



# Are pit lakes an environmentally sustainable closure option for opencast coal mines?

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## Synopsis

The aim of the study is to determine if pit lakes are a sustainable coal mine closure option in South Africa. The water balance, chemistry, limnology, and bacterial population of three selected pit lakes were investigated. The lakes are in the three major coal basins of South Africa and are associated with different lithologies and mining methods. The major factors driving the water balance of the pit lakes are direct rainfall, runoff, inflow from old mine workings, and groundwater infiltration, with the major losses being evaporation or discharge onto surface. The study indicated that pit lakes can be designed as 'terminal sinks' to provide a sustainable mine closure option. The pit lakes sampled have an alkaline pH, and mostly a sodium/calcium sulphate water with total dissolved solids content of less than 3000 mg/l. The phytoplankton and microbiological data indicates that the pit lakes support aquatic life. The study shows that correctly designed pit lakes can be an environmentally sustainable closure option for South Africa's coal mines. A suggested design manual has been developed to assist mine owners and regulators in developing sustainable coal mine pit lakes as a closure option.

## Keywords

coal mine, pit lakes, water quality, water balance, mine closure.

## Introduction

Coal mining started in South Africa in the early 1800s, initially by conventional underground methods, but since the 1950s the majority of the coal production has been from opencast operations. Coal supplies 95% of South Africa's power needs and will probably continue to do so through the first half of the 21st century. In addition, South African coal production for export and domestic non-power generating purposes is estimated to be 150 Mt/a.

Opencast coal mines generally leave a final void due to the mining method, or insufficient overburden to fill the void left by mining, or as a water management strategy. When the mining operations cease, the void fills with water and forms a lake, which is generally referred to as a 'pit lake'. The author estimates that there are over 120 pit lakes in the three major coalfields, namely the Witbank, KwaZulu-Natal, and Waterberg coalfields. This study evaluates the environmental sustainability of using pit lakes as a closure option for coal mines in South Africa. The current South African mining and environmental legislation states that in order for a mine to achieve closure, all pit lakes should be backfilled.<sup>1</sup>

The major factors that determine the environmental sustainability of a pit lake are the water balance and quality. A positive water balance results in discharge from the pit lake onto the surface. A further consideration for environmental sustainability is the chemical and biological nature of the water. Pit lake water quality varies depending on the geology, mining method, and catchment characteristics. In general, pit lake water quality may not comply with legislated catchment water quality standards. This investigation considered three pit lakes with the focus on the two major drivers of pit lake sustainability, namely water quality and water balance.

The pit lakes studied were selected on the basis that they are representative of the three major South African coalfields, considering differences in geology and climatic conditions. The factors affecting pit

<sup>1</sup>See list of references for applicable legislation

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lake water balance (and as a result the variation in water level) are groundwater, direct rainfall, and runoff, while the losses from the pit lakes are evaporation, surface discharge, and flow into the surrounding aquifers. The water balance of each of the pit lakes was evaluated to determine the major inputs and losses. The major inputs were identified as groundwater from either the aquifer or backfilled material, and the major loss was evaporation. Pit lake morphology, volume, and surface area are the major design considerations to prevent discharge of lake water into the catchment.

The chemical and biological evolution of the water quality determines the long-term ecological sustainability of pit lakes. The inorganic chemistry study concentrated on the water quality and vertical stratification. The vertical variation in pH, temperature, dissolved oxygen, and redox potential was measure on a systematic basis in each of the pit lakes. The biotic study investigated the phytoplankton, chlorophyll-a, and the microbiology of each of the lakes.

The waters in the pit lakes are alkaline and have elevated total dissolved solids (mainly calcium sulphate) compared to the ambient surface and groundwater. The pit lakes support life in the form of chlorophyll-a, phytoplankton, microorganisms (bacteria), vegetation, and aquatic life.

A fundamental change in thinking and legislation is required for pit lakes to be accepted as an environmentally sustainable closure option for South African coal mines. This will prevent uncontrolled discharge from opencast mining operations and avoid the expense of ongoing water treatment and associated impacts. Correctly designed pit lakes offer an environmentally sustainable closure option for opencast coal mines in South Africa. Sufficient data was collected in the study to develop a guideline for the design of coal mine pit lakes in the Southern African coalfields. The manual considered the water balance of the pit lakes and the biological and chemical processes that drive the water quality.

### Pit lake water balance

Pit lake water balances in South Africa are largely controlled by evaporation, as evaporation exceeds precipitation by a factor of 2 to 3. As a result, if the inflow into a pit lake is managed it is unlikely that it will discharge onto surface and into the catchment. The water balances of the pit lakes were calculated based on a generalized mathematical expression (after Gammons *et al.*, 2009):

$$\Delta S = (P + SW_{in} + GW_{in}) - (E + (T) + SW_{out} + GW_{out})$$

where

$\Delta S$  is change in storage, which is the volume of water in the lake

$P$  is the precipitation falling onto the pit lake

$SW_{in}$  is the sum of any surface water inputs, which includes runoff and diverted streams

$GW_{in}$  is groundwater entering the lake

$E$  is the evaporation from the lake

$T$  is plant transpiration, which is often negligible

$SW_{out}$  is surface water leaving the pit lake, and includes pumpage

$G_{out}$  is the groundwater leaving the pit lake

$SW_{in}$  can be managed by minimizing runoff into the pit lake.  $GW_{in}$  can be minimized (by allowing groundwater levels to rebound) so that evaporation will exceed the sum off all inflows into the pit lake and the lake will act as a water sink.

### Pit lake water quality

A major consideration is the final pit lake water quality on closure of a mine. This affects the environmental classification and as a result the environmental sustainability of the lake. Conceptual models of pit lake geochemistry are described by external and internal processes, with many of the internal processes being mediated by algae and microbes (Gammons *et al.*, 2009).

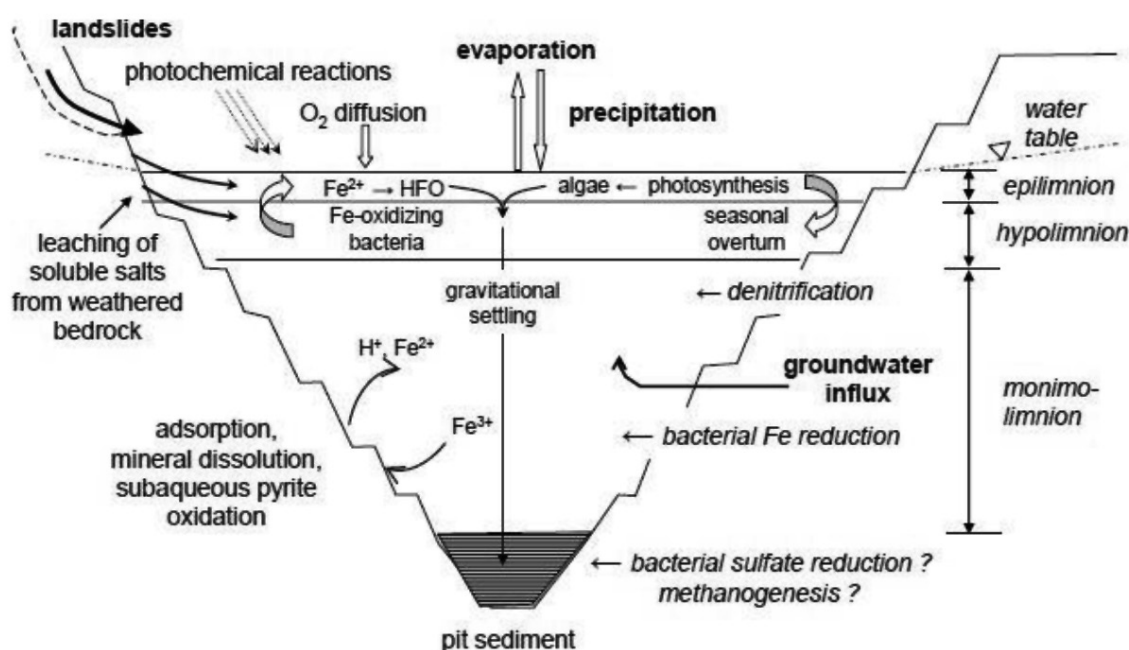


Figure 1—Chemical processes in pit lakes (Gammons *et al.*, 2009)

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External processes comprise wallrock runoff and inflow from groundwater, and flow from surface and subsurface mine waste facilities. The quality of the inflows into the pit lake also impacts the evolution of the water quality. Figure 1 summarizes the chemical processes that determine the pit lake water quality.

### The evolution of a pit lake at a South African coal mine

After mining ceases, water levels in the pit lake rebound to approximately pre-mining groundwater levels. The inflows into the pit lake are rainfall, groundwater, and surface runoff. As water levels rebound the relative contribution of groundwater to the overall pit lake water balance decreases. Rebounding groundwater enters the pit via the dewatered aquifer and from mining activities. The groundwater transports the products of pyrite oxidation, mainly sulphate, iron, and acidity, and dissolves secondary minerals that might have formed in the dewatered aquifer or the backfill material.

### Pit lake morphology

The pit shape is important from a water balance and quality point of view for the following reasons.

- Large surface area compared to mean depth, linear/elongated pit lake morphology. These pit lakes are more prone to the effects of evaporation and evapo-concentration. Larger surface areas increase losses by evaporation, with lower potential for discharge/overflow, and ensure a groundwater gradient towards the pit lake, to act as a hydrological sink.
- Small surface area to mean depth ratio or cone-shaped pit lakes. These pit lakes tend to form an isolated bottom layer, called the monimolimnion, with inferior water quality compared to the rest of the lake. If the chemistry and physical structure of the pit lake are stable, the isolated layer may be beneficial for detaining heavy metals. Conversely, an isolated layer may not be desirable, as sudden storms events may disturb the chemocline and cause this layer to turn over and mix poor, metal-rich water through the whole water column with deleterious effects on the overall water quality.

Thus, pit lakes with high depth to width ratios are less susceptible to complete lake turnover (Gammons *et al.*, 2009). Therefore, the relative depth is a good measure for the shape of the pit lake basin (Schultze, 2012). The relative depth is also referred to as the 'aspect ratio' and can be described as a comparison of the maximum depth ( $Z_{max}$ ; m) of the lake to the lake surface area ( $A_{surface}$ ; m<sup>2</sup>). The relative depth is expressed as a percentage (Castendyk, Eary, and Balistreri, 2015; Vandenberg, Mccullough, and Castendyk, 2015). The calculation of relative depth is shown in Equation [1]:

$$Z_{relative(\%)} = \frac{50 \times z_{max} \times \sqrt{\pi}}{A_{surface}}$$

### Case studies

Three case studies, namely the pit lakes at Mafutha, Kriel, and Rooikop, were undertaken. The characteristics of the pit lakes are shown in Tables I and II.

Mafutha is single open pit 90 m deep from which 250 000 t of material were removed. The pit is surrounded by an undisturbed aquifer and surface runoff into the pit is largely from the sidewalls. The pit lake has reached equilibrium where groundwater inflow plus direct rainfall equals evaporation, thus resulting in very minor variations in pit lake water levels. The pit lake water at Mafutha is alkaline with a TDS of 1000 mg/l and a sodium chloride type water.

The Kriel site comprises several hydraulically linked open pits left by the extensive opencast mining operations. The pit lakes are hydraulically connected due to the highly permeable backfilled opencast material between the lakes. In this system the major inflows are direct rainfall, runoff, and significantly greater recharge through the overburden spoils. Inflow exceeds evaporation and groundwater outflow, resulting in periodic outflow onto the surface. The pit lake water is alkaline with a TDS of 3500 mg/l and is largely a sodium calcium sulphate water.

The Rooikop pit lake is hydraulically connected to both underground and opencast mine workings. Inflow is from groundwater recharge to the underground workings from the opencast spoils and surface runoff. The pit lake is alkaline with

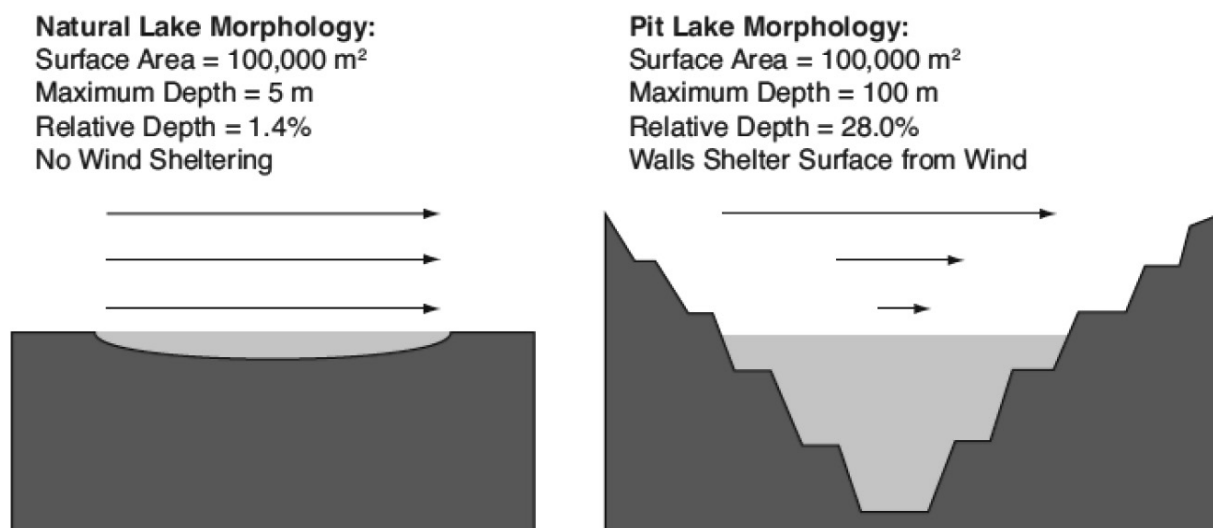


Figure 2—Morphology of natural lakes compared with pit lakes (Castendyk and Eary, 2009)

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Table I

### Pit lake physical characteristics

	Mafutha	Kriel	Rooikop
Coalfield	Waterberg	Witbank /Mpumalanga	Natal
Nature of pit lake	Deep single open pit	Multiple pits hydraulically connected	Single lake
Mining method	Bulk sample	Opencast rollover method	Opencast and underground
Age (years)	8	Operational to 13 years old	12
Surface area (m <sup>2</sup> )	26 600	272 530	17 100
Volume (m <sup>3</sup> )	505 800	797 071	86 681
Dominant inflows	Groundwater, rainfall	Groundwater, rainfall, runoff	Underground mine workings, Runoff from backfill, and natural topography
Dominant outflows	Evaporation	Evaporation	Discharge, evaporation
Morphology (%)	38.4	3,2	6.8
Depth (m)	70	7-10	10

Table II

### Comparison of pit lake chemistry, phytoplankton, and microbiology measured during the 2016-2017 study period

Pit lake	Mafutha	Kriel	Rooikop
pH		8.4	8.4-7.9
Temperature (°C)	27.2 (epilimnion, summer) 18.6 (hypolimnion, summer) 18.6 (whole pit lake, winter)	20.6 (summer) 13.5 (winter)	20 (summer) 15.3 (winter)
Dissolved oxygen (mg/l)	7.53 (epilimnion, summer) 1.3 (hypolimnion, summer) 6.95 (whole pit lake, winter)	R44: 2.03 (summer), 5.7 (winter) R42: 4.9 (summer), 8 (winter)	8.3 (summer) 7.9 (winter)
TDS (mg/l)	1000	3443	1208
Total hardness (as mg/l CaCO <sub>3</sub> )	186	1210	712
Sodium (mg/l)	301	434	18
Total alkalinity (mg/l)	326	197	118
Sulphate (mg/l)	94	1930	608
Chloride (mg/l)	314	35	2.5
Nitrate-NO <sub>3</sub> (mg/l)	9.7	0.24	<0.1
Water type	Na-Cl	Na/Ca-SO <sub>4</sub>	Ca-SO <sub>4</sub>
Chlorophyll-a (µg/l)	2	10.5	3.7
Trophic state classification <sup>a</sup>	Oligotrophic	Mesotrophic to eutrophic	Oligotrophic to mesotrophic
Phytoplankton (dominant phylum, genus)	<i>Chlorophyta, Ankistrodesmus</i>	<i>Cryptophyta, Cryptomonas</i> and <i>Chlorophyta, Ankistrodesmus</i>	<i>Chlorophyta, Chlorella</i>
Microbes (dominating phylum; genera)	Proteobacteria; <i>Acinetobacter</i> , <i>Synechococcus</i>	Proteobacteria; <i>Hydrogenophaga</i> , <i>Chlorobaculum, Pseudomonas, Nodularia</i>	Bacteroidetes; <i>Flavobacterium, Luteolibacter</i>
Stratification and mixing	• Strong thermal stratification (October to March/ April) • Turnover (late autumn/ winter)	• Weak thermal stratification (October to March/April) • Turnover (late autumn/ winter)	• Weak thermal stratification (October to March/April) • Turnover (late autumn/ winter)
Classification <sup>b</sup>	Slightly alkaline, low TDS Holomictic, monomictic	Slightly alkaline, high TDS Holomictic, monomictic	Circum-neutral, low TDS Holomictic, monomictic

<sup>a</sup>Trophic state classification according to de Lange *et al.* (2018). Only September data for Rooikop and Kleinfontein.

<sup>b</sup>Classification of pit lakes according to Eary (1999) and Boehrner and Schultze (2008)

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a total dissolved solids content of 1200 mg/l and the water is calcium sulphate type.

## Are pit lakes an environmentally sustainable closure option for South African coal mines?

The use of pit lakes in the South African coal mining industry as an environmentally sustainable closure option must consider the following aspects, which should be incorporated into the closure design.

### Water balance

It is critical that the sum of the inflows into the pit lake is less than evaporation to prevent major changes in pit lake water levels. Positive pit lake water balances result in discharge onto surface. Negative water balances result in the pit lake becoming a hydraulic sink. As a result, a carefully designed pit lake where the inflows are equal to or less than the outflows will result in a stable pit lake that will not discharge onto surface. The morphology is a critical factor in determining the environmental sustainability of a pit lake.

### Water quality

The pit lakes studied in this investigation are all alkaline with variable dissolved solids contents and which support phytoplankton, microbes, vegetation, and aquatic life. Although the water quality may not comply with the catchment water quality objectives, the pit lakes are environmentally sustainable. The pit lakes were also seen to support a host of other aquatic life such as birds, fish, amphibians and mammals.

### Conclusion

The surface area of a pit lake is vitally important. A large surface area maximizes evaporation, which directly affects the water balance. In addition, surface runoff should be controlled to avoid excess flow into the pit lake during storm events, which may lead to a temporary positive water balance and uncontrolled discharge into the catchment. Should the pit lake be suitably designed, it forms a water sink and prevents uncontrolled discharge from the mining operations.

The water quality in the pit lakes investigated is alkaline with evaluated dissolved solid content, but is able to support chlorophyll-a, phytoplankton, and microbes. Although the water quality may not comply with catchment water quality standards, it supports a stable ecosystem.

Correctly designed pit lakes are a sustainable closure option for South African coal mines. It is recommended that the current South African legislation be reviewed in order to accommodate pit lakes as a sustainable closure option. However, each pit lake is unique and as a result must be evaluated on a case-by-case basis.

Details of the study can be found in the South African Water Research Commission report TT 797/1/19 (Johnstone, Kennedy, and Mpetle, 2019).

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