Assessing Different Coal Combustion Residue Scenarios in Opencast Coal Mines, Mpumalanga, South Africa

Annalisa Vicente[1], Jacobus Nel[1], Kelley Reynolds-Clausen[2]

[1]The Institute of Water Studies, University of the Western Cape, Private Bag X17, Bellville 7535, South Africa, 3345954@myuwc.ac.za, jmnel@uwc.ac.za

2 Eskom Holdings SOC, Research, Testing and Demonstration, Private Bag 40175, Cleveland, 2022, South Africa, reynolka@eskom.co.za

Abstract

This study assesses the flow and transport characteristics of backfilling opencast coal mines with coal combustion residues (CCR's), in order to assess its feasibility. Generic models were constructed to simulate six backfilling scenarios, which include: (1) No CCR's (2) CCR's above water table, (3) CCR's below water table, (4) CCR's in middle of pit, (5) CCR's down gradient, and (6) CCR's below weathered zone. Results indicate that all scenarios have the potential to contribute to a less negative environmental impact. This paper demonstrates the model setup and approach using Scenario 5 where a rise in water levels in the pit was achieved, reducing acid mine water generation and re-directing plume migration.

Keywords: Fly ash, coal ash, backfill, opencast coal mines, feasibility, flow and transport, effect

Introduction

South Africa relies heavily on coal to generate electricity and meet the countries energy demands (National Electricity Regulator 2004). The result of coal mining are numerous abandoned coal mines within the region of Mpumalanga, South Africa (McCarthy 2011). Several of the shallow underground mines have collapsed and most are discharging acid mine water (AMW), causing elevated contaminant concentrations in nearby surface and ground water bodies (McCarthy 2011). Additionally, the burning of coal for power generation produces large amounts of coal combustion residues (CCR's) annually (Reynolds-Clausen and Singh 2016), which are disposed of in holding ponds or landfill sites, with limited space. Therefore, there is a need to prevent AMD generation from abandoned mines, whilst consequently disposing of coal ash.

A proposed solution is to backfill opencast coal mines with CCR monoliths. Therefore, it is important to understand the hydraulic behaviour of CCR monoliths when disposed of in an opencast coal mining environment. However, limited studies have focussed on understanding this applications behaviour in order to assess its feasibility and determine whether this activity will have a positive, negligible or negative effect on groundwater quality. This study aims to address this gap by assessing the flow and transport characteristics of CCR's under numerous backfilling scenarios by achieving the following objectives: (1) To develop conceptual models of backfilling scenarios, (2) to determine the changes in the hydrogeological flow regimes, and (3) to identify changes in contaminant concentrations and plume migrations.

Methods

Generic transport models were constructed to represent the following CCR backfill scenarios in Mpumalanga, South Africa: (1) mine spoils only / no CCR's, (2) CCR's above the water table, (3) CCR's below the water table, (4) CCR's in middle of pit to the surface, (5) CCR's down gradient to the surface, and (6) CCR's below the weathered zone.

A three-dimensional MODFLOW USG control volume finite-difference grid was set up, consisting of 8 layers (10 meter thickness), 100 × 100 cells in each, with a 10 m cell size. All layers are flat, whereby the upper second and third layers (20 – 30 meters below ground level) attain a north and south general head boundary introducing a 10m flow difference. Drain boundaries are temporarily placed in the pit during the active mining phase to simulate mine dewatering. Additionally, drains were placed at the lower portion of the pit (discharge zone) to simulate mine water discharge. The mining pit is square in shape with a length / breadth of 300 m and a depth of 30 m. The total size of the square model spans an area of 80 000 000 m^2, with the opencast mine placed in the centre spanning an area of 90 000 m^2.

Hydrogeological properties

All hydrogeological properties are representative of the Witbank Coalfield in Mpumalanga (Hodgson and Krantz 1998; Bart and Sci 2008; Steyl 2011). The Witbank Coalfields comprise of four main hydrogeological units; the weathered, the primary unconfined, semi-confined and confined aquifers. The area receives 688 mm/annum with a recharge rate of 21 mm/a (3 %) (Kirchner 1991). A summary of the study site input parameters are presented in Table 1 on the next page.

Coal ash properties

The hydraulic conductivity of coal ash is known to decrease over time as it is exposed to moisture and oxygen (USEPA 1994). Two main local studies, conducted by October (2011) and co-researcher Johnson (2019), have formed the basis on which hydraulic conductivity values of coal ash in Mpumalanga are derived (Table 2). These hydraulic changes are accounted for in the model by using the function of 'time variant materials' within the MODFLOW-USG code. A summary of the coal ash numerical input parameters are presented in Table 3 on the next page.

Mine spoil properties

Mine spoils are extremely heterogeneous, varying in hydraulic conductivity over several orders of magnitude. Despite their heterogeneity, a general approximation of mine spoil hydraulic conductivity is 10-1 m/d (Hodgson and Krantz 1998). As the mine spoils age, levelled mine spoils become less permeable due to the decomposition of material, compaction and silting up of channels (Rehm et al. 1980). This is accounted for in the model by varying recharge rates throughout the mining cycle. Additionally, mine spoils contain pyrite minerals, forming acid mine water (AMW) when exposed to sufficient amounts of air and water (USEPA 1994). As AMW is the source of contamination in the model, it is simulated as a non-reactive SO4 concentration when mine spoils are recharged in conjunction to their respective mining phases (Table. 5). A summary of the mine spoils numerical input parameters are presented in Table 5 on the next page.

Results and Discussion

The conceptualization of practical CCR backfilling scenarios were made on the basis of preventing AMD formation, by either limiting the oxygenation or saturation of mine spoils. Resulting in the development of six backfill scenarios, which include backfilling with: (1) mine spoils only / no CCR's, (2) CCR's above the water table, (3) CCR's below the water table, (4) CCR's in middle of pit to the surface, (5) CCR's down gradient to the surface, and (6) CCR's below the weathered zone. All the simulated results were compared against backfilling with mine spoils only (baseline scenario) to evaluate the effect that CCR backfilling will have on opencast coal mines. This paper primarily focusses on scenario 5, which is presented in Figure 1.

Flow model results simulated water levels of 11.00 meters below ground level (mbgl) upon entering the pit and 14.00 mbgl when exiting the pit, creating a hydraulic flow difference of 3.00 m (Figure 2). Groundwater entering the pit experiences a 12.05 % rise in water levels in the upper portion of the pit. Groundwater flow is limited by the ash monolith, which due to its low permeability, forces water to flow around the ash monolith. Groundwater recharge over the ash monolith induces a perched water table of 4.28 mbgl and 10.06 mbgl for layers 1 and 2 respectively.

Solute transport results indicate that scenario 5 did not exhibit a southwards extending contaminant plume, but instead displayed a minor 50 m horizontal eastwards and westwards plume (Figure.

Table 1 Hydrogeological numerical input parameters

Hydrogeological Zone / Aquifer	Layer	Thickness (m)	Hydraulic Conductivity (m/day)	Specific Storage	Specific Yield	Porosity
Weathered	1	10	0.12	0.002	0.02	0.05
Unconfined	2 - 4	30	0.07	0.001	0.01	0.03
Semi-confined	5 - 6	20	0.05	0.001	0.01	0.03
Confined	7 - 8	20	0.004	0.001	0.01	0.03

Table 2 Coal ash variable input parameters

Mining stage	Hydraulic conductivity (m/day)	Recharge (%)
Backfill	0.8	10
10 years post-backfill	0.1	10
15 years post-backfill	0.01	8
100 years post-backfill	0.001	5

Table 3 Coal ash ***numerical input parameters***

Layer	Thickness (m)	Hydraulic Conductivity (m/day)	Specific Storage (1/m)	Specific Yield (m^3/m^3)	Porosity (m^3/m^3)	Recharge (m/a)
1 - 3	30	0.001 – 0.1	0.008	0.08	0.05	0.01 – 0.0002

Table 4 Mine spoil variable input parameters

Mining stage	Recharge (%)	SO4 Concentration (g/m^3)
Backfill	10	3500
10 years post-backfill	10	3500
15 years post-backfill	8	2000
100 years post-backfill	5	2000

Table 5 Mine spoil numerical input parameters

Layer	Thickness (m)	Hydraulic Conductivity (m/day)	Specific Storage (1/m)	Specific Yield (m^3/m^3)	Porosity (m^3/m^3)	Recharge (m/d)
1 - 3	30	1.1	0.02	0.2	0.25	0.01 – 0.0002

3). Consequently, reducing down gradient plume concentrations by 90.33 %, providing an improvement to the direct down gradient water quality, with an additional lateral spreading of the plume into the adjacent aquifers.

Conclusions

It has been concluded that all modelled CCR backfilling scenarios provide a less negative environmental impact, improving groundwater quality discharging from opencast coal mines. The benefits provided by the more favourable scenarios include: 1) increase in pit water levels keeping larger volumes of mine spoils saturated, thus reducing the formation of AMD; and 2) management of water levels to retain and direct the contaminant plume within the pit, thus directing plume migration to increase management options, and 3) reducing recharge in areas where CCRs are exposed to the surface, thus reducing total volume of water in the system.

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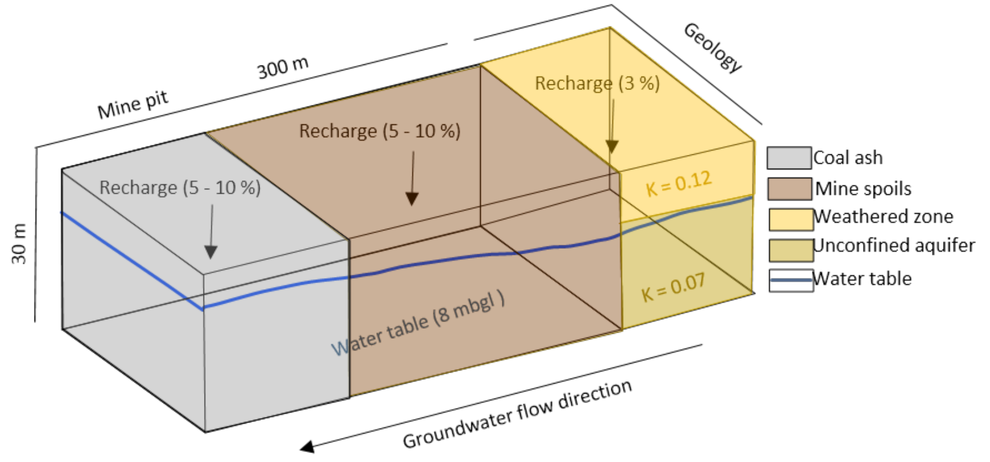

Figure 1 *Conceptual model of scenario 5*

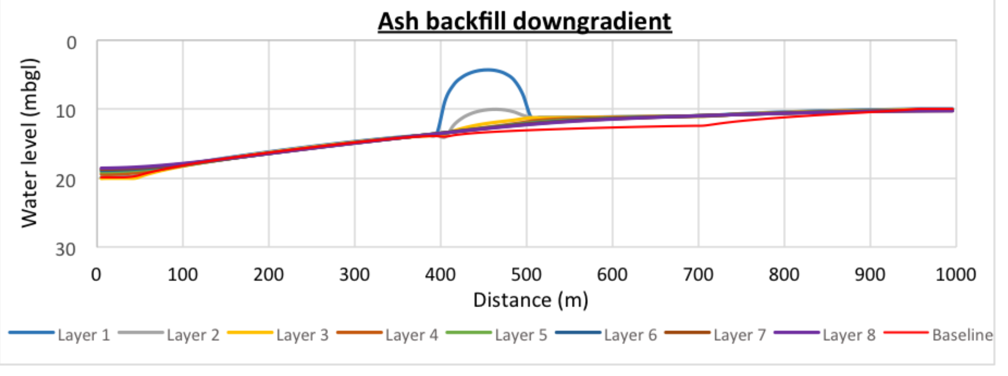

Figure 2 *Simulated water levels of scenario 5*

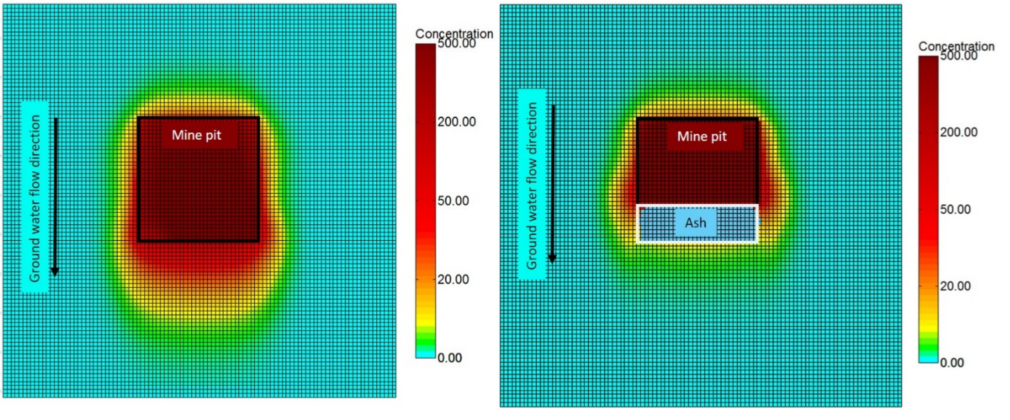

Figure 3 *Comparative contaminant plume results of the baseline scenario (left) and scenario 5 (right)*

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