Coupled Groundwater-Surface Water Modelling Workflow to Support Risk Assessment of an Abandoned Underground Coal Mine Due to Natural Water Rebound

Nachayada Phonseela[1], Thomas Booth[1]

[1] *WSP, United Kingdom*

Abstract

This study aims to develop a coupled groundwater-surface water flow and solute transport modelling tool to evaluate the influence of mine water rebound from an abandoned underground coal mine sitting under limestone and sandstone aquifers and nearby streams. The developed workflow relies on MODFLOW6 and the FloPy Python library and aims to identify contaminant migration pathways towards potential receptors of mine water discharge by estimating increases in chloride concentration. The results indicate that if poor-quality mine water rises to levels where it can discharge into the local and regional aquifers, it will primarily travel through the limestone aquifer and streams and pose a risk of pollution to extensive regions of the aquifers and surface water bodies. Furthermore, significant groundwater-surface water interaction is expected to occur downstream of the mine, with contaminants migrating from the aquifer into streams close to the mine location and from the streams into the aquifer downstream of the mine.

Keywords: Risk assessment, groundwater, modelling, transport, coal, abandoned, underground mine

Introduction

Mine water rebound refers to the process where water floods abandoned deep mines after the cessation of dewatering operations (Merritt & Power 2022; Younger & Adams 1999). This often leads to polluted water either discharging to the surface or contaminating nearby aquifers (Younger & Adams 1999). Therefore, development of predictive groundwater flow and solute transport modelling tools that identify contaminant migration pathways and potential receptors of mine water discharge is essential for the effective planning of mitigation strategies.

The primary objective of this study is to develop and implement a coupled groundwater-surface water flow and solute transport modelling tool to evaluate the influence of mine water rebound from an abandoned underground coal mine on the overlying limestone and sandstone aquifers and nearby streams. The modelling workflow aims to identify contaminant migration pathways towards potential receptors of mine water discharge, by estimating increases in chloride (Cl) concentrations.

The solute transport model is based on an existing regional groundwater flow model, developed using MODFLOW6 (MF6) and the FloPy Python library. This approach allows a dynamic representation of groundwater-surface water interactions in both space and time, for both flow and solute transport. As part of this study, the regional groundwater flow model was adapted and imported into Groundwater Vistas 9 (GWV9) to provide a user-friendly modelling interface for the client. Solute transport capabilities were added to GWV9, to represent the evolution of chloride. This integration allows the model to be used as an effective predictive tool and ensures seamless compatibility with MF6, facilitating the efficient and straightforward implementation of management scenarios.

Modelling Framework

The study area is an abandoned underground coal mine, located below regionally important limestone and sandstone aquifers. Since the cessation of dewatering operations during post-closure, the mine has been facing natural mine water rebound, with highly saline waters with high concentrations of chloride.

The modelling work focuses on chloride, with a source concentration of 16,500 mg/L, assuming non-reactive behaviour. The study considers the following pollution source cases, as shown in Fig. 1 and Table 1:

- The risk of mine water rebounding into the limestone aquifer (overlying the coal unit) where the distance between mine workings and the base of the limestone aquifer is less than 50 meters, in locations A and B (see Fig. 1).
- Unused shafts as a source of contaminants into groundwater.
- Potential diffusion of contaminants throughout the entire mining block.
- The risk of artesian mine water discharge near the unused shaft, leading to overflow into the nearby river.

Four predictive scenarios were conducted, considering the discharge locations described above for different combinations of discharge rates per location, adding to a total of 28 L/s estimated for the considered worst-case scenario (see Table 1). The simulation of mine water rebounding into the limestone aquifer used injection well boundary conditions. For Scenario 4, the potential artesian mine water was modelled by introducing a direct inflow into the nearby river.

Flow and Solute Transport Modelling Workflow

Import of Regional MODFLOW6 Groundwater Flow Model into Groundwater Vistas

The regional groundwater flow model covers an area of approximately 7,000 square kilometres (km^2) and consists of four layers representing three geological units that sit above an underground coal mine. These geological units comprise mudstone (layer 1), sandstone (layer 2), and limestone (layers 3 and 4).

The regional groundwater flow model was imported into GWV9 using Python scripting based on the FloPy library. The hydraulic parameters from the original groundwater flow model were directly incorporated into the developed GWV9 model without any alterations.

In the GWV9 model, the surface water component is integrated within the model to simulate the dynamic interactions between surface water and groundwater. This integration allows for a coupled process where changes in surface water bodies, such as rivers and lakes, directly influence groundwater levels and vice versa. The model uses the Streamflow Routing (SFR) Package to represent these interactions, ensuring that

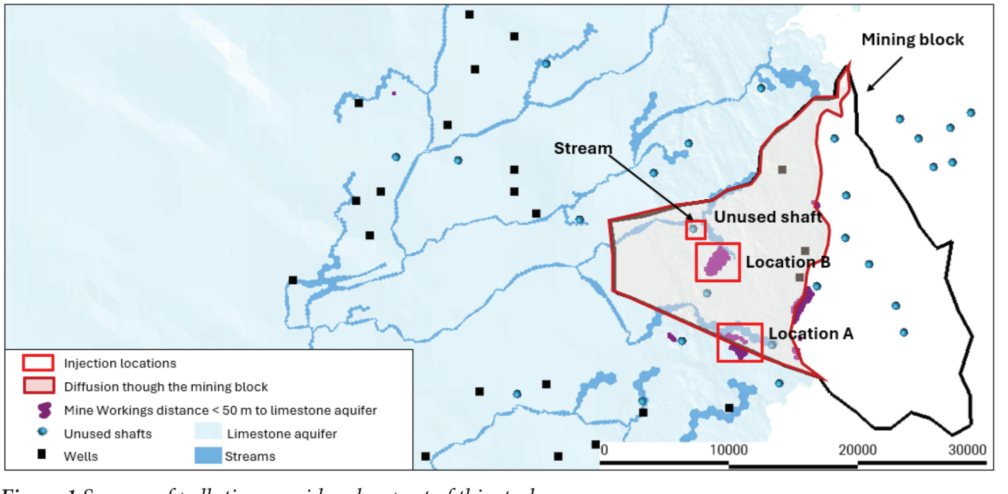

Figure 1 Sources of pollution considered as part of this study.

Table 1 *Mine water discharge per scenario.*

	Discharge location				
Scenario	Aquifer at Location A*	Aquifer at Location B*	Aquifer at unused shaft*	Artesian water into nearby river**	Re-infiltration artesian water**
Scenario 1 (28 L/s)	9.3 L/s	9.3 L/s	9.3 L/s	–	–
Scenario 2 (28 L/s)	–	28 L/s	0.0 L/s	–	–
Scenario 3 (28 L/s)	28 L/s diffuse throughout eastern mining area			–	–
Scenario 4 (28 L/s)	–	–	5 L/s	16.3 L/s	6.7 L/s

* See Figure 1.

** Scenario assumes artesian water moving as runoff into river, with a fraction re-infiltrating before reaching the river.

both surface water and groundwater systems are accurately simulated.

Implementation of Steady State Version of the Model

The developed transport modelling tool was configured to simulate 100 years under the mean annual conditions observed during 2009–2019. To achieve this, the developed GWV9 model was converted into a steady-state model by implementing the mean boundary conditions of the original groundwater flow model from 2009–2019. This steady-state model represents conditions at the beginning of the solute transport model. The piezometric heads generated by the developed GWV9 model were compared to the average annual heads from the original groundwater flow model for the same timeframe. This comparison revealed an almost identical match for the calibration targets, as illustrated in Fig. 2.

Implementation of Solute Transport Modelling

Solute transport capabilities were integrated into the developed GWV9 model, with transport porosities considered equal to specific yield values. Dispersivity values were derived from the study of Arriaza and Ghezzehei (2013), based on a potential plume dimension of up to 10 kilometres. The model employed a longitudinal dispersivity of 100 m, a transverse dispersivity of 10 m, and a vertical dispersivity of 1 m. Chloride was treated as non-reactive, with no consideration for sorption or degradation processes, and modelled as increase in concentration from a zero-background concentration.

To accommodate the solute transport modelling process within the current capabilities of GWV9, external modifications were required for specific MF6 packages. These include the Streamflow Routing (SFR), Streamflow Transport (SFT), Dispersion (DSP), and Iterative Model Solution (IMS) packages.

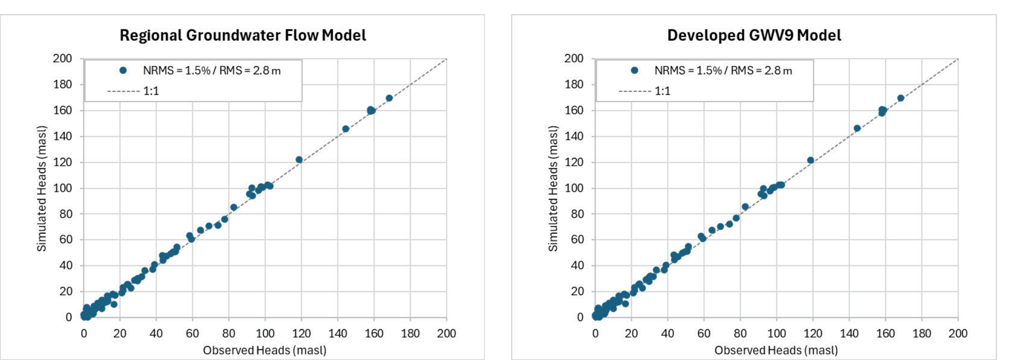

Figure 2 *Calibration results for the regional groundwater flow model period 2009–2019 (average) (left) and developed GWV9 model (right).*

Modelling Results

The chloride concentration results presented in Fig. 3, Fig. 4, Fig. 5 and Fig. 6 show increase of chloride concentrations in aquifers and streams relative to background levels, exceeding the standard drinking water limit of 250 mg/L set by the US Environmental Protection Agency (EPA) (1988). The simulation results indicate that for the considered worst-case scenario potential pollution from the mining block could affect the water quality of the overlying aquifers and nearby streams. Elevated concentrations are particularly noted in nearby streams for the artesian mine water discharge scenarios (Scenario 4) (Fig. 6).

According to the simulation results, mine water leakage from potential sources mainly moves through the limestone aquifer and streams, ultimately reaching potential receptors such as principal aquifers (limestone and sandstone), streams and rivers, and groundwater abstractions. In the mining area, the stream functions as a gaining stream, allowing contaminated groundwater to enter and cause surface water contamination. As contaminants travel along the streams, they can discharge

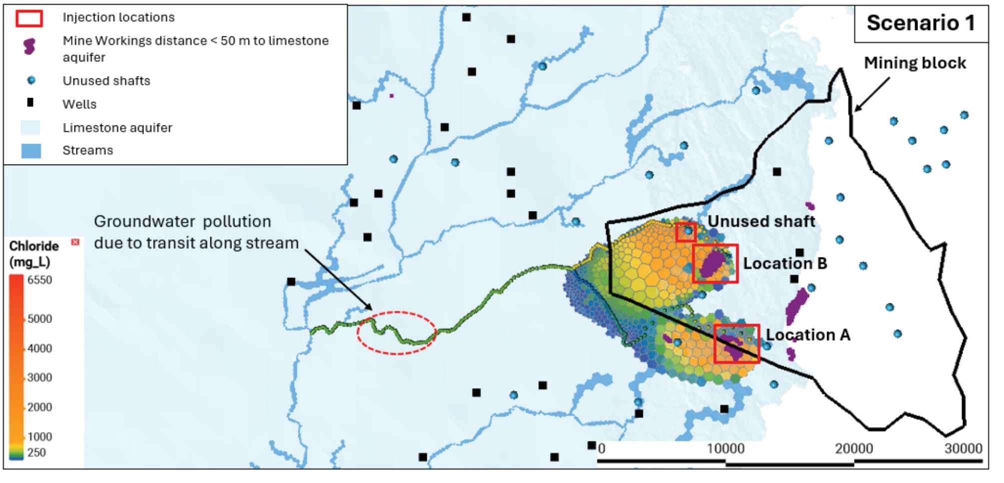

Figure 3 Simulated concentration results of chloride for Scenario 1, considering an inflow of 28 L/s into the aquifer equally distributed between Location A, B, and the unused shaft. Chloride source is 16,500 mg/L.

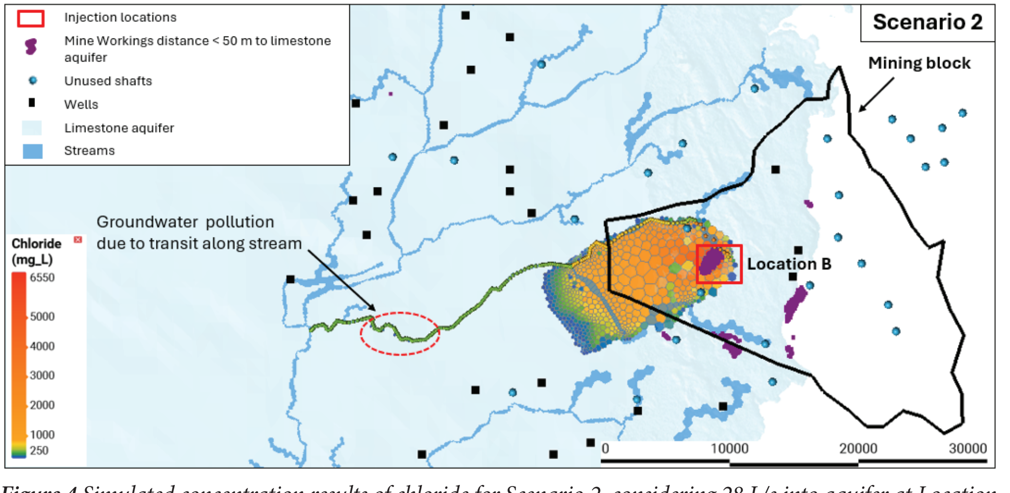

Figure 4 Simulated concentration results of chloride for Scenario 2, considering 28 L/s into aquifer at Location B. Chloride source is 16,500 mg/L.

into the aquifer downstream of the mining block, where the stream transitions to a losing stream. This results in the aquifer becoming contaminated as it receives polluted surface water. This interaction between groundwater and surface water is visible in Scenarios 2 (Fig. 4) and 4 (Fig. 6). It is crucial to highlight that modelling was based on mean annual conditions, and consequently concentrations could be higher during dry periods when flow conditions are low.

Conclusions and Recommendations

A summary of the solute transport modelling outcomes is presented below, including the main conclusions and recommendations.

- The model suggests that extensive regions of the aquifer and streams could be at risk of pollution if poor-quality mine water, which travels primarily through the limestone aquifer and streams, rises to levels where saline mine water discharges into the local and regional aquifers, either diffusely or from specific areas within the mining block above the coal unit.

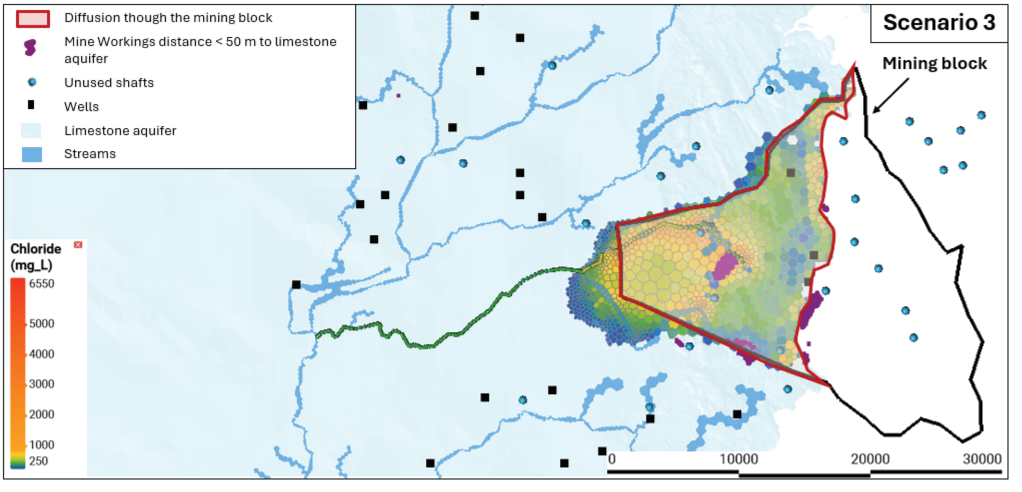

Figure 5 *Simulated concentration results of chloride for Scenario 3, considering 28 L/s into aquifer diffused across the eastern mining block. Chloride source is 16,500 mg/L.*

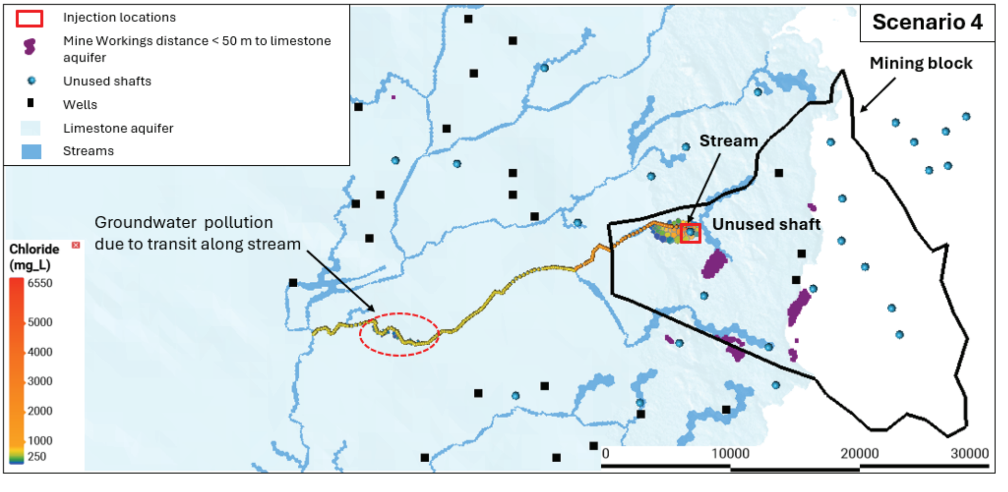

Figure 6 *Simulated concentration results of chloride for Scenario 4, considering 5 L/s into aquifer at unused shaft and 23 L/s of mine water as runoff into nearby river. Chloride source is 16,500 mg/L.*

- Substantial groundwater-surface water interaction is expected, where contaminants migrate from the aquifer into the stream and vice versa depending on the location and time of the year, with relatively fast travel times in the streams.
- The modelling results are based on mean annual conditions. Therefore, both groundwater and stream concentrations could be higher than predicted during low flow conditions. Thus, implementation of a transient version of the developed GWV9 model is recommended to be able to simulate seasonal variations of concentrations.
- The study is based on a theoretical scenario; thus, the modelling results do not reflect actual conditions. However, the simulations suggest severe potential consequences, necessitating the consideration of risk management measures, including monitoring and mitigation strategies.
- The developed GWV9 model was run as a deterministic model for each scenario, producing a single outcome based on the input parameters. Deterministic models do not account for variability or uncertainty. Conducting sensitivity analyses is recommended to understand the impact of key parameters and capture the range of possible outcomes and inherent uncertainties.

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