The Water Balance of South African Coal Mines Pit Lakes

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Abstract

Pit lakes form in open cast mines which extend below the groundwater level, after dewatering stops. Groundwater levels are disturbed during mining and associated dewatering operations. The information presented in this paper serves to determine if pit lakes are an environmentally stable/ viable solution for South African coal mines after closure.

Pit lake water balances to approximate the final water volume and rest water elevation were constructed with the use of a Goldsim program. Two case studies of South African Coal Mine Pit Lakes will be discussed;

- The first study area is a standalone pit lake located in the Waterberg Coalfield and no backfilled has been used in attempt to close the final void; and
- The second study area consists of a series of 7 pit lake (of which only 4 are investigated for this study) associated with a single mining operation and is located in the Highveld Coalfield. Some portions of the mine have been rehabilitated.

Both study areas are located in climatic settings where average annual rainfall exceeds mean annual evaporation. Pit lake water balance modelling demonstrates that both study areas operate as terminal sinks, with the great evaporation potential keeping the pit lake water levels below discharge points. Climate plays an important role in understanding the key drivers of the pit lake water balance and therefore extreme weather conditions to address the effects of wet and dry scenarios were applied to the models to determine if the pit lakes would result in mine water discharge during wet weather events.

The net losses or gains of the pit lakes were determined from stage curves which were based on the bathymetric survey of each pit lake. While the accuracy of the water balances is dependent in the accuracy of the input parameters, a limitation to the water balance modelling is gaps in the data. Water balance modelling is applied to determine the behaviour of the coal mine pit lakes under investigation and their potential for mine water overflow.

Keywords: Pit Lakes, Water Balance, Closure Option

Introduction

A water balance model is described as an accounting for the volume of water flow rate from all probable sources (Gholamnejad, 2008). The final pit lake volume is influenced by a range of factors such as rainfall, evaporation, hydrogeology and the pit geometry. Water balance models are generally based on the law of conservation of mass which states that whatever water enters the storage should equal to the water stored or released from storage. In its simplest form, the equation may be written as:

$$\text{Inflow} = \text{Outflow} \pm \Delta\text{Storage}$$

The aim of the present study is to develop water balance models for South African Coal pit lakes, to increase understanding of the pit lake hydrology before concluding whether or not pit lakes are an environmentally suitable method for South African open pit coal mines. Depending on the components of the pit lake water balance, it may take several years before equilibrium state is reached (ÜNSAL, 2013). Calculations are conducted to determine the behaviour of the pit lakes over a predictive period of 20 years (2018-2038).

Pit lakes in semi-arid climatic settings are usually classified as ‘flow-through’ or ‘terminal sinks’ (McCullough et al., 2013). Once mining stops, groundwater levels rebound and together with rainfall and runoff, contribute to fill the final void. Terminal sinks may form in arid environments where the potential evaporation is higher than the mean precipitation and the pit lake water elevation is below the surrounding pre-mining groundwater level (Niccoli, 2009). If the pit lake water level reaches the pre-mining groundwater elevation and water is released into the aquifer as groundwater seepage, the pit lake is classified as a ‘flow-through’ (McCullough et al., 2013).

Figure 1 shows the locations of the areas under investigation. Each study area demonstrates unique hydrogeological conditions and therefore, conceptual models were constructed separately.

Methods

Climatic data for input were obtained from Water Resources of South Africa database (WRC, 2015). Aquifer parameters were obtained by means of constant drawdown test, which involved the abstraction of a measured volume of water from a borehole whilst the water levels are recorded. Pump test data was analysed using the Jacob-Cooper solution.

Runoff coefficients suggested by (Hodgson and Krantz, 1998) were applied to the runoff calculations using the equation provided by (Castendyk, 2009) which is as follows:

$$Q=CIA$$

Where Q is the runoff inflow volume, C is the runoff coefficient, I is the total precipitation and A is the area over which runoff occurs.

(Marinelli and Niccoli, 2000) provides a set of analytical equations for groundwater inflow to a cylindrical pit (used to estimate flow to Pit Lake A), as follows:

$$Q_1=W\pi\,(r_0^2-r_p^2)$$

Where Q_1 is the inflow from the pit walls, W is the recharge flux, r_0 is the radius of influence, and r_p is the radius of the pit lake.

Groundwater inflow through the pit bottom is given by the equation:

$$Q_2 = 4\times r_p \times (K_{h2}/m_2) \times (h_0 - d);\ m_2 = (K_{h2}/K_{v2})^{1/2}$$

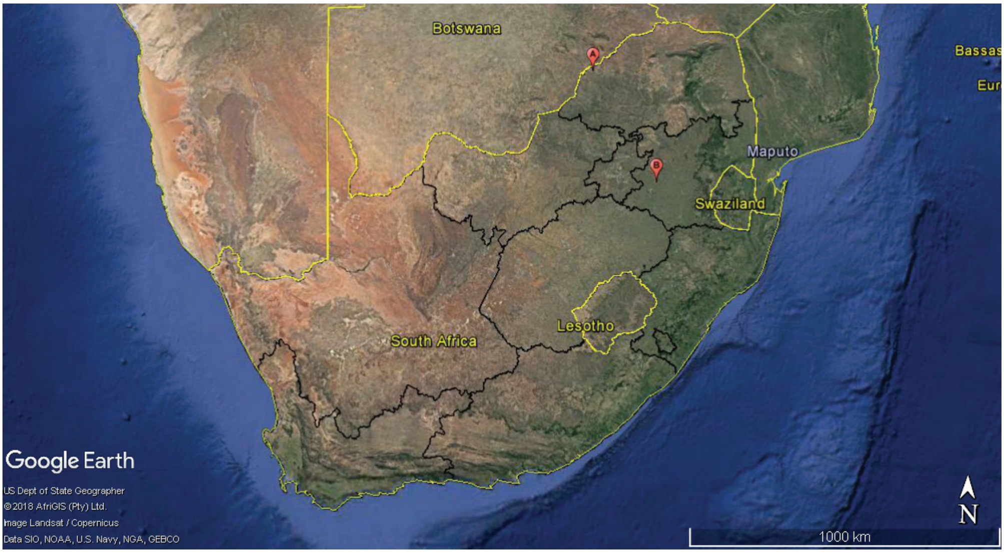

Figure 1 Locality map of study areas

Where r_p is the radius of the pit lake, K_{h2} and Kv2 are the hydraulic conductivity for the materials below the confining layer, h_0 is the pre-mining groundwater level and d is the pit lake depth.

The Dupuit-Forchheimer analytical equation given below was used to estimate groundwater inflow to Pit Lake B:

$$Q_g = \pi.K\,(h_0^2 - h_w^2)/\ln\,(r_0/r_w)$$

Where K is hydraulic conductivity (m/d), h_0 is the pre-mining groundwater level (m), h_w is the depth of the pit lake (m), r0 is the radius of influence (m) and r_w is the radius of the pit lake (m).

(Singh and Atkins, 1985) suggests the usage of an equation given by (Mansur and Kaufman, 1962) to calculate the radius of a rectangular open pit:

$$r = (2/\pi) \times (Y.W)^{1/2}$$

Where Y is the length of the open pit, W is the width of the open pit and r is the equivalent radius of the mine. This equation is applied to Pit Lake B to account for the irregular shape.

The conceptual models were constructed from all available information, including borehole logs, to graphically illustrate the hydrogeological factors affecting the open pits. Water balance models were developed with the use of Goldsim Academic version to account for the volume of water in the pit lakes and to predict future pit lake water levels and volumes over wet and dry scenarios.

Models were run under probabilistic simulations using the Monte Carlo approach with 50 realizations. Rainfall was modelled as a stochastic element, assuming a gamma distribution. This simulation approach was used with intend to account for uncertainty and incorporate variability (McPhail, 2005).

Case Study 1

Pit Lake A is situated in the Waterberg Coalfield of South Africa, and formed as a result of bulk sample excavation. The total volume of the pit lake is approximately 101 99 00 m^3. Mining started in 2009 and ended in 2010, after which the final void filled with water. Main facilities of the mine consists of the open pit of approximately 90 m depth, with a waste rock storage area located southwest of the open pit. Groundwater flow is towards the Limpopo River, in a north easterly direction. The area experiences mean annual precipitation of 438 mm and an average potential evaporation of 1950 mm/a. The Waterberg Coalfield is classified as an arid climate area. Topography of the area is naturally undulating, dipping gently towards the Limpopo River. Geological setting of the area consists of the complete Karoo Supergroup succession with coal-bearing zones present in the Vryheid and Grootegeluk Formations of the Ecca Group.

Figure 2 illustrates the components of the water balance model take into consideration during calculation. The topography of the area is fairly flat and therefore runoff is minimal. Runoff from in-pit slopes is however, expected to affect the water balance as the slopes are more compacted compared to the topsoil.

Pit in-filling time series data which has been monitored from the time of closure was

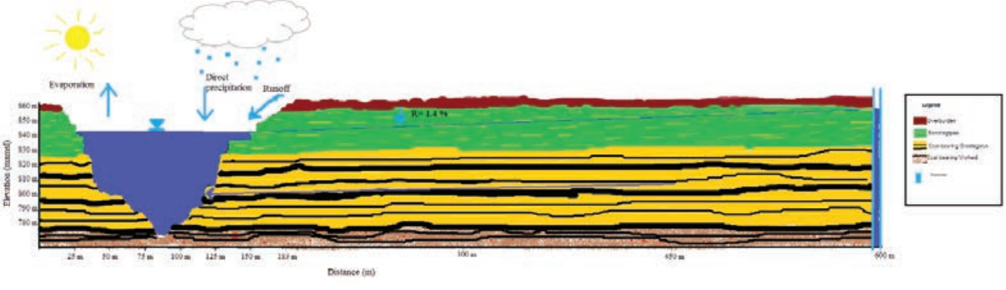

Figure 2 Pit Lake A Conceptual Model

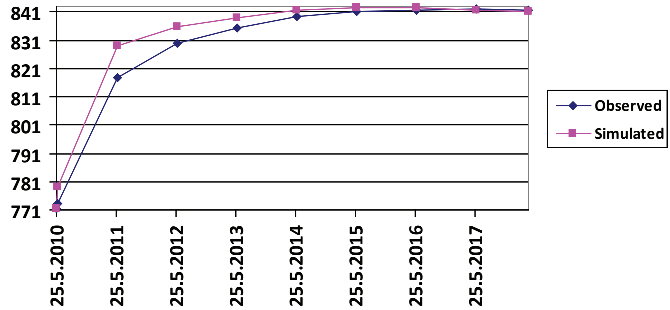

Figure 3 *Simulated vs. Observed pit lake water levels*

Table 1. *Water balance summary for Pit Lake A*

Runoff (m^3)	Rainfall (m^3)	Groundwater Inflow (m^3)	Evaporation (m^3)	Volume of water in pit lake (m^3)	Percentage Filled (%)
14066	58896	644384	218087	499259	49

used to calibrate the model and Figure 3 compares the simulated pit lake elevation results determined using the most probable scenario and the observed pit lake elevation. A 98% correlation exists between the simulated and observed results.

Table 1 below is a summary of the cumulative volumes of water which has contributed to the current balance of water in the pit lake. Groundwater accounts for. 90% of the total volume contribution. Rainfall and Runoff account for 8% and 2% respectively.

Wet case scenario shows that the volume of water in the pit lake could reach 549 580 m^3 at an elevation of 844 mamsl, while the dry case scenario shows that the volume of water in the pit lake could reach 455 577 m^3 at an elevation of 838.5 mamsl.

Case Study 2

Pit Lake B is situated in the Highveld Coalfield of the Mpumalanga Province of South Africa. Seven pit lakes are present at this site which is partially backfilled and rehabilitated. Two streams are within the vicinity of the mining area, serving as the lowest elevations for surface drainage. Geologically, the study area is underlain by a thin sequence of Dwyka and Middle Ecca strata lying on an undulating floor composed of felsites, granites and diabase associated with the Bushveld Complex (Buchan et al., 1980). The coal bearing zone is approximately 70 m thick with five coal seams. Mean annual precipitation value for the catchment is 671 mm and average annual evaporation is 1600 mm.

Figure 4 demonstrates the conceptual model for the Kriel site where material has been backfilled into the open pit in an attempt to close the void. However, the pit lakes remained as final voids after backfilling. Areas near the streams where not mined, these areas are represented by the undisturbed Karoo strata as illustrated. Information regarding the undisturbed geology were obtained from borehole geological logs.

Final pit lake voids are of varying sizes and ages. Properties of the pit lakes were determined from analyses bathymetric surveys. Points at which mine water will overflow to the surface were modelled using the digital elevation model of the mine area surface and pit lake bathymetries. Global Mapper version 13 was used to simulate water level elevations to the points where overflow would occur.

No in-pit filling data were available for Pit Lake B, however, simulated results were compared to LiDAR elevation data which was only recorded from 2013. Table 3 shows is a summary of the cumulative volumes of water which have contributed to the current balance of water in the pit lakes.

The rest water elevation of the pit lakes at the time of reporting was 1536 mamsl, which is also assumed to be the water elevation in the backfilled material. Extreme wet weather conditions could potentially cause the pit lakes to overflow.

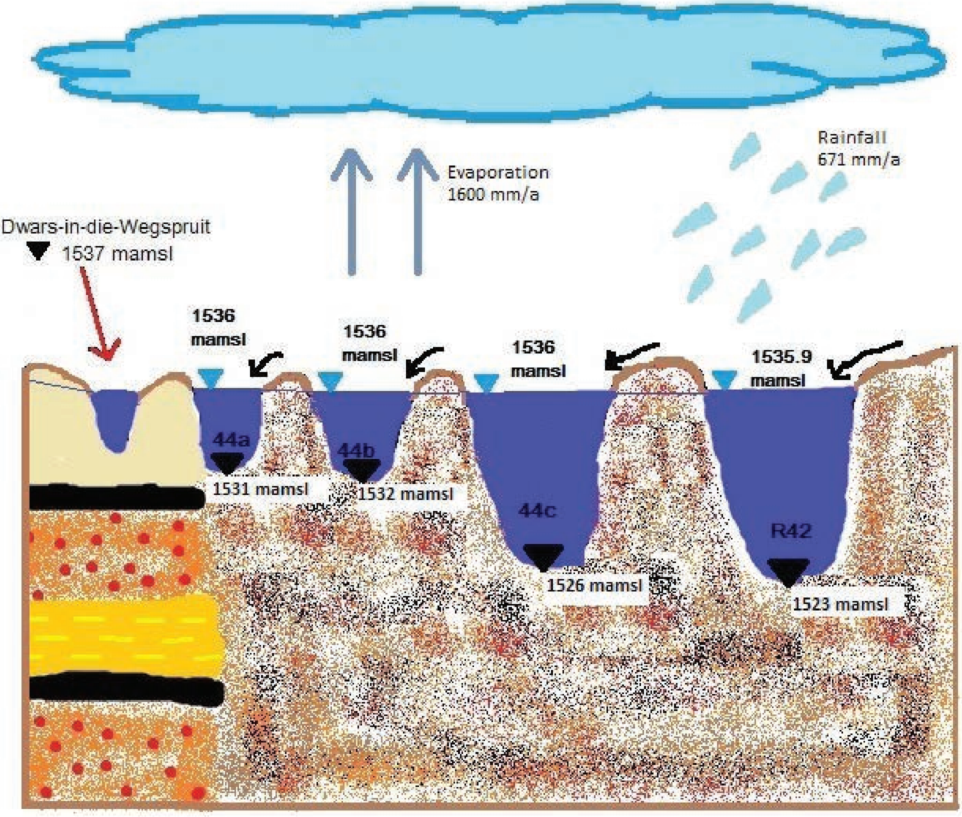

Figure 4 Pit Lake B Conceptual Model

Table 2. Geometrical properties of the pit lakes

Pit Name	Age (years)	Depth (m)	Total Volume (m3)	Point of Overflow(mamsl)
44a	13	6	424932	1537
44b	13	5.4	96687	1537
44c	13	10.5	202428	1537
R42	13	13.1	356489	1537

Table 3. Water balance summary for Pit Lake B

Pit Name	Groundwater Inflow (m^3)	Rainfall (m^3)	Runoff (m^3)	Outflow (m^3)	Volume achieved (m^3)	Percentage filled
44a	1108000	1100000	245795	2198000	255713	60
44b	222846	344601	187817	687884	67379	70
44c	250828	236866	146460	472094	162060	80
R42	564644	400940	86477	724813	327268	92

Conclusions

The pit lakes may be classified as terminal sinks due to the resultant negative balance. Pit Lake B would require management for water level elevations to avoid the risk of overflow. It is unlikely that Pit Lake A will overflow.

(Westcott and Watson, 2007) suggests the evaluation of features such as geology, bathymetry and water balance before deciding on a closure option. Pit Lake A may be considered for recreational (i.e. boating and diving) due to it great depth. Pit Lake B is shallow in depth, and easily accessible. An advantage for livestock to access water without any major engineering work required. There is a potential for farm fishing as fish have been identified at both sites.

For the improvement of results, it is recommended that measurement of site specific data such as rainfall and evaporation; and daily pit lake water levels be monitored especially for Pit Lake B. Based on the analysis of available data and constructed models, the hydrogeological systems of the pit lakes under investigation are expected to remain terminal sinks.

Acknowledgements

The authors wish to thank the Water Research Commission for funding the project and Anglo American Inyosi Coal: Kriel Colliery and Sasol Mafutha where the studies were conducted.

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