Post-Mining Hydrogeology of Underground Collieries – Effects of Hanging Wall Subsidence

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Abstract

Underground mining-related hanging wall subsidence and collapse have been shown to notably affect overlying aquifer hydraulic properties. These areas commonly fill with rubble due to progressive collapse with pervasive fracturing throughout the subsidence zone that is likely to reach surface. Post-mining hydraulic heads equilibrate between areas, via interconnected underground mining voids. This often results mine water discharge from low-lying subsidence zones, which was previously not accounted for and when omitted from numerical modelling, produce inaccurate calculations. Based on these findings, the incorporation of the hydraulic properties of subsidence zones in numerical flow models is considered critical.

Keywords: Subsidence, Hydrogeology, Numerical Modelling, Mine Water, Discharge

Introduction

Historically, mining related subsidence has been excluded from the conceptual hydrogeological understanding of decommissioned collieries in South Africa. It was commonly assumed that remedial actions to support hanging walls after closure of underground collieries in the country would be implemented successfully. However, based on surface observations using LiDAR at various underground collieries around the Secunda area in South Africa, hanging wall subsidence is currently taking place, and is predicted to continue in future. Observed subsidence is due to progressive failure of hanging walls from the mining void upwards (Van der Merwe, 2018). This is likely due to the absence of roof support within the mining void, or unsuccessful support methods employed (Canbulat *et al.*, 2005). Van der Merwe (2018) identifies four types of hanging wall failures including subsidence caused by high-extraction mining, pillar failure, progressive roof collapse and sub-surface erosion. For the purpose of this study, the focus was directed to progressive roof collapse. Canbulat *et al.* (2018) describe this process as the gradual collapse of material from the immediate roof of the mine, termed the goaf area, progressing upward towards the surface. This progressive failure forms a cavity that is filled with rubble over time, partially attributed to material bulking, and the progression of the cavity is eventually choked at the intersection of the caving angles in the overlying strata, which could reach surface in shallow mining areas (Van der Merwe, 2018). Associated with this process is deformation of strata above the roof collapse area and changes in permeability throughout the collapse zone. According to the work of Tammeta (2015) this results in increased hydraulic conductivity in the collapsed and deformed strata. Throughout the collapsed zone, hydraulic conductivity is raised by approximately 3 orders of magnitude, with hydraulic conductivity increasing by 1 to 2 orders of magnitude in the overlying deformed zone. Based on the stress vectors in the strata, and by implication, this also raises the vertical hydraulic conductivity of the collapsed zone and the overlying deformation zone.

Assuming the underlying mining void is not compartmentalised by underground mining seals, the mining void, along with roof collapse zones, becomes a continuous hydraulic conduit. Subsequently, overlying topography becomes the main control on hydraulic head distribution, rather than coal seam geometry. Additionally, subsidence areas are likely to cause ponding on surface with elevated recharge entering the mining void, along with increased inflow from the overlying aquifer through collapse zones. These circumstances therefore become pertinent to the numerical flow modelling of the mine flooding process, as well as the calculation of potential mine water discharge areas. This study focuses on the incorporation of the hydraulic properties of collapsed hanging wall areas into numerical groundwater models. Incorporation of these hydraulic properties addresses the above-mentioned collapse zone omission and explains variations in modelling results.

Methods

Available data for the underground colliery investigated were collated to create a conceptual understanding of the flow mechanics of the aquifer-collapse zone-mining void system. A review of groundwater levels was conducted to understand the variation in hydraulic head between the mining void, the overlying aquifers and the collapsed subsidence zones. Hydraulic testing data ifrom pump tests were evaluated and sourced from Tammeta (2015) to understand the localised hydraulic parameter variations within- and above collapse zones. This included various storativities. Rainfall data was sourced from the South African Department of Water and Sanitation, with recharge calculations performed using the chloride method. For subsidence areas, the work of Hodgson and Krantz (1998) was consulted to identify reasonable recharge rates. Geological logs from local exploration boreholes were supplied by the mining operation, elucidating the local geology and structural discontinuities. Local rivers and streams were identified as constant head boundary conditions for numerical flow modelling purposes. Information described above was compiled into a conceptual model which was translated into a numerical flow model (Fig. 1).

Based on the available information, the numerical model construction can be described as follows:

A three-dimensional numerical model was employed to simulate stresses to the aquifer system in both a spatial and temporal context. The finite element 3D-modelling package FEFLOW 7 was used. Boundary conditions were selected to coincide with physical hydrogeological boundaries such as watersheds and local streams. The model mesh consists of 3315936 mesh nodes and 3529130 mesh elements. Recharge to the aquifer in undisturbed areas was specified as 0.00005 m/d while recharge to subsided areas was specified as 0.0002 m/d. Undisturbed hydraulic conductivity of the fractured rock sedimentary aquifer was specified as 0.0035 m/d based on hydraulic testing data, with the hydraulic conductivity of collapsed areas specified as 3 m/d and overlying deformed

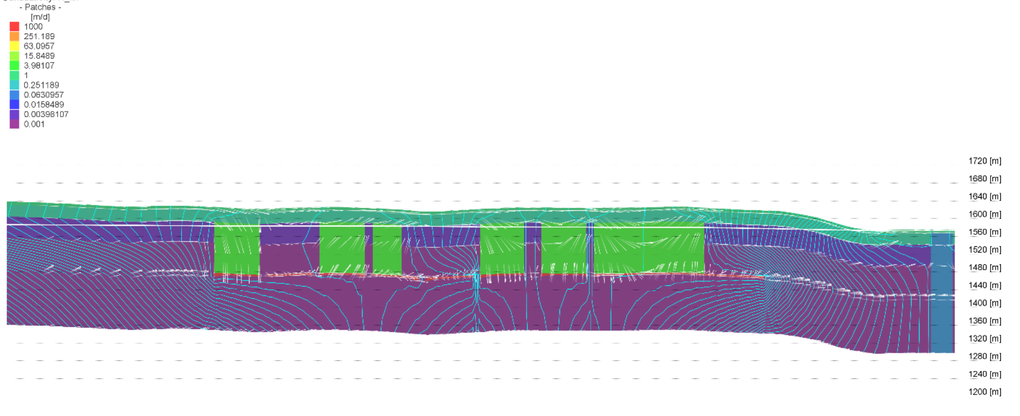


Figure 1 Conceptual cross-section illustrating groundwater flow in the mining void-collapse zone-aquifer system

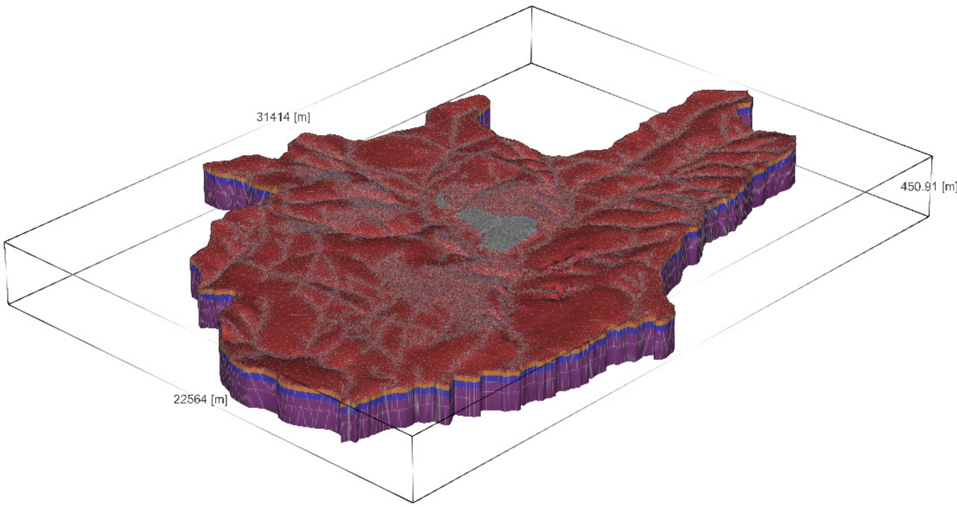


Figure 2 *Numerical model mesh pre-mining*

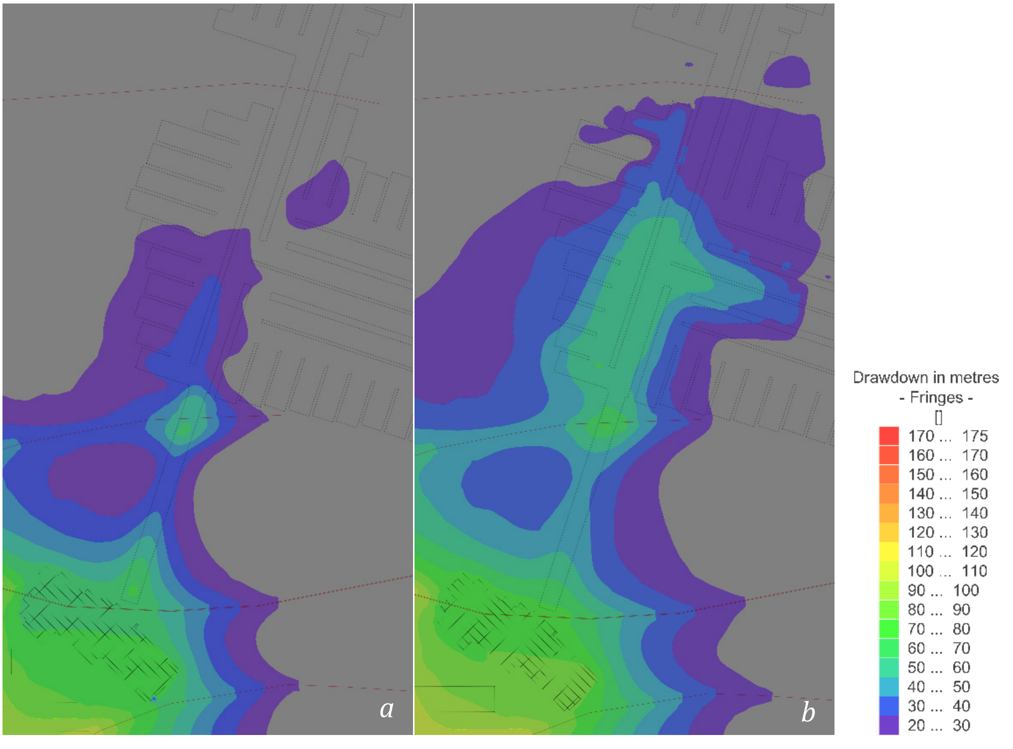


Figure 3 *a) Drawdown during mining excluding hanging wall subsidence b) Drawdown during mining including hanging wall subsidence*

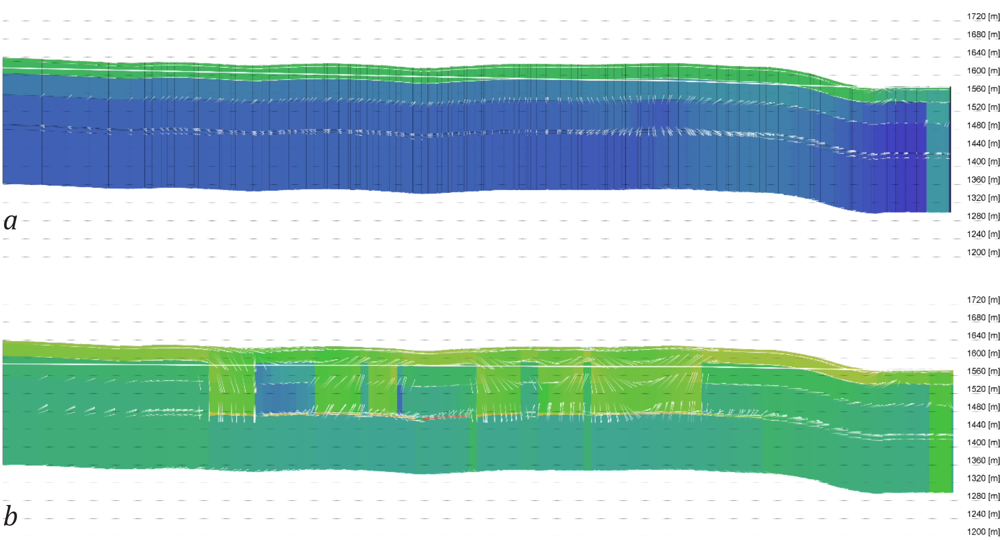
strata as 0.35 m/d. The model included 11 layers to account for vertical refinement with constant head boundaries specified at surface in the local streams, along with a maximum head elevation constraint. The calculated hydraulic heads for the pre-mining situation were compared to hydrocensus information (Fig. 2).

Upon completion of the numerical model construction and -calibration, flooding of the mining void was simulated for two scenarios. These included a scenario where the hanging wall remained intact, and a scenario where multiple hanging wall collapse zones formed after mining. Additionally, a comparison of the mine water discharge areas and volumes was also performed.

Results and Discussion

Model results showed a notable variation in drawdown between the model including collapse zones, when compared with the model including an intact hanging wall (Fig. 3). Calculations illustrate a much larger inflow volume into the mining void in the model including collapse zones. Additionally, the drawdown was much more evident in the model including the collapse zones during the operation of the underground mine. This is due to the elevated hydraulic conductivity of the collapsed zones. When comparing the models calculating post-mining conditions, it is evident that the model containing collapsed hanging wall zones showed a regional lowering of the phreatic surface at higher elevations. Mine water discharge was calculated to take place into the local streams through the soil profile at relatively lower elevations, with a loss of baseflow to streams at relatively higher elevations in the model. Furthermore, a hydraulic linkage, via the underground mining void, was calculated to be present between collapsed hanging wall zones, subsequently equilibrating hydraulic heads between mining panels. Therefore, flow in collapsed zones was calculated to be downward in areas with relatively higher surface elevations and upward in areas with relatively lower surface elevations. A return to the pre-mining flow field after closure can be observed in the graphical illustration of the model calculations including an intact hanging wall above the underground mine workings (Fig. 4).

The implication of these findings is that collapsed hanging wall zones and the associated subsidence have a notable effect on aquifer hydraulics and resulting hydraulic heads post-mining, which cannot be ignored. If the mining void is not compartmentalised by high-pressure seals, a linkage between collapsed zones will likely form. This leads to a flattening of the phreatic surface between these zones with head elevation decreases



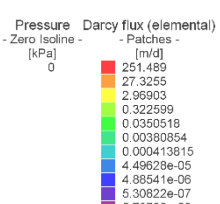


***Figure 4** a) Flow directions and groundwater flux after mine flooding and excluding hanging wall subsidence b) Flow directions and groundwater flux after mine flooding and including hanging wall subsidence*

in relatively higher topographic elevations and head elevation increases in relatively lower topographic areas. Therefore, mine water discharge is not limited to unsealed drill holes, adits or shafts, but can occur as diffuse seepage through the soil profile in subsidence zones in relatively lower topographic elevations, depending on the head distribution. This is also evident in haulages where deformation and collapse are pervasive throughout the mining panel, as described by Van der Merwe (2018).

Conclusions

As hanging wall subsidence in South African underground collieries has recently become a better understood phenomenon, the subsequent effects relating to post-mining hydrogeology have also become clearer. This study illustratesthat hanging wall subsidence and collapse zones form conduits of elevated hydraulic conductivity to surface and influence aquifer hydraulic properties. The incorporation of the changes in aquifer hydraulic parameters into numerical flow models have shown significantly different results to models excluding hanging wall collapse and subsidence. This has implications for the calculation of mine water discharge areas and volumes, as well as inflows to the underground mine during operation. This study illustrates the equilibration of hydraulic heads between hanging wall collapse zones after mine flooding via connected underground mining voids. Mine water discharge areas are thus likely to form through low-lying subsidence zones, rather than being limited to anthropogenic conduits. Therefore the quantified understanding of hanging wall subsidence should be included in numerical modelling calculations to improve accuracy and subsequently, mine water management.

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