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A Review of Mine Water Rebound Predictions from the VSS–NET Model

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Abstract Mine water rebound predictions made in the late 1990s and early 2000s were critically reviewed in light of subsequent monitoring data and available literature. The VSS–NET physically-based groundwater model simulates the rebound process by representing both laminar and turbulent flow; the latter is observed in mined out voids, including shafts, adits, and underground roadways. We found good agreement between modelled and predicted rebound rates at a coal mine (Whittle Colliery) in NE England. The rebound from an abandoned tin mine in Cornwall, England (South Crofty), which closed in 1998, took place more rapidly than initially predicted by the VSS–NET model; however, by back-fitting the storage coefficient, the observed rate was matched by the model. In a third case study from a coal mine in South Wales, we managed to reproduce the flow rate from an adit reasonably closely following rebound. However, at a fourth site, a better fit to the rebound curve was obtained using a simpler, lumped model. These studies show the value of using models to predict rebound and discharge from flooded mines, which is important since these mines can produce a long-term legacy of pollution and can cause serious environmental impacts downstream.

Keywords Abandoned mines · Coal mines · Hydrological modelling · Groundwater modelling · Metal mines

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Introduction

Understanding the process of mine water rebound is crucial in mitigating the long-term impacts of untreated discharges of contaminated water on the environment (Younger et al. 2002). The critical aims of mine water impact studies have been to assess the likely longevity of water pollution emanating from old mines and to anticipate contaminant loading in abandoned mine discharges (AMD). The predicted loads and timing of AMD emergence are important in designing remediation systems. In many instances, pump and treat systems can be used to prevent uncontrolled discharges, without which mine waters have frequently (worldwide, from the 1990s onwards) broken out following closure and the cessation of dewatering, which prevented problems such as flooding of nearby working mines (Younger et al. 2002).

Several years have passed since predictions of groundwater rebound in abandoned mines were made in the UK by the mine water research team at Newcastle University. The physically-based VSS–NET model (Adams and Younger 2001) was applied to several recently abandoned coal and metal mines in the UK. Predictions of both groundwater rebound and mine water discharge were made based on the available hydrogeology and meteorological data at the time, and a series of mine plans assembled from various sources to provide estimates of the areal extent and geometry of mined-out voids. These studies were undertaken to inform stakeholders (e.g. regulatory agencies) of the probable date(s) when mine water rebound would finish (i.e. water levels would reach the ground surface or some other decant point, causing uncontrolled AMD discharges to commence), and the flow rate that would issue from these. The water quality issues surrounding the emergence of the mine water at the surface were not directly modelled by Adams and Younger (2001), but were investigated in later studies (e.g. Evans et al. 2006; Nuttall 2003; Nuttall et al. 2002; Younger 2004). This paper revisits the original case studies and compares model predictions made years ago with what actually took place following closure, using a variety of data sources. The original predictions were made with a degree of uncertainty that was mostly expressed in terms of the variability of the future climate.

Methods

Modelling

The modelling of groundwater rebound in abandoned mines was carried out as part of a research project funded by the UK Environment Agency (EA) and some regional water supply companies (Younger and Adams 1999). The VSS–NET model was a new component of the SHETRAN physically-based modelling system that linked the pre-existing variably saturated subsurface (VSS) component (Ewen et al. 2000) with a hydraulic model (NET), capable of simulating turbulent flow in open mine voids during and after the rebound process. These voids include roadways (access tunnels), shafts, and adits (in this context, defined as sloping mine entries that permit discharge of mine water to the surface). The VSS–NET model is therefore able to capture both laminar and turbulent flow processes during rebound (Adams and Younger 2001). It is most suitable for single seam mines since each layer of interconnected workings requires a discrete pipe network with prescribed boundary conditions (usually a fixed head at either a flooded shaft or adit discharge point). Multiple seam workings require additional networks to be included, at extra computational expense. Future scenarios of alternative climates (which determined the recharge rate to the mine via SHETRAN's surface and VSS components) were explored in terms of 'wet', 'dry' or 'average' conditions ('wet', for example, used the wettest 2 years of rainfall data from the recent meteorological record). The variability of model parameters, while recognised as significant, was not discussed explicitly (Adams and Younger 2001), except in one case study discussed below. At the time of the modelling, simulations to capture the rebound process (typically spanning predictions of 2–4 years) were run overnight on either a high performance workstation or a PC.

Study Areas

The four case studies discussed below are:

The *Ynysarwed-Blaenant* coal mines (subsequently referred to as *Ynysarwed*) in South Wales were a system of connected mines that discharged water uncontrollably into the River Neath and a neighbouring canal following rebound in the Blaenant Colliery. Rebound commenced in 1993 when the pumps were switched off after closure in 1990; the Ynysarwed mine had closed much earlier, in the 1930s. This case study was first described in Younger and Adams (1999); subsequently, the lumped GRAM (Groundwater Rebound in Abandoned Mines) model was used to simulate rebound in the Cefn Coed shaft (connected to the Blaenant workings; Adams and Younger 2001).

The *Whittle Colliery* in NE England was abandoned in April 1997; the cessation of pumping allowed mine water to rebound and flood the old mine workings. A connection to the surface via old shafts and the streambed of a local watercourse (Hazon Burn) threatened the nearby River Coquet with uncontrolled AMD, probably when rebound reached a critical decant level $\approx$65 m above ordnance datum (AOD), the approximate mean sea level in the UK. This case study was first published by Adams and Younger (2001). The site's hydrogeology and mineralogy was described by Younger (2004).

The *South Crofty Tin Mine* in Cornwall, SW England closed in March 1998; pumping ceased in May 1998. The resultant mine water rebound threatened to increase flow in an adit drainage system (the Dolcoath Adit) that formerly discharged relatively clean water from older, flooded, shallow workings (Adams and Younger 2000). This decant point is subsequently referred to as the 'adit level'.

A fourth application of the VSS–NET model was for the abandoned Deerplay coal mine in NW England (Nuttall et al. 2002). This case study differed from the other three in that the aim was to reproduce the water levels before, during, and after a pump test conducted using a borehole drilled into the flooded, abandoned workings. The model was able to successfully reproduce most of the field observations from that test. No future predictions of water levels or mine water discharge rates (either controlled or uncontrolled) were made, and a full scale treatment plant was commissioned a few years later with a pumping rate ca. 9 L/s (Johnston et al. 2007).

Original Predictions

The following predictions were made for the first three mines:

Ynysarwed The system had already rebounded when modelling commenced and the adit began discharging mine water in early 1993. The GRAM model successfully reproduced the observed rebound in the shaft up to 2000 (Adams and Younger 2001) more accurately than VSS–NET could. The VSS–NET model was therefore set up using the initial heads predicted by GRAM and was able to match the observed discharge from the adit reasonably

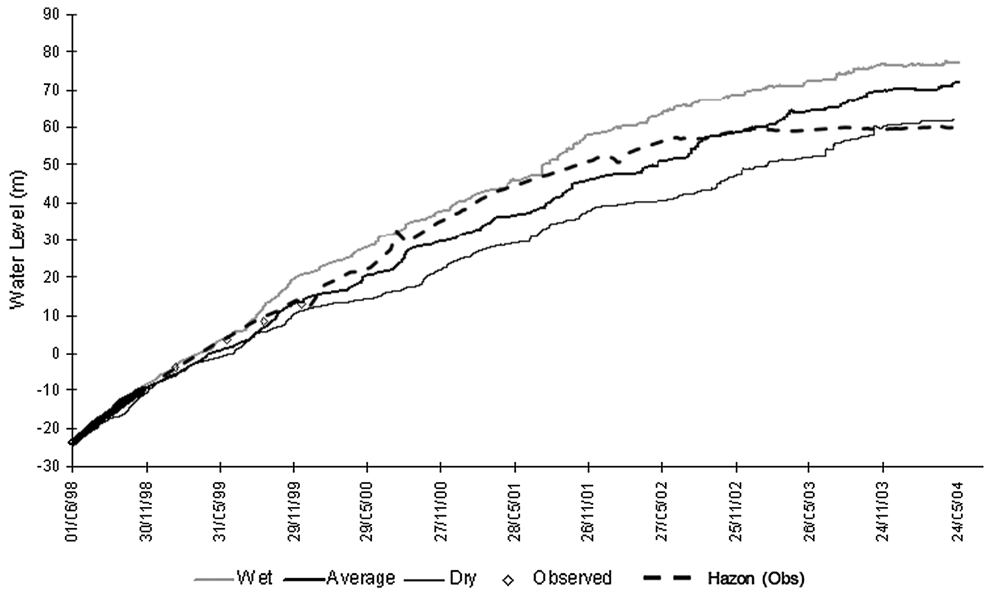

Fig. 1 Predicted and observed water levels in Whittle Colliery during rebound from June 1998 to May 2004. The envelope of model predictions represent different recharge scenarios. Observed water levels in Hazon Borehole, indicated by the *black dashed line*, were obtained more recently

accurately from 1995 to 1997 (Younger and Adams 1999). In this case study, the performance of the two models indicates how a simpler model structure (i.e. GRAM) may be more applicable to a complicated system of interconnected mine workings.

Whittle Colliery The system was actively rebounding when the modelling was carried out and predictions were made of water levels until June 2004. The observed data, indicated by black diamonds (Fig. 1) were available at the time of modelling to help calibrate the model. It was planned to start pumping mine water from a borehole drilled into the main drift, once a 50 m AOD level was reached, and then treat the discharge using a constructed wetland system (Nuttall 2003). Sensitivity analyses using the model were also carried out to investigate: whether the nearby and already flooded Bilton Banks workings were likely contributing additional inflow to the mine, and the effect of removing the pipe network and only simulating laminar flow in the workings on groundwater levels during rebound (Adams and Younger 2001).

South Crofty This system had commenced rebound in May 1998 before the VSS–NET modelling was carried out and weekly (approximately) water level observations were available to assess the model performance up to May 2000 (Adams and Younger 2000). A follow-up modelling study commissioned by the EA (results shown in Adams and Younger 2002) used the latest available monitoring data up to Nov. 2000 to graphically back calculate the rebound rate during the period where water levels in the Cook's Kitchen Shaft were available, by calibrating the storage coefficient in the model to match the observations. There was considerable uncertainty in the rebound rate through strata known as "killas" (metamorphic rocks) due to the unknown porosity and presence or absence of mined out voids, i.e. its storage coefficient. Predictions improved over a 2 year period and matched the observed rebound curve, resulting in water levels reaching the adit level on 8 Nov. 2000, causing water from the deeper workings to commence flowing into the Dolcoath Adit and subsequently into the Red River near the town of Redruth (Adams and Younger 2002).

Discussion

In Adams and Younger (2001), three different modelling approaches were reviewed, which can be classified according to the subsurface flow regimes that were simulated: laminar flow only, using MODFLOW; turbulent flow, using the lumped GRAM model, and turbulent and laminar flow, using VSS–NET. In the third case, the addition of a pipe network reduced the hydraulic gradient significantly across the mined system in the model domain, compared to simulating laminar flow only (demonstrated using the Whittle conceptual model without pipes). Moreover, although it was not explicitly proven by these case studies, the areal extent of the cone of depression surrounding flooded out workings during rebound should be significantly smaller at sites where turbulent flow dominates, compared to sites with laminar flow only. This was proven in Australia by Dudgeon (1985), who showed that a finite element model incorporating turbulent flow was better able to reproduce the cone of depression and seepage face in and around an open pit mine than a laminar flow solution.

The predicted rebound rates in the shafts at the three mines discussed here differed from what would be obtained assuming laminar flow only, as shown graphically in Younger and Adams (1999). This concept was explored further at a system of interconnected mines (Frances and Michael) in East Fife, Scotland (Nuttall et al. 2002), where hydraulics theory was used to verify the presence of turbulent flow during rebound.

The predictions of timing of rebound and flow rates from the abandoned mines were probably more sensitive to first, the storage coefficient (mostly comprised of open, mined-out voids), and second, the recharge rate, rather than other hydraulic properties, as evidenced from the South Crofty case study (Adams and Younger 2002), where the sensitivity of the rebound predictions to the storage coefficient was examined. Current information on each case study site was reviewed and the following retrospective findings were made:

Ynysarwed

This mine was studied by several authors following construction of a mine water treatment system. Evans et al. (2006) reported that flow rates from the adit were decreasing over time, from around 36 L/s (2,160 L/min) in the 1990s to 25–30 L/min in 1999–2000. Johnston et al. (2007) quoted a flow rate through the constructed wetland of 30 L/s (Sept. 2006 data), which suggests either that Evans et al. (2006) underestimated the flow rates by nearly two orders of magnitude or that the flow rate from the adit into the treatment system dramatically increased in the mid-2000s. The UK Coal Authority (the regulatory body charged with monitoring and treating mine water discharges from abandoned coal mines) were monitoring Cefn Coed shaft until 2006 and concluded that rebound had by then reached equilibrium. However, evidence from a nearby EA borehole, also drilled into the flooded interconnected workings, indicated that water levels continued to rise during the latter part of the decade and were in fact threatening to decant through a pipe attached to the shaft to the surface water system (Wyatt et al. 2011). These findings indicate the importance of both long term monitoring and predictive modelling in estimating likely flow rates and long term water levels associated with the rebound process.

Whittle Colliery

The VSS–NET model predicted that rebound to 50 m AOD would occur given "average" climatic conditions in May 2002 (Adams and Younger 2001). Younger (2004) reported that the Coal Authority pumping station commenced pumping mine water from the drift in January–February 2002 on a test basis, and on a full-scale operational basis in May 2002 (Nuttall 2003). In terms of predicted water levels, Fig. 1 shows the envelope of model predictions superimposed on the actual rebound curve from water level data in Hazon Borehole (dashed line). The water level in the borehole increased to close to the upper bound ("wet" scenario) model prediction in mid-2001, and was still within the predicted bounds when pumping started in 2002. The model predictions in Fig. 1 did not account for pumping or any observations post-1999; hence, the water level was predicted to rise towards 70 m AOD, which, in practice, was prevented. Pumping stabilized water levels in Hazon borehole between 52 and 55 m AOD. Levels in the pumping borehole itself are slightly less, indicating the development of a shallow cone of depression in the workings.

The predicted discharge rate from the flooded workings into surface water was predicted to range from 0.8 to 2.6 ML/day, with a median of 1.7 ML/day (20 L/s). Johnston et al. (2008) reported that the pump and treat scheme at Whittle was pumping just under 20 L/s from the flooded workings, with September 2006 data. Latest figures from the Coal Authority website suggest that 23 L/s is required to maintain the water levels at equilibrium (http://coal.decc.gov.uk/en/coal/cms/environment/schemes/ whittle/whittle.aspx). These figures are similar to the initial rate following commissioning of the scheme (Nuttall 2003). The VSS–NET model predicted that 20 L/s had to be pumped in order to obtain steady–state in the flooded workings, verifying the model's accuracy.

South Crofty Tin Mine

Obtaining post-closure information about this mine has been difficult since ownership has changed hands several times and little information can be obtained from the public domain, for commercial reasons. However, in the early 2000s, the upper workings (above the adit level, below which the mine remains flooded) were opened to tourist visits to a depth of approximately 45 m below ground (see http://www.cornwall-calling.co.uk/mines/camborne/South-Crofty.htm). Plans to dewater the flooded workings require a pumping rate of about 20 ML/day; the pumps are not yet operating (as of July 2014).

The predicted and actual rebound at the mines described above indicates the importance of considering the variability of both the climate and the internal structure of the mines. It is possible, especially at Ynysarwed, that above average rainfall since 2000 has exacerbated the situation and sustained the (now treated) AMD discharge from the adit. The legacy of flooded workings may require long term operation of both pumping stations and treatment systems if AMD loads remain high following their "first flush" peak (Younger et al. 2002). Physically based modelling of the rebound process should be seen as an important step in predicting AMD. However the resources required are fairly onerous and alternative methods (e.g. using design curves that mimic the rebound observed in the above cases) should be considered (Adams and Younger 2001), if data and resources are not available for a more detailed modelling study.

Conclusions

At the time of the modelling studies, only one mine (South Crofty) had experienced rebound of flooded mine water to the decant point where discharges to the surface water environment had commenced. Subsequently, a pump and treat scheme was constructed at the Whittle Colliery site to prevent a breakout of uncontrolled mine water and an AMD treatment system was installed downstream of the Ynysarwed adit to treat the uncontrolled discharge there. The subsequent observations of water levels during rebound, and flow rates from the adits and treatment systems (receiving pumped mine water) have shown the value of predicting mine water rebound.

The results from the physically-based VSS–NET model were mostly acceptable, as far as observations were available to validate them, except for one mine (Ynysarwed), where the simpler, lumped, GRAM model performed better in terms of predicting the rebound curve. At Whittle Colliery, the predictions of both the date that rebound would reach a key decant level and the required pumping rates (to maintain equilibrium in the flooded workings) were unerringly accurate. Future applications of both model types and simpler, empirical "design curve" type estimates of rebound should be made, depending on available data and computing resources, to assess the likely potential and longevity of mine water rebound, especially considering that the future climate is highly uncertain; this uncertainty should be considered as essential for inclusion in any study.

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