An Investigation of the Water Quality of Four Coal Mine Pit Lakes in South Africa

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Abstract

Extensive opencast mining in the South African coal fields dating from the 1870's had left numerous pit lakes of various age and sizes. These pit lakes pose risks to the environment in terms of discharge and release of contaminated water into the surrounding water resources. A study of the water quality of four existing end-pit lakes in the Mpumalanga, Waterberg and KZN coal basins has been undertaken, with the aim of establishing the physical structure and hydrochemistry of typical coal mine pit lakes found in South Africa. Current results of this Water Research Commission funded project show that the water chemistry varied markedly between coal fields, while it was found that thermal stratification occurred as a function of the depth of the pit lake. Shared chemical characteristics of the pit lakes included slightly alkaline pH, EC between 120-500 and low trace metal concentrations, indicating the mature nature of these lakes. The lakes are very well vegetated with significant algal biomass and water plants.

Keywords: Pit lakes, physiochemical parameters, water quality, phytoplankton

Introduction

According to De Lange et al. (2018) approximately 6000 abandoned or ownerless mines exist in South Africa. Pit lakes are water bodies that formed in the final voids of opencast mines and were generally left unrehabilitated, as they were in operation prior to the introduction of environmental legislation in South Africa (De Lange et al. 2018). Hence, most of these lakes are ownerless, with only a crude estimate of their exact number (De Lange et al. 2018). Furthermore, in South Africa, pit lakes are commonly associated with coal mines, especially in the Mpumalanga and KZN coal fields, which host the majority of mineable coal in the country and are associated with the phenomenon of acid mine drainage (AMD) (Hancox and Götz 2014). Subsequently, preconception of poor water quality, in terms of acidic pH, high TDS and elevated heavy metals exists regarding pit lakes, with related liability and costly remediation. However, in certain cases, as pit lakes age, they can achieve neutral pH without any special remediation measures, even if the water quality started out as acidic. This phenomenon was demonstrated by Lake Nenkersdorf and Lake Bergwitz in Germany, which turned neutral within 5 and 25 years, respectively (Jordan and Weder 1995).

In opencast areas, much of the groundwater influx is dependent on the state of post mining rehabilitation. A hydraulic link exists whereby rainfall infiltrates into the spoil and then into the final void. The final pit lake is essentially a product of the receiving water quality over the duration of flooding. Nevertheless, current research of mine water in South Africa lacks detailed investigations of pit lakes. Several factors influence the final water quality of a pit lake, such as geology, hydrology, climate, pit shape, water balance, physical and chemical limnology, lake geochemistry, and sediment biogeochemical processes and wall rock reactivity (Castendyk et al 2015). The study presented in this paper aims to fill the current gap by presenting the physiochemical profiles of temperature (T), electrical conductivity (EC), dissolved oxygen (DO), redox potential (ORP) and pH, water chemistry and phytoplankton composition of four end pit lakes (age 8 to 17 years) measured during field investigations conducted between November 2016 to November 2017. The end purpose of the study was to evaluate the evolution and current status of the water quality, in terms of their hydro- geochemistry and biological quality.

Description of Study Sites

The selected study areas are situated in the Waterberg coal basin (WB pit lake), Mpumalanga (KC pit lakes) and KZN coal fields (RK pit lake) of the Karoo Supergroup, east of 26°E, South Africa, shown in Figure 1. The coal, mainly low-grade sub-bituminous to mid-bituminous, occurs in the Vryheid formation in the Ecca Group of the Main Karoo Basin, where coal seams are contained in a 70 m thick succession of alternating bands of coal and sedimentary formations. In the northern sub-basins, the coal is contained in the Grootegeluk formation and Vryheid formation, with a stratigraphic thickness of 120 m (Hancox and Götz 2014). Pyrite (FeS_2) is a dominant sulphide mineral present in South African coal, but many studies have also shown an abundance of acid buffering minerals, such as calcite ($CaCO_3$), occurring with the coal seams. Consequently, mine waters are not necessarily acidic, but often high in dissolved salts (Usher, 2003).

The WB pit lake showed the highest probability to have a monimolimnion based on its high relative depth. The other three pit lakes were linear and shallow with small relative depths. Table 1 gives a summary of the physical characteristics of the four pit lakes.

Methods

Physiochemical Parameter Profiles

Physiochemical profiles of the pit lakes were obtained: the decisions of sampling methodology were based on the structure of the profiles. Profiling was conducted on three occasions for every pit lake during November 2016 to November 2017, where profiles were obtained in at least two locations in every pit

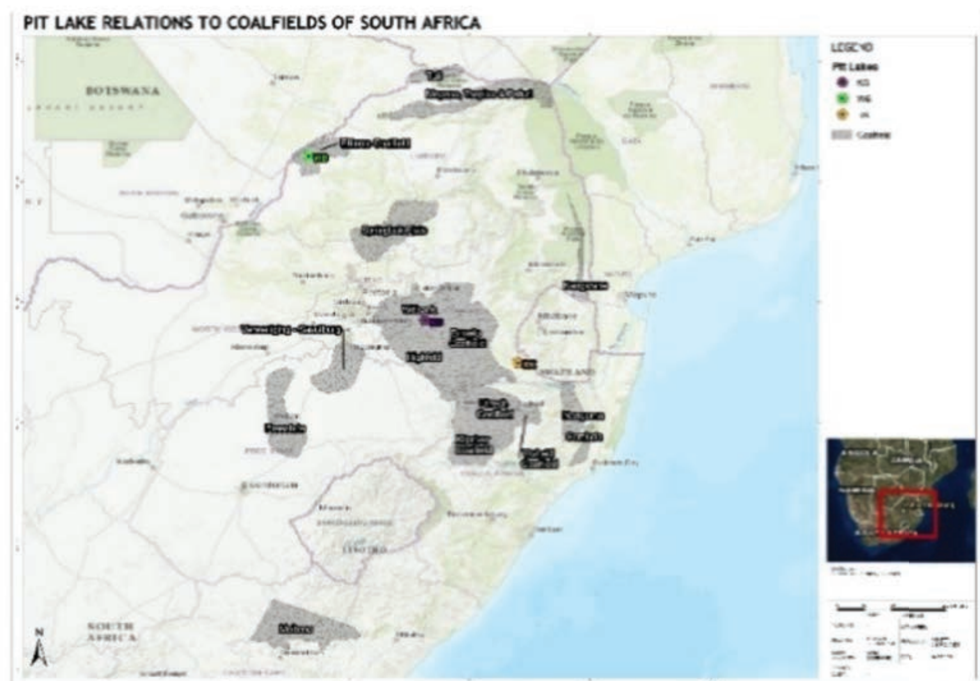

Figure 1 *Study area locations in the Main Karoo basin (Mpumalanga coal fields- KC (a) and KC (b) and KZN coal fields - RK) and Northern sub-basins (Waterberg coal basin- WB pitlake) (Modified after Snyman,1998).*

Table 1. Physical characteristics of the pit lakes, their mining history, age and relative depth (O/C = Opencast; U/G = Underground).

Pit lake	Method of Mining	Mining history	Age of pit lake (years)	Max sat. depth (m)	Max surface area (m^2)	Max volume (m^3)	Relative depth (%)*
WB	O/C bulk	08/2009-	8	70	18 241	487082	46
KC (a)	excavation	05/2010	16	6.8	180 130	393 225	1.4
KC (b)	O/C strip, roll over	1996 –2002		12	51 230	249 694	4.7
RK	O/C, U/G bord & pillar	1999-2006	17	12	12 968	367 124	9.3

*Relative depth ($z_{relative\%}$), which is the ratio of maximum depth (zmax) to lake surface area ($A_{surface)}$ (Castendyk et al 2015), as per z_(relative (%))= (50 × z_max × √π)/√(A_surface).

lake to establish lateral homogeneity of the water. Accordingly, physiochemical profiles obtained at the deepest location in each pit lake were used for sampling depth determinations. The field measurements of T, DO, EC, pH and ORP were conducted in vertical profiles using a calibrated EXO1 multiparameter probe (YSI Incorporated, Yellow Springs Instruments). A reading was taken at 0.3 m depth intervals, and allowing 5 seconds response time for equilibration of the DO sensor with the water, in order to obtain the most accurate readings possible.

Water Sampling and Analysis

Sampling and analysis proceeded for water chemistry, chlorophyll-a concentration and phytoplankton communities. Based on important changes observed in the profiles, with specific attention to sharp changes in T, EC and ORP, water sampling was conducted at specific depths in the pit lakes. A purging pump connected to the appropriate length of hose and a power source was used to conduct the sampling. Collectively, 101 samples were analysed for inorganic chemistry and a further 10 for chlorophyll-a and phytoplankton for the four pit lakes during the study period. The following sets of samples were collected at each decided depth in the pit lakes during every sampling event: (1) a 1 L unfiltered, unacidified sample for alkalinity (determined by titration in the laboratory) and major anions (Ion Chromatography) (2) a 1 L sample, filtered (0.45 µm MCEO syringe filters) and acidified to pH<2 with conc. $HN0_3$, for dissolved metal concentrations (ICP-OES) (3) 2L unfiltered, unacidified sample for chlorophyll-a concentrations where the sample depth was based on changes in DO and T in the profiles (4) a 100 ml sample for phytoplankton taken at same depth as chlorophyll-a and preserved with 1%. Additionally, groundwater samples were collected from monitoring boreholes on the respective sites, by purging the borehole and bailing. All samples were kept at 4°C and transported to their respective laboratories within 24 h.

Results and Discussion

All four pit lakes were holomictic during the study period. Holomictic pit lakes are typically well mixed and consist of an epilimnion and hypolimnion, separated by a zone of rapidly decreasing temperature, the metalimnion. The aforementioned was observed clearly in the deep WB pit lake (Figure 2), which displayed stratification of T and DO during the summer months, and a homogenous EC with depth. During the winter turn-over in WB, the EC remained at 180 mS/m, the T cooled to a uniform 18°C and the whole water column became oxygen-saturated (8mg/L). For the shallower KC (a&b) and RK pit lakes (Figure 3 and Figure 4), weak thermal stratification was observed during the summer, which was subject to wind action, with uniform EC. Lower DO concentrations were detected in the KC(a) pit lake. KC(a) also showed a reduced layer at the bottom, with corresponding decrease in pH and increased EC at the same depth. Even though the RK pit lake is the oldest of the lakes, it had the lowest EC, indicating lower overall mineralisation.

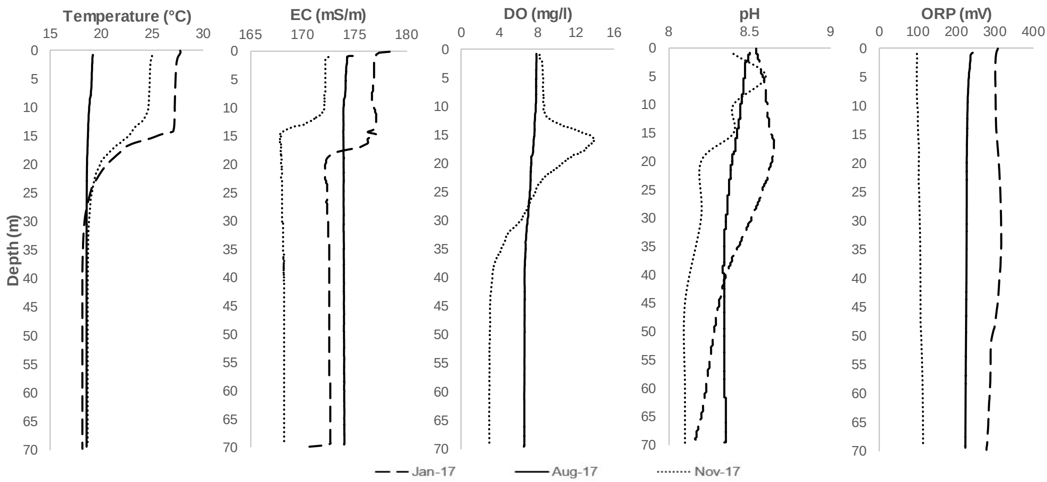

Figure 2 *Profiles of T, EC, DO, pH and ORP for WB pit lake showing a thermocline at 13-16 m and an oxygen maximum at approximately 15 -16 m.*

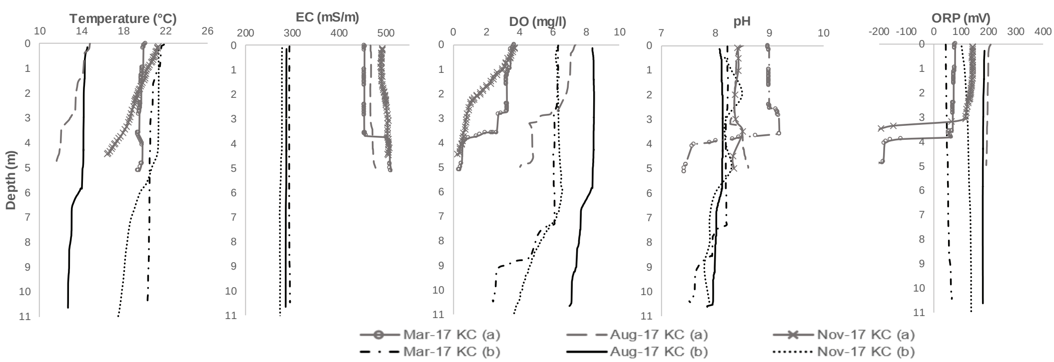

Figure 3 *Profiles of T, EC, DO, pH and ORP for KC (a) and KC (b) pit lakes during the March, August and November 2017 surveys.*

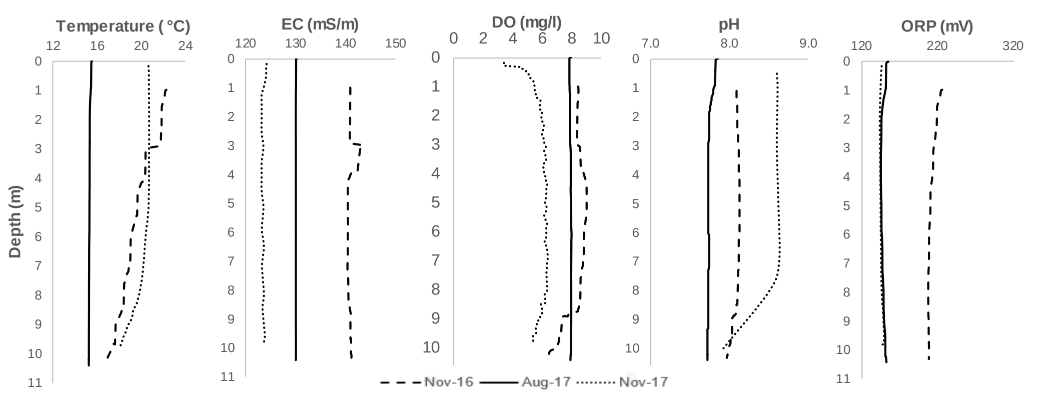

Figure 4 *Profiles of T, EC, DO, pH and ORP for RK pit lake, showing a thermocline at 3 m in November 2016.*

Water Chemistry

A Piper diagram (Piper 1944) was used to characterise the hydrogeochemical facies of the coal mine pit lakes and groundwater samples. The diagram (Figure 5) indicated that the pit lake waters may be classified as Na-Cl, Na-SO_4 and Ca-SO_4 facies types for WB, KC and RK, respectively. The groundwater from the studied regions which filled the pit lakes, classified as Na-Cl, Na-HCO_3 and Ca-HCO_3 types for the WB, KC and RK sites, respectively.

A general trend of pit lake water evolving towards permanent hardness, typically plotting in block B of the Piper diagram, was observed for the pit lakes of KC and RK. Hard water and high salt concentrations are typical of South African coal mine waters (Usher 2003). Geologically, the aquifers of the Karoo Supergroup consist of weathered regolith overlaying layers of siltstones, sandstones, carbonaceous shale and coal of the Ecca Group. These formations mainly contain inert minerals, together with mainly calcite (rather than dolomite) and accessory pyrite. Natural buffering of AMD by the surrounding or co-disposed rock therefore releases SO_4 and Ca (and Mg) into the water according to Reaction 1, which gives rise to hardness (Gomo 2017).

$$FeS_2 + 2CaCO_3 + 3.75O_2 + 1.5H_2O \leftrightarrow Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2CO_2 \quad \text{Reaction 1}$$

At the RK site, the contribution of the mine groundwater rising though old underground workings and leaching sulfide oxidation products to the pit lake, was visible in the high SO_4 concentrations relative to that of the surrounding aquifer. The KC pit lakes displayed dominance of both Na and Ca, with SO_4. Here, the pit lake water was influenced by groundwater flowing through, and interacting with the heterogeneous spoil materials in the backfill, adding SO_4 to the water by leaching pyrite oxidation products.

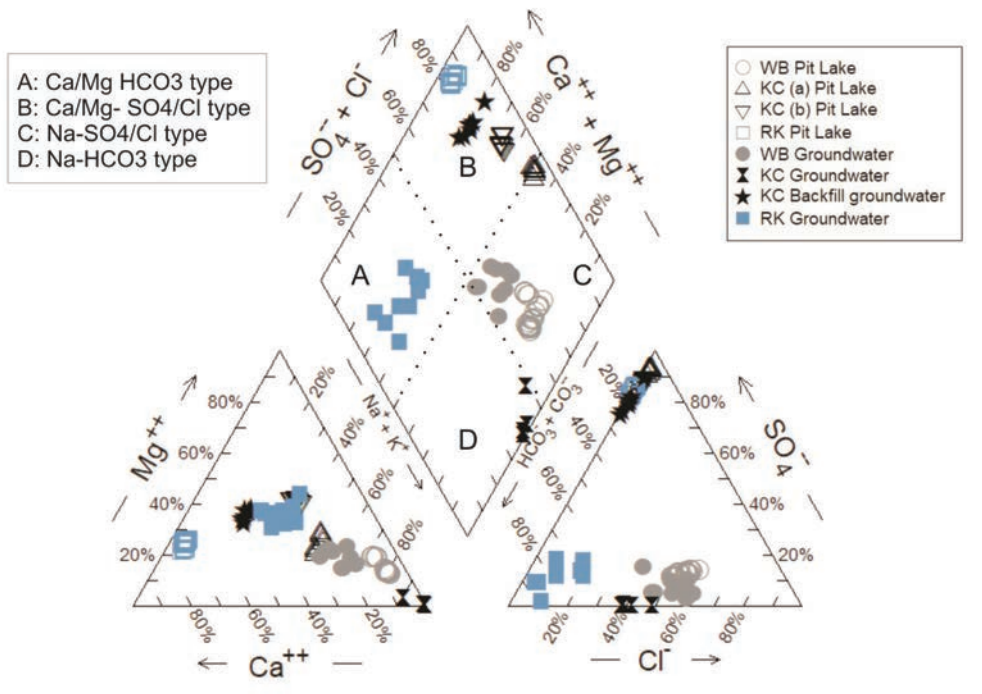

Figure 5 Piper diagram showing the plotting from all the coal mine pit lakes and groundwater samples.

Furthermore, the natural aquifer at KC was classified as $Na-HCO_3$ type, where the origin of high HCO_3 could be due to coalification processes, as explained by Usher (2003), and the Na enrichment explained by reactions of cation exchange of Ca and Mg in favour of Na taking place in exchange sites of clay minerals. The pit lake water of WB evolved towards higher Na concentrations, and had Na/Na+Cl (in meq/L) ratios of >0.5, which, according to Hounslow (1995) indicates the process of albite weathering or ion exchange. At the high pH and oxidative ORP conditions encountered in the WB, KC and RK pit lakes, Fe and Mn were expected to be present in low concentrations. Fe and Mn are typically removed from the solute load by adsorption on Fe oxyhydroxides and precipitation. Higher relative Mn concentrations in the water can be explained by the stability of Mn over a wider range of pH and redox potential, as well as the slower oxidation of Mn relative to that of Fe (Denimal et al 2005).

Table 2 shows the arithmetic mean and standard deviation values for dissolved components, as well as pH and EC for all the samples taken during all the seasons at all depths in the pit lakes. Moreover, water in the pit lakes were compared to groundwater data from the studied sites (Table 2). Major differences between groundwater and pit lake compositions were found for Ca, Mg, Na HCO_3, SO_4 and Cl concentrations.

Phytoplankton

Freshwater organisms, especially phytoplankton, have been found to reflect changes in environmental conditions and as such, biota found in polluted waters are different than those found in non-polluted waters (Wetzel, 2001). Furthermore, pit lakes pose unique habitats to organisms where conditions, such as light availability, nutrient levels and pH are especially stressful, hence the diversity of organisms are expected to be lower than in natural environments. In the studied pit lakes, total phosphorous (TP) and inorganic nitrogen were both limiting factors, with concentrations of less than 250 µg/L TP and 100-115 µg/L inorganic nitrogen for KC and RK pit lakes, classifying them as oligotrophic to mesotrophic (Wetzel 2001). WB pit lake showed a higher load of inorganic nitrogen, mostly due to $NO_{3-}N$ (267 µg/L) but also classified as oligo-mesotrophic according to Wetzel (2001). The average chlorophyll-a concen-

Table 2. *Arithmetic mean and standard deviation values of the water components concentration (mg/L), pH and electrical conductivity (mS/m) from studied coal mine pit lakes and groundwater in the same study sites.*

	Ca	Mg	Na	K	Fetotal	Mn	HCO3	Cl	SO_4	pH	EC
WB pit lake											
Mean(n=24)	24.8	30.8	306.9	20.1	<0.05	<0.01	363	319.2	100.4	8.4	185
SD	2.2	4.6	30.8	3.1	-	-	38	14.1	6.8	0.17	5.9
KC pit lakes											
Mean(n=38)	213	185.8	423.8	28.3	0.09	0.22	220	36	2108	8.1	360
SD	55.5	82.7	175.8	8	0.2	0.33	38	12	752.3	0.3	90.4
RK pit lake											
Mean(n=17)	219.6	45.5	18	5.5	<0.05	0.017	141	2.6	607.7	7.8	137
SD	13.7	4.2	1	0.3	-	0.013	12	0.3	25.9	0.13	4.5
WB GW											
Mean(n=10)	77	32	218	29.7	<0.05	0.22	437	307	37	7.15	168
SD	4	2	42.8	8.5	-	0.09	12	55.6	1.5	0.35	15.5
KC GW											
Mean (n=4)	2.3	0.87	357.6	4.8	0.06	<0.01	516	200	1.4	8.4	156
SD	0.3	0.16	36.7	1.2	0.07	-	72	18.4	1.3	0.41	32
KC backfill											
Mean (n=8)	399.7	182.2	202.2	29.3	0.04	2.13	538	22.6	1639	7.3	329
SD	23	33.1	10.8	1.5	0.01	0.4	165	3.8	166.2	0.2	12
RK GW											
Mean(n=10)	7	4.7	6.6	2.6	0.4	<0.01	35	4.5	5.4	7.4	9.2
SD	1.9	0.8	1.4	0.4	0.5	-	12	1	2.4	0.12	2.6

GW Groundwater, SD Standard Deviation, Mean Arithmetic trations were 6 µg/L, 12 µg/L and 5 µg/L for WB, KC and RK, respectively. Many freshwater pollution algae were analysed in the pit lakes and identified up to genus level. Overall, Chlorophyta and Cryptophyta dominated the pit lake waters, with *Ankistrodesmus*, *Chlorella*, *Cryptomonas* and *Chlamydomonas* being present in the highest cell volumes. These phytoplankton species have been found in other South African freshwater impoundments, such as the studies conducted on the Loskop dam in the Olifantsriver Catchment. The specific role and relevance of the phytoplankton in the presented pit lakes will be investigated in a future paper.

Conclusions

Waters from the studied coal mine pit lakes showed high content of dissolved elements and circum-neutral to alkaline pH. A comparison between the groundwater and coal mine pit lake waters indicated that the respective mining processes and connectivity to underground workings or rehabilitated backfill may have played a notable role in the evolution of the final pit lake water qualities of the RK and KC pit lakes. The stand-alone WB pit lake showed water qualities much closer to that of the natural surrounding aquifer. All the pit lakes showed holomictic circulation patterns which did not seem to impact on the chemical signatures of the pit lakes. From a water quality point of view, the research so far, indicates that intentional flooding of a final void in a coal mine area looks like a viable solution for mine closure.

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References

Castendyk DN, Eary LE, Balistrieri LS (2015) Modelling and management of pit lake water chemistry: Theory. Applied Geochemistry 57: 267-288, doi: 10.1016/j.apgeochem.2014.09.004.

De Lange WJ, Genthe B, Hill L, Oberholser PJ (2018) Towards a rapid assessment protocol for identifying pit lakes worthy of restoration. Journal of Environmental Management 206: 949-961, doi: 10.1016/j.jenvman.2017.11.084.

Gomo M (2017) Conceptual hydrogeochemical characteristics of a calcite and dolomite acid mine drainage neutralised circumneutral groundwater system. Water Science. doi: 10.1016/j.wsj.2018.05.004.

Hancox PJ and Götz AE (2014) A Review article: South Africa's Coal fields - A 2014 perspective. International Journal of Coal Geology 132 170-254, doi: 10.1016/j.coal.2014.06.019.

Hounslow AW (1995) Water quality data: Analysis and interpretation. New York: Lewis Publishers.

Jordan H, Weder HJ (1995) Hydrogeologie–Grundlagen und Methoden. F. Enke Verlag, Stuttgart.

Snyman CP (1998) Coal. In: Wilson M.G.C. and Anhaeusser C.R. (Eds), The Mineral Resources of South Africa, sixth ed, Handbook 16, Council for Geoscience, Pretoria.

Usher BH (2003) The development and evaluation of hydrogeochemical prediction techniques for South African coal mines. PhD Thesis, University of the Free State, South Africa.

Wetzel RG (2001) Limnology: Lake and River Ecosystems, third ed. Academic Press, San Diego, California, 1006 pp.