plotted in Figure 2c. The plot shows water levels in Frances Colliery rising at a constant rate corresponding to a constant mean volume of void and a constant inflow from the sea and direct infiltration, until sea level is reached. When minewater reaches sea level the component of sea water inflow ceases and the rate of inflow decreases (cf vertical groundwater inflow). Minewater recovery in the Michael and Balgonie ponds exhibit similar responses, but these are also affected by inter-action between ponds.

Whittle colliery, England, minewater recovery prediction

Whittle colliery worked the Shilbottle seam of the Carboniferous Middle Limestone Group in Northumbria. Whittle was connected to the Shilbottle colliery which worked the same seam. Shilbottle closed in 1982 and following closure of Whittle in March 1987, pumping ceased and the workings were allowed to flood. The Environment Agency was concerned that flooding would lead to discharge of contaminated water with pollution of the River Coquet, which is designated a Site of Special Scientific Interest and is used for public water supply abstractions. As a consequence Environment Agency hydrogeologists were asked to predict the rate of flooding and timing and location of discharges. This case study is based on the work undertaken by the Environment Agency (Butler, 1998).

Assessment of the geometry, geology and water levels measured in a number of boreholes and shafts in the workings indicated that the mine system was hydraulically inter-connected and could be considered a single pond and that the main sources of water to the system were leakage from surface water courses, direct infiltration at seam outcrops and vertical groundwater flow from overlying aquifers. Lateral groundwater flow was considered to be insignificant because the host rocks are mainly mudstones.

The volume of void for successive elevation intervals was estimated based on mine plans and seam thickness, and based on the rate of flooding at the time of study the inflow rate was also estimated.

The predicted recovery is shown in Figure 2d and shows the rate of rise increasing with time due to decreased volume of void at higher elevations. Figure 2d also shows the measured rate of minewater recovery. The recovery plot followed the predicted pattern for several months before deviating on a more gentle gradient than predicted.

The reason for this is likely to be that there was locally some connection between limestone aquifers and the workings. This would have had the effect of introducing head dependency and therefore slowing the rate of recovery with time. The conceptual model was probably correct in all but this aspect, and even this aspect was considered and evidence that there was no significant connection between the limestones and the workings cited.

St Salvy zinc mine, France, closure implementation

St Salvy mine, located in south western France, closed in December 1993. SRK provided technical advice throughout implementation of the closure on water related issues. The mine worked a hydrothermal vein deposit emplaced at the edge of the metamorphic aureole of the St Salvy granite massif. The host rocks are Cambrian schists varying in lithology from arenaceous to argillaceous black schists (Sadler, 1998).

Concern was raised about the potential for contaminated water to discharge at the surface and SRK was commissioned some 18 months after closure of the mine and initiation of the flooding process. The focus of the study was on predicting quality and quantity of discharge and designing a water treatment scheme. However in June 1995 it was predicted that the discharge would occur between March and July 1996. The prediction was based on the conceptual model and extrapolation of the recovery curve.

The conceptual model was based on geology, geometry, pumping data, recovery data and pumping during recovery. The key aspects was that the inflow rate was independent of head in the workings and that the recovery was volume of void controlled. The main sources of water were interpreted as vertical groundwater flow from near surface fractured strata and direct infiltration around shafts and declines.

The recovery curve is shown in Figure 2e. The curve shows the effects of increased volume of void where the recovery slows as the water level rises through each mine level. The discharge occurred in December 1996, some 6 months after predicted. The reason for this discrepancy between predicted and actual discharge timing is likely to be a decrease in inflow rate as the minewater level rose into the upper fractured zone, reducing hydraulic gradients and therefore inflow rates. This is analogous to a change in inflow source from vertical groundwater to lateral groundwater. The process was not adequately accounted for in the conceptual model which assumed fractured ground was mainly at a higher elevation than the workings.

Les Malines zinc mine, France, closure implementation

The Malines mine worked a number of sulphide ore bodies within Cambrian meta-sediments, including karstic calc-schists, in the south of France. The mine closed in 1991 and in 1996, SRK was commissioned to assess whether a surface discharge would occur, and if it would predict its location, quantity and quality and design appropriate treatment plant. At this stage recovery was near complete.

A conceptual model was developed on the basis of the geology and mined geometry, sparse operational pumping data, recovery data and a pumping test to assess the current inflow rate. This indicated that the main control on recovery was lateral groundwater inflow, with direct infiltration contributing to seasonal variation.

The recovery hydrograph is shown with rainfall data in Figure 2f. The recovery response is broadly of a Theis type, but affected by high groundwater recharge rates and probably volume of void. The early part of the recovery is less affected by recharge, partly because the seasonal contrast in rainfall was less pronounced during this period, and partly because the steep drawdown cone prevailing during the early period is less responsive to seasonal changes in groundwater level, than when equilibrium is being approached.

It was predicted that a discharge would occur early in 1997 if conditions were not unusually dry. Discharge was not allowed to occur and a pump and treat system was installed close to prevent uncontrolled discharge.

Las Cruces copper project, Spain, feasibility study and EIA

The Las Cruces orebody, near Seville, has been the subject of a recent feasibility study and EIA undertaken by Rio Tinto. SRK carried out the EIA and worked closely with WMC, who were undertaking a dewatering feasibility study, on water aspects of the EIA. The orebody is a massive sulphide occurring within the Iberian Pyrite Belt. The orebody occurs within Palaeozoic volcanics and shales and is overlain by the Tertiary Niebla-Posadas regional sandstone aquifer (<5 m – 20 m thickness) and Tertiary marls of about 130 m thickness.

The dewatering study focussed on minimising the amount of water which would enter the workings and potentially become contaminated. Groundwater recovery predictions were made using MODFLOW calibrated to regional groundwater level data and pumping tests, to assess the potential impacts on water quality in the aquifer. The mineworkings were to be backfilled and no discharge of minewater to surface was anticipated as equilibrium water levels were below the land surface at the mine site.

The main source of water to the mineworkings was expected to be the Niebla-Posadas aquifer and the upper part of the underlying Palaeozoic host rocks. The predicted recovery curve is presented in Figure 2g. The curve shows relatively slow recovery as the mined void is filled and the aquifer resaturates through lateral groundwater flow, between elevations of –140 m and –100 m. This is followed by rapid recovery after the mineworkings and aquifers become resaturated and water levels rise through the Tertiary marls, flooding the mine shaft.

The late stage represents a period of gradual recovery as the regional water table recovers to its pre-mining condition.

Lisheen lead zinc mine, Ireland, feasibility study

The Lisheen lead zinc mine is currently being developed in the Carboniferous Limestone of central Ireland. The limestone is well karstified and has acted as a regional aquifer supporting local wells. The feasibility study was undertaken by SRK between 1993 and 1995. This work included development of dewatering requirements as it was decided that in order to minimise the risk of major sudden inflows and to limit the amount of minewater coming into contact with the sulphide orebody, pre-dewatering would be the appropriate water management strategy.

The area is relatively flat and access to the orebody at a depth of some 200 m was likely to be via a shaft or drift. The mine plan included for backfill of workings with cemented tailings. Discharge of minewater to the surface was not anticipated, although movement of minewater through the aquifer would be expected following mine closure.

As part of the development of an initial closure plan, minewater recovery was simulated using MODFLOW. The model was calibrated to hydrographic information from numerous boreholes and pumping test data from several large scale tests. The predicted recovery curve for an imaginary monitoring well close to the orebody is shown in Figure 2h.

This response is a Theis type response, showing the overall dominance of groundwater on the system, the relatively low storage of the backfilled workings and the lack of direct connection between the deep workings and the surface.

Mine development began in 1998 and therefore there is no recovery data on which to validate the model and predictions.

CONCLUSIONS

Prediction of the rate of minewater recovery is an important part of mine closure planning. Predictions should be based on a sound conceptual model which describes the geometry and hydrogeology of the mined system and identifies the main sources of water to the workings.

Understanding of the principal sources of water may dictate the methods used to predict recovery, since certain sources such as lateral groundwater inflow are more amenable to numerical groundwater flow modelling, whilst others such as direct infiltration are more amenable to mass balance approaches based on inflow rate and volume of void.

Preliminary predictions undertaken during feasibility studies can be improved upon during the life of the mine through incorporation of operational data, such as pumping rates and tonnages into the conceptual model. Where a long recovery period is anticipated monitoring of early recovery data will further enhance the conceptual model. Pumping and recovery data can also be used for numerical and analytical model calibration.

Prediction of recovery should be targeted towards the problem which needs to be solved. It is often sufficient to know whether a problem is likely to manifest itself in six months, one year, five years or ten years. This level of accuracy will allow for adequate monitoring, revision of predictions and planning. In other cases where recovery is rapid, environmental impacts associated with recovery are inextricably linked to recovery rate or timing of future expenditure is critical, more accurate predictions are required.

The case studies presented here have been compiled from various studies which usually involved recovery prediction. Where possible subsequent monitoring data has been plotted for comparison post-validation of predictions. This gives us an insight into the reliability of predictions, which irrespective of the method used are only as good as the conceptual model on which they were based.

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