Simulating groundwater rebound in a recently-closed tin mine

Russell Adams, Paul L. Younger

Water Resources Systems Research Laboratory, Department of Civil Engineering, University of Newcastle Upon Tyne, Newcastle Upon Tyne, NE1 7RU, United Kingdom, Tel: +44(0)191 222 7113, Fax: +44(0)191 222 6669, e- mail: r.adams@ncl.ac.uk, p.l.younger@ncl.ac.uk.

Abstract: The recent closure of the South Crofty Tin mine, the last working mine of this type in Europe has raised questions over possible environmental consequences. During several centuries of operation, the mine was dewatered by a series of pumps located at different levels in the mine. Older workings near the ground surface were dewatered by a series of adits which discharge into nearby rivers and streams. The quality of water draining from these shallow workings is generally good and no treatment is required. However, because of bad experiences at the nearby Wheal Jane tin mine, the UK Environment Agency are concerned about the quality and quantity of water which will discharge from the deeper workings once groundwater rebound is complete. In order to address this problem and make predictions of the timing and volume of the discharge, computer simulation using the SHETRAN/VSS-NET model has been carried out. This model has already been applied to the simulation of groundwater rebound in several UK coalfields. However, the hydrogeological characteristics of coal mines differ considerably from the South Crofty mine. In this mine, the country rocks comprise granite and metamorphic slates, these strata have almost no transmissivity and very low storage. Most of the groundwater flow is therefore in the "drives" and "stopes" from which tin ore was extracted. The inflows to the mine during its operation were mapped and quantified, and were found to be mainly head-dependent. These inflows usually originated from fault zones in the rock, and also nearby disused and flooded workings, which surround the modern mine. Predictions of the rebound are compared with the observed water levels in the main shaft which have been measured since the mine closed. These predictions have then been extended into the future to estimate the time at which surface discharges of minewater into the shallow adit system, and thence into the local river, will commence.

1 INTRODUCTION

South Crofty Mine, located in Cornwall, South West England, began extracting copper ore in the early 1600s, with production switching to tin ore from the mid-nineteenth century. In October 1985 the price of tin fell dramatically on world markets with a consequent contraction of the Cornish tin industry. During the 1990s the mine continued to operate at a loss, and closure was announced in 1997, by which time South Crofty was the last remaining tin mine in Europe. Figure 1 shows a plan of the modern mine and its environs.

The possible impacts of the closure of South Crofty have been well documented in a series of reports, commissioned by the Environment Agency (Knight Piésold & Partners, 1994, 1996, 1997), and also prepared by the mining company (South Crofy plc, 1998 a&b). This case study was commissioned by the Environment

Agency, who were eager to obtain rebound times from a physically-based model rather than from simple void-filling calculations (Adams & Younger, 1999).

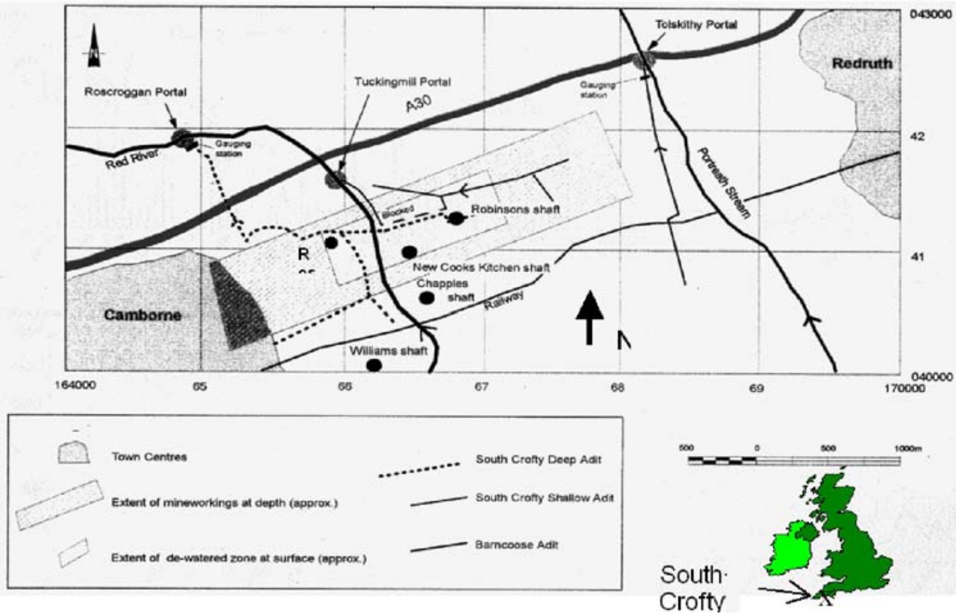

Figure 1 Location map of South Crofty Mine, showing the extent of the modern workings, principal shafts and drainage adits.

The Agency became involved in the contingency planning for closure due to concern over the high risk of polluting discharges affecting the surface water courses (in particular the Red River which flows close to the mine), following a rebound of mine water. Before mine closure, mine water discharging into the Red River from the Dolcoath (Deep) Adit originated from long-abandoned shallow workings and was generally of good quality (Knight Piésold & Partners, 1997). A second adit (Barncoose) also drains shallow workings above the modern mine into Portreath Stream; however this adit is at a higher elevation than Dolcoath Adit. It was anticipated therefore, that rebounding mine water would reach Dolcoath Adit before Barncoose Adit. Figure 1 shows the location of the mine and the various adit systems, some of which date back to the eighteenth century. At closure the adit system was slightly modified to ensure that the mine water would emerge from the circular, brick-lined Roskear Shaft, and flow via a short section into the main Adit.

The Agency's concern about the pollution risk associated with the South Crofty discharge was partly a consequence of the serious pollution incident caused by the discharge of mine water from the nearby Wheal Jane tin mine in January 1992 (Knight Piésold & Partners, 1995). The Agency was anxious to prevent a similar incident following closure of South Crofty, however it is anticipated at the time of writing that the quality of the water decanting from South Crofty will be better than the Wheal Jane mine water due to a lower acid-generating potential of the ore minerals in South Crofty (Knight Piésold & Partners, 1997). The "first flush" of mine water however, could result in increased concentrations of copper and zinc in particular in the Red River (which had previously received pumped water from the mine of generally acceptable quality), and some treatment of the discharge may be required (Environment Agency *pers.comm*. 1999) in order to comply with the Environmental Quality Standards[1] (EQS) limits for these metals.

2 MINE LAYOUT

Workings in South Crofty were divided into a series of near-horizontal levels. Each level formed the base of the stopes (workings), which were driven vertically to extract the tin ore. In traditional Cornish mining terminology, the level is named according to its depth and the shaft used to haul its ore to the surface (e.g. 310 Cooks), with the number referring to the depth (in fathoms, 1 fathom = 1.83 m) from adit level in the named shaft to the connection to the workings. The other datum used in more modern references to the mine is the metric mining datum, located 2000 m below sea level. Elevations relative to this datum are referred to subsequently as "m AMD". Ground surface (at Cooks Kitchen Shaft) is approximately 2111 m AMD, adit level 2051 m AMD. The most modern and deepest workings in South Crofty were at 470fm (1200m AMD) level, up to 900 metres below ground surface. The total plan area of the workings (as implemented in the conceptual model) is around 2 km^2.

3 MINE HYDROGEOLOGY

During the operation of the mine, water was pumped from four major pumping stations from 420fm (1295 m AMD) level (the deepest) to 195fm (1730 m AMD) level (the shallowest), using Cooks Kitchen Shaft. Between 225fm (1695 m AMD) level and adit level were old workings which were partly de-watered by the 195fm level pumps. Estimating the volume of the de-watered workings was extremely important in order to make accurate rebound predictions, therefore mining engineers with first-hand experience were consulted. The volume was estimated at around 4.5 million m^3.

An assessment of the historical record of pumping was made in order to derive an estimate of the inflow rate of water (water make) during the operation of the mine. Secondly, the dewatered volume of the mine was examined from the data and diagrams in the various reports (South Crofty plc, 1998a), in order to assist in the setting up of initial and boundary conditions in the conceptual model described below.

The 195fm pumps were used to pump water from the lower workings to the ground surface. The water make from the 195fm and higher levels was negligible

[1] EQS are based on the EC Dangerous Substance Directive (Directive 76/464 *On Pollution Caused by Certain Dangerous Substances Discharged into the Aquatic Environment* and associated daughter directives).

due to engineering work carried out in the early 1990s to divert water from the shallow workings into the adit system and away from the mine (Carnon Consolidated, 1990). A large flooded area of old workings, called “the Pool”, located between 195fm and 225fm (1700 to 1730 m AMD) levels was used as a reservoir to store the water before it was pumped from the 195fm level. From Table 1, assuming that the water pumped at each level migrated downwards to the pump station immediately below, it is clear that the levels between 225fm and 340fm (1495 to 1700 m AMD) were contributing the bulk of the water make (55%), with the deeper levels contributing less water make. The highest inflows originated from the eastern side of the mine also exceeded the inflows from the western side. The largest inflows originated from the 290 and 260fm level (1584-1667 m AMD) and were thought to originate from higher flooded workings connected via a major fault zone to the modern mine (M.Owen *pers.comm.*).

Table 1 Pumped mine water totals at different levels

Level (fm) (m AMD)	195 (1760)	340 (1495)	380 (1422)	420 (1340)
Average Pumped Total (m^3/hr) 1989-97	273	273	124	48
Average Make (m^3/hr) 1989-97	0	151	76	48

3.1 Meteorological Data

The meteorological data recorded at stations near the mine were obtained and examined in order to: (i) assess the likely recharge into the mine; (ii) to examine the relationship between rainfall and the volume of water pumped from the mine. A long record (starting 1950) was obtained from three local raingauges. The 1961-1990 average annual rainfall at the gauge nearest the mine was 1106 mm. In order to assess the likely timing of rebound in the mine it was necessary to study a long record of rainfall. The current baseline climate period of 1961-1990, plus the recent record to 1998, were analysed. Two extreme scenarios were investigated. The aim was to produce an appraisal of the post-closure behaviour of the mine under "best case" (i.e., extreme dry conditions) and "worst case" (i.e. extreme wet conditions) and produce an "envelope" of different times at which flow into Dolcoath Adit from Roskear Shaft would commence. The magnitude of the extreme conditions was predicted from the long-term rainfall record for the area. The two scenarios are described below.

3.2 Calculation of Infiltration into the Mine

The infiltration into the mine was calculated from the rainfall and evapotranspiration data using Equation 1. No infiltration is possible if actual evapotranspiration exceeds rainfall.

$$I = 0.25 \times (P - E) \qquad I \geq 0 \tag{1}$$

Where: I = infiltration
P = rainfall
E = actual evapotranspiration
(All units are in mm).

Values of infiltration were calculated on a daily time series for January 1989 to January 1998. In equation 1 the factor 0.25 is derived by assuming that surface runoff equalled 75% of net rainfall. In an urban district like the Camborne-Redruth conurbation in which South Crofty Mine is situated, infiltration can be as low as 25% of net rainfall. This is due to direct runoff into the local storm drainage and sewer system, from where the rainfall will be discharged directly to local surface watercourses. The high runoff is a consequence of having large paved areas such as industrial estates and car parks in the vicinity of the mine.

3.3 Relationship of Pumping data with Rainfall

The relationship between net rainfall (i.e. infiltration) totals and pumped totals was examined in order to assess (a) which inflows to the mine were head-dependent (b) the time taken for fluctuations observed in the rainfall to be shown in the variation in water pumped from the mine. A series of regression analyses were performed on the pumping totals from the individual pumping stations. The aim was to try and identify which inflows were likely to be head-dependent and which inflows originated from rainfall infiltrating the shallow workings and shafts. The results

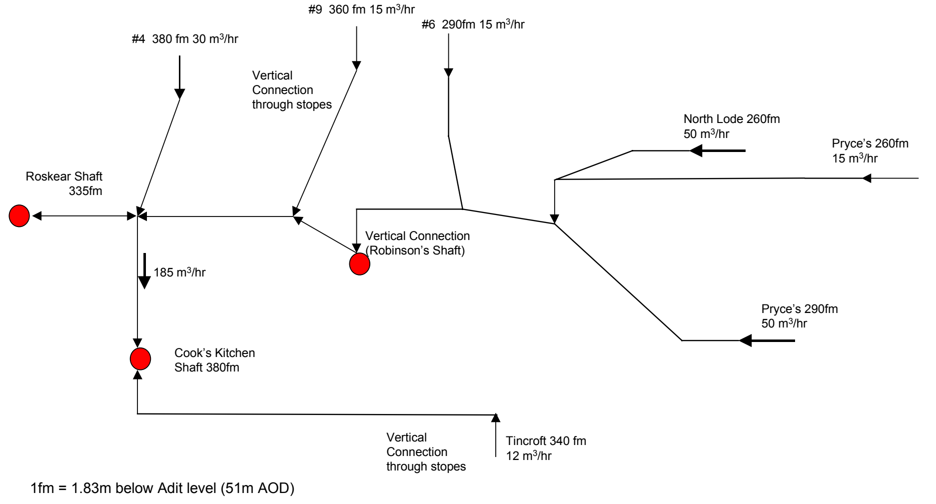

Figure 2 Schematic diagram of modelled inflows and the pipe network included in the conceptual model, depicting flow rates and location (by mined level).

indicated that the inflows to the deeper pumps were head-dependent and not from infiltrating rainfall. For the purpose of this study, the inflows were taken as average values, as insufficient data were available for any detailed analysis. Figure 2 shows the locations and magnitudes of the different inflows included in the final model.

4 HYDROGEOLOGICAL MODELLING OF REBOUND

4.1 Overview of the SHETRAN/VSS-NET Model

The simulation of rebound in South Crofty Mine was carried out using the SHETRAN physically-based modelling system (Ewen *et.al* in press), incorporating the VSS-NET component (Adams & Younger, 1997). The VSS-NET component can represent (i) laminar flow in variably-saturated 3-D porous media (Parkin, 1996), and (ii) turbulent flow in open roadways or shafts as a result of the flooding up of old mine workings.The model had been previously applied to UK abandoned coal mines (Younger & Adams, 1999).

A 3-D model such as SHETRAN requires large data sets to parameterise the model domain. In the case of South Crofty, the model domain was selected based on the following assumptions.

i. The lateral extent of the mine is defined by the location of the modern workings from 195fm (1730 m AMD) to 445fm (1295 m AMD)
ii. The mine was de-watered at the time of closure to at least the depth of the lowest workings. The initial conditions in the model were set up accordingly (see below), and the bottom boundary of the model is defined by the level of the lowest stopes on the 445fm (1340 m AMD) level.
iii. Intact rock (granite and slates) is assumed to be impermeable and assigned a low matrix porosity and hydraulic conductivity. Therefore outside the dewatered area of the mine there is negligible groundwater flow even from saturated old workings to neighbouring unsaturated de-watered workings.
iv. Areas where the mine plans indicate stoping have a much higher hydraulic conductivity and a porosity calculated from the void volume divided by the total area of the workings (K = 1 m/day, porosity = 0.4 to 1.1 %).
v. The head-dependent inflows will be routed to Cooks Kitchen Shaft at 380fm (1422 m AMD) level by a pipe network, according to a schematic diagram (South Crofty plc 1998b; see Figure 2).

4.2 Simulations

The first simulation carried out by the model was a baseline simulation representing an “historical” period during which the model results could be compared with the observed water levels measured in the mine during rebound. For this period, the historical rainfall data and actual evapotranspiration data were available so daily infiltration values to be calculated using Equation 1. After this simulation was run, the two extreme meteorological scenarios, described above, were run. These simulations are listed below.

a) "historical". The model was run from 1st February 1997 to 31st December 1999, and the water level rebound predicted by the model compared with the dips taken in Cooks Kitchen Shaft. A pumping well (in the model) was located at the corresponding grid element, and the pumping rate was calculated from the historical pumping rates for 1997 and the first two months of 1998.

b) “wet” Infiltration values were calculated from the 1965-1968 rainfall series. These data were used to run the model from January 2000 onwards.

c) “dry” Infiltration values were calculated from the 1990-1993 rainfall series. Again, these data were used to run the model from January 2000 onwards.

5. RESULTS

5.1 Historical Simulation

The “historic” simulation was initially run for the final year of mining operations (the year ending March 1998), to establish steady-state conditions by pumping water from Cooks Kitchen Shaft. Later, the simulation was extended after more recent rainfall data became available. After pumping of the mine ceased in March 1998, water levels in the mine, and in the model, began to rise. Figure 3 shows the predicted water levels in Cooks Kitchen Shaft (solid line), obtained from the model results, against the observed water level dips (shown as black triangles). The time axis begins in May 1998, since before this time there were few measurements of water level taken. In general the model predictions are within 20 metres of the observed water levels, and the general rate of increase of water level has been reproduced. There is a slight underprediction of water levels during Summer 1999 once the water level reached 1650 m AMD, this could be due to an overestimation of the storage coefficient in this level of the mine (260fm). The rate of rebound of mine water in the upper levels would also be underestimated if the head-dependent inflows were reduced to zero too early during the rebound process, since there were no data on the head elevations in the water-bearing workings producing the inflows. At the start of rebound, head-dependent inflows totalled 182 m^3/hr, this was approximately 60% of the total inflow to the mine (depending on the net rainfall).

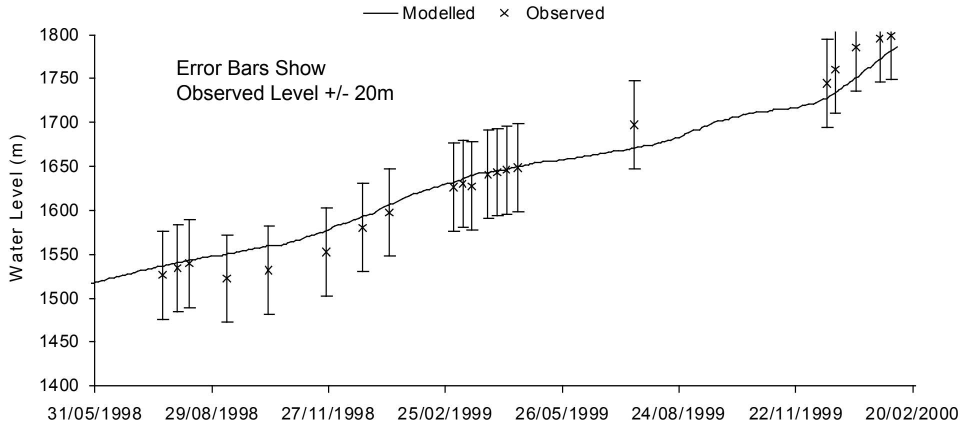

Figure 3 Observed and modelled water levels in Cooks Kitchen Shaft from June 1998 to January 2000.

5.2 Future Scenarios

From January 2000 onwards, the “wet” monthly time series of recharge values were used in the model. The simulation was run until the water levels in Roskear and Cooks Kitchen Shafts were predicted to reach adit level (2051 m AMD). An estimate of the volume of water, which will discharge from Roskear Shaft into the Dolcoath Adit was also made. The predicted water level in Roskear Shaft is shown in Figure 4 by the black line, the black triangles show the observed water levels recorded in January 2000 for comparison[2]. Again, the underprediction of the levels is around 20 metres, however the model has encouragingly reproduced the sharp increase in the rate of rise of water level in January 2000. The predicted water levels in Roskear Shaft under the "dry" scenario are shown by the grey line. The results of the "wet" and "dry" scenarios are summarised in Table 2.

Table 2 Predicted rebound times and discharge rates under different scenarios

Rainfall Scenario	Days to start of discharge	Discharge starts	Month when water reaches 2031m	Maximum Discharge Rate (ML/day)
Wet	1362	November 2001	September 2001	0.95
Dry	1500	April 2002	February 2002	0.9

[2] In Cooks Kitchen Shaft, however the water levels in both shafts are virtually identical during rebound.

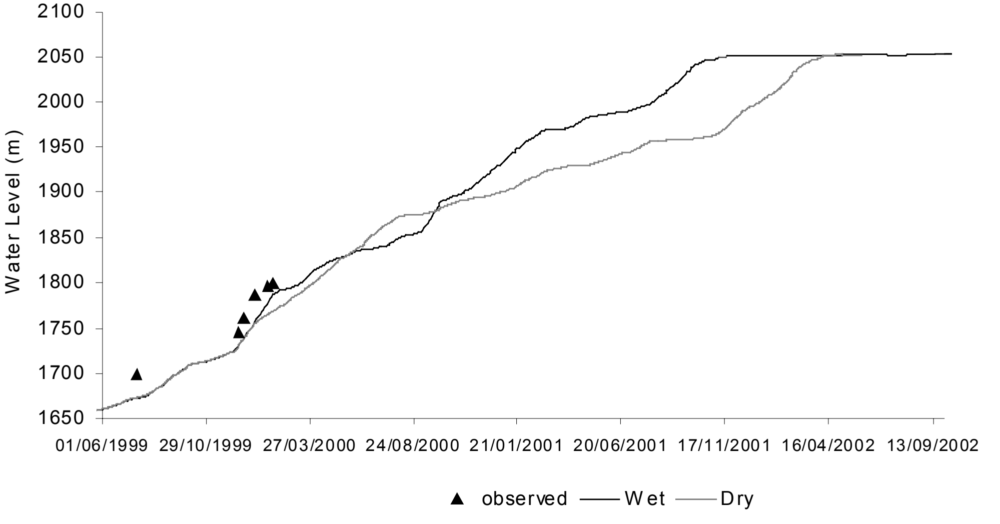

Figure 4 Modelled water levels in Roskear Shaft from June 1999 until emergence of mine water in Dolcoath Adit, under wet and dry recharge scenarios.

6 CONCLUSIONS

The conceptual model developed to simulate rebound in South Crofty Tin Mine has predicted dates of mine water emergence in the Dolcoath Adit, the time taken for rebound will depend on the climatic conditions in the next two years. The increase in discharge from the Adit has also been predicted. The model has also incorporated head-dependent inflows of water into the mine workings from adjacent flooded mines, these were thought to be active during the early stages of the water level rise in the mine. During the early stages of water level rise, predicted water levels in the main shaft were almost always within 20 metres of the observed levels. The study also showed a method of distinguishing head-dependent from rainfall-derived inflows by regressing historical pumping rates with rainfall data. The results will be used for contingency planning in case the water discharging into Dolcoath Adit is of poor quality and requires some treatment. The pollution potential of South Crofty is thought however, to be less severe than nearby Wheal Jane Tin Mine which closed some years ago.

ACKNOWLEDGEMENTS

The authors would like to thank the following:
Mark Owen (Mining Geologist formerly with South Crofty plc).
Jim Wright, Clare Marsden & Tamsin Howells, Environment Agency (South West Region).

Ben Sansom (Knight Piésold & Partners Ltd).
The modelling work made use of a UNIX workstation funded jointly by United Kingdom Nirex Limited and NERC grant GR3/E0009.

REFERENCES

Adams, R. & P.L. Younger, 1997. Simulation of groundwater rebound in abandoned mines using a physically based modelling approach. In Veselic, M., and Norton, P.J., (Editors), *Proceedings of the 6th International Mine Water Association Congress, "Minewater and the Environment"*, held Bled, Slovenia, 8 - 12th September 1997. Vol. 2, pp 353 - 362.

Adams, R. & P.L. Younger, 1999. *Modelling the Timing of Rebound at South Crofty*. Report to the Environment Agency, South West Area, Nuwater Consulting Services Ltd. 31pp.

Carnon Consolidated (J.A. Buckley), 1990. *South Crofty Hydrology Study.*

Ewen, J., Parkin, G. and O'Connell, P.E., *in press.* SHETRAN: a coupled surface/subsurface modelling system for 3D water flow and sediment and contaminant transport in river basins. *ASCE Journal of Hydrologic Engineering*.

Knight Piésold & Partners, 1994. *South Crofty minewater study, final report to National Rivers Authority South Western Region*, Exeter, UK.

Knight Piésold & Partners, 1995. *Wheal Jane Minewater Study, Environment Appraisal and Treatment Strategy, Report to the National Rivers Authority South Western Region*, Exeter, UK.

Knight Piésold & Partners, 1996. *South Crofty Mine closure contingency plan, final report to Environment Agency,* Bodmin, UK.

Knight Piésold & Partners, 1997. *South Crofty strategic closure study, provisional report to Environment Agency,* Bodmin, UK. 39pp + figures.

Owen, M.L., & N. Leboutiller, 1998. *South Crofty Mine, closure ore reserve*, South Crofty plc, Camborne, UK.

Parkin, G., 1996. *A three-dimensional variably-saturated subsurface modelling system for river basins*. PhD Thesis, Department of Civil Engineering, University of Newcastle Upon Tyne, UK.

South Crofty plc, 1998a. *Dolcoath Deep Adit, report on its condition and the South Crofty Mine decant location*, Report to Environment Agency, Bodmin, UK.

South Crofty plc, 1998b. *South Crofty Mine closure.* Internal Report., Camborne, UK.

Younger, P.L. & Adams, R., 1999. Predicting mine water rebound. A practical guide for hydrogeologists. Environment Agency R&D Technical Report W179. Bristol, UK.

Symulowanie odbudowy ciśnień wód podziemnych w ostatnio zamkniętej kopalni cyny

R.Adams & P.L.Younger

Streszczenie: Niedawne zamknięcie kopalni cyny South Crofty, ostatniej czynnej kopalni tego typu w Europie, wywołało dyskusję na temat możliwych konsekwencji dla środowiska. W czasie kilku stuleci swojej działalności kopalnia była odwadniana za pomocą systemu pomp usytuowanych na różnych poziomach kopalni. Starsze wyrobiska znajdujące się bliżej powierzchni były

odwadniane za pomocą systemu sztolni odprowadzających wodę do pobliskich rzek i strumieni. Jakość wody odprowadzanej z płytkich wyrobisk jest generalnie dobra i nie ma potrzeby jej oczyszczania. Nieznana jest jednak ilość i jakość wód, które wypłyną z głębszych wyrobisk, gdy odbudowa ciśnień wód podziemnych będzie zakończona. Przeprowadzono symulację komputerową czasu i objętości wypływu wód przy użyciu modelu SHETRAN/VSS-NET. Model ten stosowano już do symulacji odbudowy systemu wód podziemnych w kilku kopalniach węgla w Wielkiej Brytanii. Jednak warunki hydrogeologiczne kopalń węgla kamiennego różnią się znacznie od warunków panujących w South Crofty. W kopalni cyny skały zbudowane są z granitu i łupków metamorficznych, która to warstwa jest prawie nieprzepuszczalna i charakteryzuje się małymi zdolnościami retencyjnymi. Większość wód podziemnych występuje w wyrobiskach, z których wydobywano cynę. Dopływy do kopalni w czasie jej pracy były odwzorowane i określone pod względem ilościowym. Stwierdzono, iż wielkość zasobów wód podziemnych zależała od kształtowania się wysokości ciśnień wód. Dopływy wód do wyrobisk pochodziły głównie ze stref uskoków, jak również leżących w pobliżu nieczynnych i zalanych zrobów, które otaczały współczesną kopalnię. Wykonywane prognozy odbudowy ciśnień są dokonywane w oparciu o obserwacje stabilizacji zwier-ciadła wód w głównym szybie. Prognozami objęto czas od początku zatapiania kopalni do momentu uaktywnienia się powierzchniowego odpływu wód kopalnianych do systemu rowów i następnie do lokalnej rzeki.