Water Quality in a Mining and Water-stressed Region

DOI:

[10.1016/j.jclepro.2017.10.030](https://doi.org/10.1016/j.jclepro.2017.10.030)

Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Mhlongo, S., Mativenga, P., & Marnewick, A. (2018). Water Quality in a Mining and Water-stressed Region. *Journal of Cleaner Production*, 171, 446-456. <https://doi.org/10.1016/j.jclepro.2017.10.030>

Published in:

Journal of Cleaner Production

Citing this paper

Please note that where the full-text provided on Manchester Research Explorer is the Author Accepted Manuscript or Proof version this may differ from the final Published version. If citing, it is advised that you check and use the publisher's definitive version.

General rights

Copyright and moral rights for the publications made accessible in the Research Explorer are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Takedown policy

If you believe that this document breaches copyright please refer to the University of Manchester's Takedown Procedures [<http://man.ac.uk/04Y6Bo>] or contact uml.scholarlycommunications@manchester.ac.uk providing relevant details, so we can investigate your claim.

Manuscript Number: JCLEPRO-D-17-01711R3

Title: Water Quality in a Mining and Water-stressed Region

Article Type: Original article

Keywords: water quality; acid mine drainage; process capability index

Corresponding Author: Dr. Annlizé Marnewick,

Corresponding Author's Institution: University of Johannesburg

First Author: S'phamandla Mhlongo

Order of Authors: S'phamandla Mhlongo; Paul T T Mativenga; Annlizé Marnewick

Abstract: The aim of this study was to evaluate trends in water quality and mineral footprint along the catchment of a dam located in a coal mining area and water-stressed region. The study was conducted along the upper Olifants River, which is the catchment of Witbank Dam, in the jurisdiction of Emalahleni Local Municipality in South Africa. The study analysed water quality data over an eight-year period, obtained from the water authorities, and two-year data from the municipality. The analysis focused on water quality determinants such as pH, turbidity, total dissolved solids, sulphates and manganese. The analysis was conducted in line with South African National Standard 241:2015 on drinking water. By using allowable mineral concentration limits and thresholds, a statistical process capability index was calculated to determine the efficiency of controls on the potential of water being contaminated by land use and mining activities. It was found that the coal mining region was associated with adverse effects on the raw water quality. The paper presents a generic method in terms of a concentration-independent process capability index for monitoring deterioration of water across many water quality determinants. The results provide a warning signal to stakeholders. There is a time-critical and growing deterioration of water quality, which may pose health risks to consumers if there is no reduction in contamination sources or improved efficacy of water purification systems.

Title: Water Quality in a Mining and Water-stressed Region

Authors:

Author 1: S'phamandla Mhlongo

Affiliation: Postgraduate School of Engineering Management, Faculty of Engineering and the Built Environment, University of Johannesburg, 1 Bunting Road, Auckland Park , 2092, Johannesburg, South Africa

Author 2: Paul T Mativenga

Affiliation: School of Mechanical, Aerospace and Civil Engineering, Faculty of Science and Engineering, The University of Manchester, Manchester, M13 9PL, United Kingdom

Author 3: Annlizé Marnewick

Affiliation: Postgraduate School of Engineering Management, Faculty of Engineering and the Built Environment, University of Johannesburg, 1 Bunting Road, Auckland Park , 2092, Johannesburg, South Africa

Corresponding author:

Annlizé Marnewick

amarnewick@uj.ac.za

Faculty of Engineering and the Built Environment

+27 11 559 1735

Water Quality in a Mining and Water-stressed Region

S'phamandla Mhlongo^a, Paul T Mativenga^b, Annlizé Marnewick^a

^aPostgraduate School of Engineering Management, Faculty of Engineering and the Built Environment, University of Johannesburg,
1 Bunting Road, Auckland Park, 2092, Johannesburg, South Africa

^bSchool of Mechanical, Aerospace and Civil Engineering, Faculty of Science and Engineering, The University of Manchester,
Manchester, M13 9PL, United Kingdom

Abstract

The aim of this study was to evaluate trends in water quality and mineral footprint along the catchment of a dam located in a coal mining area and water-stressed region. The study was conducted along the upper Olifants River, which is the catchment of Witbank Dam, in the jurisdiction of Emalahleni Local Municipality in South Africa. The study analysed water quality data over an eight-year period, obtained from the water authorities, and two-year data from the municipality. The analysis focused on water quality determinants such as pH, turbidity, total dissolved solids, sulphates and manganese. The analysis was conducted in line with South African National Standard 241:2015 on drinking water. By using allowable mineral concentration limits and thresholds, a statistical process capability index was calculated to determine the efficiency of controls on the potential of water being contaminated by land use and mining activities. It was found that the coal mining region was associated with adverse effects on the raw water quality. The paper presents a generic method in terms of a concentration-independent process capability index for monitoring deterioration of water across many water quality determinants. The results provide a warning signal to stakeholders. There is a time-critical and growing deterioration of water quality, which may pose health risks to consumers if there is no reduction in contamination sources or improved efficacy of water purification systems.

Keywords: water quality, acid mine drainage, process capability index

1. Introduction

An increase in population, urbanisation, industrial growth and agricultural activities has a significant impact on the demand of scarce water resources. Furthermore, sources of contamination within the water catchment area and the pipe water supply system present challenges to the supply of clean water. The transfer of contaminants from one water body to another is a major challenge (Li et al, 2017). According to Behmel et al (2016) and Khan et al (2013) the decline of water quality in rivers, lakes and groundwater has progressively become a global issue of concern. Northey et al (2016) reported that mining operations have significant adverse water quality impacts. Mining is associated with risks such as: potential flooding of pits, uncontrolled discharges and catastrophic collapse of water pollution control dams. Gao et al (2017) indicated that the coal mining industry is facing complex water resource management challenges such as avoiding non-compliant discharge of mine affected water. Traditional measures of developing water storage infrastructures are unable to entirely address the spill-over of worked water.

Innovative measures are required to mitigate the risk of unregulated discharges including water quality monitoring, which is the standardised measurement and observation of the aquatic environment used in order to define status and trends (Behmel et al., 2016). Water quality monitoring is a growing challenge in the 21st century since a large number of chemicals are used in our everyday lives and make their way to the water sources. Various water-polluting activities take place in the water catchments. Water contamination could compromise natural ecosystems that

support human health, biodiversity and food production (Salem and Amin, 2012). Jadhav et al. (2016) noted that contaminants occur naturally or as a result of human-induced elements and can result in significant deterioration of water quality. According to Baptista and Santos (2016), monitoring plays a key role in understanding the anthropogenic impact on natural ecosystems, thus offering an important tool in the management of natural areas. In South Africa, the quality of water is monitored, measured and reported periodically in accordance with a drinking water quality standard (South African National Standard (SANS) 241:2015).

Mining poses a great risk for people accessing clean drinking water (Khan et al, 2013). The mining sector is one of the pillars of the South African economy. One challenge for the industry is acid mine drainage, which has the potential to decant into surface water sources. In South Africa, Emalahleni Local Municipal jurisdiction, in Mpumalanga, has a high concentration of coal mining activities. There are twenty-four coal mines active along the main water source catchment, as shown in Figure 1. The catchment area is in need of diligent and effective water quality monitoring and purification to prevent potential health risks.

INSERT FIGURE 1 HERE

Figure 1: Witbank Dam catchment indicating location of sampling station (Source: Nkangala District Municipality, 2017)

1.2 Mine waste water effluent

Acid mine drainage is a mine waste water effluent which is mostly generated from gold, coal and copper mining operations. It is characterised by low pH content and high heavy mineral content (Regmi et al., 2009). According to Mulopo (2014) acid mine drainage is also characterised by high total dissolved solids (TDS), high sulphates and high levels of heavy metals, particularly iron, manganese, nickel and cobalt. Acid water drainage occurs when mining operations associated with pyritic materials (iron disulphide) are exposed to oxygen and water. As a result, a reaction catalysed by bacteria occurs in water-soluble iron sulphates. Pyrites undergo oxidation in two phases, producing: (i) sulphuric acid and ferrous sulphate, and (ii) orange-red ferric hydroxide and more sulphuric acid. The generation of acid mine drainage was explained by Akcil and Koldas, 2006.

Akcil and Koldas (2006) reported that chemical, physical and biological factors are important for determining the rate of acid generation. High permeability translates to high oxygen ingress, contributing to a high chemical reactivity. This reaction is accelerated increased by high temperatures. Bacteria generates rapidly under favourable environmental conditions associated with both pH and temperature. Bacterium accelerates the oxidation of sulphides of antimony, molybdenum, gallium, arsenic, copper, cadmium, nickel, cobalt, zinc and lead. The oxidation of sulphide minerals results in acid production. Water can serve as a medium of transporting contaminants. The broader sources of acid mine drainage are mine rock dumps, tailing impoundments, underground and open pit mine workings, pumped or nature discharge of underground water and diffused seeps from replaced overburden and rehabilitated areas. According to Brown (1993), an increase in sulphate content serves as an indicator for salinity. According to Van Zyl et al. (2001), Witbank Dam had a sulphate content of 20-40 mg/l prior to mining operations and this has since escalated to an average range of 120-160 mg/l. Their paper suggests an association between underground water contamination and mining activity.

1.3. Prior Studies on the Problem Statement

Adeleke and Bezuidenhout (2011) reported that in South Africa, the required fresh water is limited and vulnerable in terms of availability, quantity and quality. The solution of water management requires improving on social and environmental conditions and using available technology to increase the accessible quantity of water. The Department of Water and Sanitation (DWS) has implemented an incentive-based programme (Blue and Green Drop) as a quality measure of the microbiological and chemical qualities of drinking water and effluent. Nkhonjera (2017) indicated that Olifants River had a decline in water availability due to increasing demand together with projected decrease in runoff in the region, which will lead to increased water stress. Additionally, the Institute of Municipal Engineering South Africa (IMESA) (2010) estimates that approximately 62 ML/d of post-closure mine decant is produced from coal mines in the Highveld Coalfield (Mpumalanga) and approximately 50 ML/d is discharged into the Olifants River. Van Zyl et al. (2001) estimated that approximately 44 ML/d of mine water are being discharged into the upper Olifants River catchment per day with a potential increase of up to 131 ML/d by 2020. De Villiers and Mkwelo (2009) discuss the efficiency of Olifants River water quality monitoring. In their study, they used seven sampling points along the catchment in areas with highly intensive coal mining activities. The highest concentration of sulphates was recorded in a sampling point with intensive mining and it was seven times higher than the permissible limit. Brown (1993) recorded the increase in concentration of TDS and sulphates in Witbank Dam from 1987-1994. Maree et al. (2013) indicate that acid mine drainage can be neutralised using limestone and/or lime. Van Zyl et al. (2001), confirmed that limestone treatment is the most cost-effective acid water neutralisation method with a potential removal of 2 000 mg/l of sulphates. The high dosage of and pH > 11) can reduce sulphates by up to 1 400 mg/l, with the precipitation of magnesium (gypsum crystallisation). Kefeni et al. (2017) mentioned that the conventional method of treatment of acid mine drainage with lime or limestone demands more landfill for waste disposal, and the need for effective acid mine drainage treatment methods are necessary where the utilisation of waste is possible through recycling or reuse. Northey et al. (2016) identified the main opportunity for the use of water footprint assessment with the mining industry which includes standardised assessment of the water use impact associated with mining and mineral processing.

2. Research Methods

2.1 Aim

The aim of this study was to determine trends in water quality and mineral footprint along the catchment of a dam located in a mining area and water-stressed region. The geographical area and boundary of the study was the city of Emalahleni. The study was conducted using raw water quality data collected and analysed by the DWS, as well as raw water quality data collected and analysed by the Emalahleni Local Municipality. Various literature sources and studies from the authorities were reviewed and utilised during the study. Interviews were conducted with the local municipality to validate information. The data collected focused more on the contamination of the surface water.

2.2 System Boundary

This study was based on the city of Emalahleni (formerly known as Witbank), in South Africa, which is 138 and 111 km east of Johannesburg and Pretoria, respectively. Emalahleni literally means the place of coal because it is situated in an area that is rich in coal reserves. The city is located in the central-west side of Mpumalanga, South Africa, as shown in Figure 2. This area has more than a century's history of coal mining. Its economical land use is associated with many coal mining operations, coal-fired energy generation, steel manufacturing and agriculture. It is regarded as one of South Africa's economic hubs and one of the fastest growing cities in the country, with a high population growth rate of 3.58% per year. The economic contribution of Emalahleni to the national gross value added (GVA), according to the 2011 census, is 1.5% nationally and 20.6% provincially.

INSERT FIGURE 2 HERE

Figure 2: South Africa map indicating provinces (Source: Nkangala District Municipality, 2017)

The city of Emalahleni is situated in a water-stressed area and primarily has access to one main water supply source, namely the Witbank Dam, supplying approximately 60% of the overall municipal water demand. The dam is situated along the Olifants River within the basin of the upper Olifants River catchment (see Figures 1 and 3).

Witbank Dam has a catchment area of 3 256 km², mean annual run-off of 125 x 10⁶m³a⁻¹, total capacity of 104 x 10⁶ m³ and a surface area of 1 211.2 ha. Land use in the catchment is associated with coal mining, coal-fired power generation and agricultural activities. There are 29 major and minor coal mining activities along the catchment and they contribute towards 47% of the country's coal production. The mining operations are accompanied by four major coal-fired power generators contributing immensely to the national power grid. Water consumption along the upper Olifants River catchment is summarised in Figure 3.

INSERT FIGURE 3 HERE

Figure 3: Summary of water consumption along upper Olifants River catchment (Department of Water Affairs, 2011a)

The area has limited alternative water supply sources and underground water has been exploited to a very limited degree as opposed to surface water for potable water supply purposes. According to the water requirements and water resources report (Department of Water Affairs, 2011b), the water demand from the Olifants River is characterised by irrigation, industrial, domestic, power generation, mining and forestry use. The future water requirement for the Olifants River catchment is illustrated in Figure 4.

INSERT FIGURE 4 HERE

Figure 4: Future water resource and water requirements in the Olifants River catchment (Department of Water Affairs, 2011a)

Figure 4 above indicates that the Olifants River has minimal capacity remaining to meet the required demand. It indicates that by 2035, the anticipated low growth will reach maximum capacity, while the high growth will do so by 2025. It can be concluded that Emalahleni is a water-stressed environment.

2.3. Case Study

The study was conducted by collecting data from the water authority's i.e. the Drinking Water Standards (DWS) and local municipality. Other sets of results were taken from the mining company along the catchment. These results were used as an indication of the origin of untreated mine waste water effluent. The water quality data acquired from the DWS covered a period of 8 years from 2003 to 2011. Samples were collected at different activity points feeding into the upper Olifants catchment. The purpose of this exercise was to monitor the release of saline mine water. The water quality data was also obtained from Emalahleni Local Municipality over a 2-year period

from 2014 to 2016. The primary purpose for monitoring the raw water source was to identify potential hazards that could impact on the health and wellbeing of the local community. The monitoring was done to ensure that all identified risks are either mitigated or removed via water treatment technologies.

All water samples were obtained through a grab sampling method and were analysed in terms of the prescribed South African National Standard (SANS) 241:2015. Process capability and the process capability index were calculated to determine the efficiency of water pollution controls on land use activities along the catchment. The samples were taken bi-weekly from their sampling stations or activity points along the catchment via installed weirs. Samples from the Emalahleni Local Municipality were taken from the point of abstraction for the water treatment plant. DWS water quality results comprised of the physical and chemical determinants, namely pH, conductivity, sulphate, TDS, chloride, total alkalinity, fluoride, calcium, magnesium, sodium, iron, manganese and aluminium. The purpose of these determinants was to determine the extent of the pollution within the catchment body and the risks. The results over the assessment period are presented in Table 1 by means of averages of observations. However, the trend, spread or conformance to agreed limits are not indicated.

Table 1: Average raw water mineral footprints along the catchment January 2003 to May 2011 (Department of Water Affairs, 2012)

Water quality measure and mineral footprint		Bethal Bridge	Boesman-spruit	Duvha Bridge	Koringspruit	Naauwpoort	Olifants Tussen Bethal	Steenkool-spruit	Witbank Dam
pH		7.74	7.73	7.90	7.71	7.37	7.86	8.07	7.78
Electrical Conductivity (EC) (mS/m)		79.54	145.76	69.59	145.03	61.49	47.85	50.52	58.18
Total Dissolved Solids (TDS)		573.97	1155.83	475.26	1097.09	413.85	289.83	333.38	372.90
Sulphate (SO ₄)		302.32	705.31	231.04	592.45	211.98	79.26	77.71	164.06
Chloride (Cl)		20.72	13.96	19.56	36.24	18.08	21.72	23.34	17.8
Total Alkalinity		92.67	92.46	101.90	158.37	63.56	124.53	132.10	95.62
Fluoride (F)		0.5	0.5	0.51	0.6	0.43	0.49	0.4	0.5
Calcium (Ca)	mg/l	73.29	144.21	61.56	142.09	55.47	31.15	32.56	46.73
Magnesium (Mg)		45.64	109.23	38.26	83.20	29.72	19.62	20.81	30.25
Sodium (Na)		32.44	36.807	29.57	77.96	24.75	36.49	34.65	28.80
Iron (Fe)		0.14	0.05	0.19	0.04	0.04	0.45	0.19	0.05
Manganese (Mn)		0.96	0.05	0.19	0.74	0.56	0.03	0.04	0.09
Aluminium (Al)		0.14	0.03	0.15	0.06	0.05	0.42	0.27	0.06

2.4 Theory and calculations

In this research, the process capability index was used to determine the extent to which the mineral footprints in the water were within the limits set for water quality in South Africa. The main measures used was the C_{pk} . The process capability index compares the output of a process to the specification limits by using capability indices. The statistical parameter C_p estimates what the process is capable of producing if the process mean were centred between the specification limits (NIST, 2017). It assumes that the process output is approximately normally distributed. C_{pk} estimates what the process is capable of producing, considering that the process mean may not be centred between the specification limits. The parameter C_{pk} was used and is calculated by Equation 1.

$$C_{pk} = \min \left[\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma} \right] \quad (1)$$

Where C_{pk} is the process capability index and USL and LSL are the upper and lower allowable or set limit for the quantity under evaluation, respectively. The parameters μ and σ are the mean value and standard deviation of the determinants, respectively. The higher the process capability index, the more under control the process output (Montgomery, 2007). On the other hand, a value that is too high may represent unnecessary precision in output control, which may co-relate to higher process cost. In a water services authority, staff have to remember the upper and lower limits for each water quality characteristic and contaminant. The beauty of a statistical process capability index is that the measure of conformance is converted to a simple numeric value. This can make it easier for staff to devise a fast method of assessing whether all water quality measures are within specifications for the intended water use.

3 Results

3.1 Water Quality Results at Sampling Stations in the Witbank Dam and Catchment Area

The analyses of this case study focused on the five determinants (pH, turbidity, TDS, sulphates and manganese) which are critical for determining the extent of contamination from mine waste water decant. The pH was analysed to determine water acidity or alkalinity. Turbidity measured the concentration of suspended matter in water. Sulphate was analysed to measure the presence of sulphur, which has the potential to form oxides and other salts (potassium, sodium, calcium, magnesium, barium, lead and ammonium). TDS were analysed to measure the amount of various inorganic salts dissolved in water. Manganese was analysed to determine aesthetic effects as a high concentration of manganese has adverse aesthetic effects.

The analyses were conducted using SANS 241-2015 and the 1996 South African DWS water quality guidelines for domestic use, agriculture (irrigation and stock) and industrial use.

3.2 pH

The average pH for all samples taken at DWS sampling stations for an assessment period of 8 years was 7.77, and the average for Witbank Dam, results taken from Emalahleni was 7.29. The results were both within the SANS 241-2015 limits of 5.5 to 9.7. The average results from DWS and their calculated C_{pk} indices for each sampling station in the 8-year assessment period are summarised as per Figure 5. The C_{pk} result from Emalahleni was 1.87, which indicates that pH was under control.

INSERT FIGURE 5 HERE

Figure 5: Average pH levels within the Witbank Dam catchment

All sampling stations indicated on Figure 5 above were within the acceptable limit of 5.5 to 9.7 for the pH value according to SANS 241-2015 limits. There were a few pH spikes with the real data sets, but these were insignificant. From Figure 5, since all the process means are within specification, it can be said that the process capability index values as measured by C_{pk} are positive. The high value of C_{pk} indices for all sampling stations indicates that pH was under

control. pH is a critical determinant that is used to control chemical reactions at the water treatment plant. It is also used to verify the stability of the final treated water.

3.3 Turbidity

There were no turbidity results from DWS and the results presented were taken only at Witbank Dam in Emalahleni. The average result for turbidity was 2.37 NTU, which is above the SANS 241:2015 limit of 1.0 NTU (refer to Figure 6 below). Turbidity had a process capability index of -0.22, which indicate that controls on the land use activities are not effective. Turbidity is associated with water that is not clear, a slight chance of adverse aesthetic effects and infectious disease transmission. It could be treated through the coagulation or flocculation process, followed by filtration. Low turbidity values with increasing metal contaminants pose additional treatment challenges and this is primarily due to the lack of bulk material in the water to facilitate the coagulation and flocculation process. A good turbidity range for a water treatment plant is between 100 and 200 NTU. To achieve this value, the plant makes use of bentonite (an inert bulking material), which provides the necessary turbidity for better chemical reactions.

INSERT FIGURE 6 HERE

Figure 6: Witbank Dam raw water turbidity values against prescribed standards

3.4 Sulphate

The overall average sulphate concentration from DWS sampling stations during the 8-year assessment period was 314.30 mg/l, which is above the SANS 241:2015 limit of 250 mg/l. Boesmankranspruit had the highest concentrations (refer to Figure 7). The average concentration of sulphates at Emalahleni was 152.24 mg/l, which was below the SANS 241:2015 limit of 250 mg/l. As shown in Figure 7, the Witbank Dam sulphate results had a process capability index of 0.76, which indicate that controls are effective but require improvement.

INSERT FIGURE 7 HERE

Figure 7: Average sulphate levels within the Witbank Dam catchment

Figure 7 shows an elevated concentration of sulphates within some areas of the catchment. The process capability indices indicate that there is significant ineffective control of sulphates since the process capability index is negative. This is also supported by high standard deviation values. High concentration rates (compared with standards) could be due to the discharge of mine or industrial waste water effluent. The concentration at Koringspruit and Boesmankranspruit can pose significant health risks to the rural community, who might be consuming water directly from these streams. The occurrence of sulphate concentration that is beyond acceptable outside specifications in three catchment areas is a major concern for locals who may use or consume water directly from these catchment areas.

The average sulphate concentration at the Witbank Dam was recorded as 164.06 mg/l and is within the SANS 241 drinking water limit. This can be explained by the dilution effect. Sulphate levels below 250 mg/l have an aesthetic impact and at levels greater than 500 mg/l, sulphate has an acute health impact.

3.5 Total dissolved solids

The average concentration of TDS from DWS sampling stations was 619.89 mg/l, which is below the SANS 241:2015 limit of 1 200 mg/l. Boesmankranspruit had the highest concentration at 1 155.83 mg/l, followed by Koringspruit at 1 097.09 mg/l. The average concentration of TDS at Witbank Dam was 403.68 mg/l, which is also below the SANS limit.

The process capability index for Witbank Dam was 1.70, which indicates that controls are effective. However, the DWS results indicate that there is significant ineffective control of TDS even though the average concentration is below the SANS 241:2015 limit. This is also supported by high standard deviation values. Results indicate that even though the majority of the sampling stations were below the limit, there is still inefficiency in the controls; this poses a significant risk should there be an increase in concentration. The majority of the complying results are approaching the upper specification limit, which indicates a risk of an unsafe water supply should the rate of increase not be controlled.

The removal of TDS above the threshold of 1 200 mg/l requires advanced technologies such as ion exchange or membrane treatment, as well as highly skilled process controllers to manage the system. High TDS values affect numerous chemical reactions, the aesthetic quality of the water and also inflicting chronic health effects.

INSERT FIGURE 8 HERE

Figure 8: TDS levels within the Witbank Dam catchment

3.6 Manganese

The average concentration of manganese at DWS sampling stations was 0.37 mg/l, while at Witbank Dam this was 4.02 mg/l; these are both above the SANS 241-2015 limit of 0.1 mg/l. Bethal Bridge had the highest concentration at 0.96 mg/l, followed by Koringspruit at 0.74 mg/l. Witbank Dam, Boesmankranspruit, Olifants Tussen Bethal and Steenkoolspruit were the only sampling stations with average concentrations below the limit (refer to Figure 9).

INSERT FIGURE 9 HERE

Figure 9: Manganese levels within the Witbank Dam catchment

Manganese results from Witbank Dam had a process capability index of -0.09, which indicate that controls are not effective. Figure 9, which show process capability indices, indicate that there is

significant ineffective control of manganese. Results show that even though some of the sampling stations are below the limit, there is still inefficiency in the controls (considerable variation in manganese concentration), which poses a significant risk should there be an increase in concentration.

The high manganese concentration at levels of 250 ug/l will affect the taste of the water or staining clothes. However, chronic health effects are inflicted at levels greater than 400 ug/l. The average concentration was within the acceptable range for agricultural activities (0.02-10 mg/l). This concentration can, however, cause severe clogging of irrigation systems at 1.5 mg/l, while a range of 0.1 to 1.5 mg/l can cause moderate clogging problems.

High manganese concentration could be treated using an oxidising process which converts manganese into an insoluble oxide, after which it can be removed by filtration. Air or liquid chlorine gas can be used to oxidise the manganese. However, at elevated pH levels, above 9.5, manganese can be precipitated and removed via a settling tank. The only disadvantage of the latter process is increased sludge production and the need to reduce the pH level below 9 before it is distributed into the network. Excessive scaling of the pipes can also take place.

4. Discussion of Findings

The results from this study are summarised in Table 2. The analysis of the process capability index reveals that water coming from the catchment into Witbank Dam is neither acidic nor alkaline and it has a pH that is within the allowable potable water limit. The activities in the catchment are not producing or adversely affecting the pH content. However, water from the catchment had high sulphate content as per results taken from Koringspruit and Boesmankranspruit catchment areas. It is noted that there are significant coal mining activities along these catchment areas. The increased concentration of sulphates has adverse effects on the water purification process, as the plant may be unable to eliminate or reduce concentration. This therefore indicates that the management of pollution sources or treatment of sulphates and other associated contaminants are becoming a necessity in order to eliminate associated risks to water consumption along the catchment. It appears that the contaminated water from the catchment is diluted in the dam and/or is affected by settlement.

Table 2: Summary of average raw water data from two scenarios

Determinant	SANS 241:2015 allowable range	DWS catchment	ELM Witbank Dam raw water
pH	5 – 9.7	7.77	7.29
Sulphates in mg/l	Maximum of 250	314.30	152.24
Total dissolved solids in mg/l	Maximum of 1 200	619.89	403.68
Turbidity in NTU	1NTU	Not tested	2.37 NTU
Manganese in mg/l	Maximum of 0.1 mg/l	0.37 mg/l	4.02 mg/l

The high sulphate concentration, together with other heavy metals such as calcium, magnesium and sodium (refer to Table 2 above), leads to increased concentration of TDS. As seen in Figure 10, there is an increasing trend of TDS concentration. It can be observed that there was a major increase in TDS of 175 mg/l in a period of 18 months (September 2014 to March 2016). This trend can therefore be projected to determine future projections (refer to Figure 10 below).

INSERT FIGURE 10 HERE

Figure 10: Projected raw water TDS values against prescribed standards

Figure 10 above indicate that if TDS concentration continues as per the 2014 to 2016 trend, it is likely that by 2019, TDS concentration will increase to above 50% beyond the limit, becoming a major threat by 2020 and exceeding allowable limits by 2022. According to the Department of Water Affairs and Forestry domestic use guidelines (1996), a TDS concentration ranging from 1 000 to 2 000 mg/l is markedly salty and may not be utilised based on poor aesthetic appearance.

It can be seen that water from the dam has high turbidity (above the potable water standard limit), revealing a high volume of suspended solids entering the dam from the catchment, since the abstraction from the dam is high, but the settlement process has already taken place. The high volume of suspended solids can serve as a vehicle to transport microbiological and other contaminants to be discharged into the dam, and reduce the dam storage volume over a long period if desludging of the dam is not conducted frequently.

It can be observed that water from the catchment has high manganese content, which has high adverse aesthetic effects. The increased manganese concentration is based on samples taken from Koringspruit, Bethal Bridge and Duvha Bridge, which were 4.09, 0.99 and 0.79 mg/l, respectively, while the acceptable upper limit was 0.1 mg/l. The above sampling areas are in proximity to mining operations. It was observed that the water with high level of contaminants from the catchment is diluted in the dam. There are seasonal spikes of manganese that are discharged into the plant; this started in July 2015.

The South African weather seasons can be summarised as follows: (1) Summer: November to January (rainy season), (2) Autumn: February to April, (3) Winter: May to July, and (4) Spring: August to October (rainy season). Figure 11 below indicate sulphates and TDS results taken from Witbank Dam. It shows that there was a slight increase in TDS in summer compared to other seasons, ranging from 50 to 100 mg/l, but it was still below the required limit for potable water. The quality trends reported in this paper have not been correlated to seasonal variation.

INSERT FIGURE 11 HERE

Figure 11: Sulphates and TDS results for Witbank Dam

The ability of the quality of water to be controlled within the catchment area is summarised in Table 3.

Table 3: Summary of average contamination control capability in catchment and dam

Determinant	DWS catchment (Cpk)
pH	1.60
Sulphates in mg/l	-0.43
Total dissolved solids in mg/l	-0.59
Manganese in mg/l	-43.29

1. CONCLUSIONS

This project investigated the water quality in a mining region served by a single dam that collects water from distributed catchment areas. The motivation was to understand the water quality in the catchment areas and how it relates to the water collected in the dam.

1. The catchment raw water from the tributaries into the main stream, which supplies the municipal dam, is heavily contaminated. This means that the catchment water is not safe for local inhabitants to drink. There is a dilution factor and natural processes which take place along the stream and in the Witbank Dam; hence the dam is less concentrated in terms of controlled minerals. The monitoring of water quality reaching the dam cannot be assumed to be a good and reliable indicator of potential problems for people drinking the water in the catchment area.
2. While taken over a longer period, the average level of a contaminant may be within limits. A high standard deviation was characteristic of some sampled stations in the catchment areas and hence poor levels of contaminant control (poor process capability). This suggests that there could be a temporal dimension that needs to be understood in order to better tackle the level of dissolved salts. Additionally, it will be important to see if this can be correlated to activity or output within the mining regions.
3. It can also be concluded that the dam plays a critical role in neutralising the heavily contaminated water from the catchment before abstraction. This could therefore be a major challenge in the event that the dam level starts to drop (e.g. drought), since contaminants such as sodium are not eliminated through settlement and evaporation. More stringent monitoring of water quality through periods of drought should be done.
4. It can be noted that water management authorities play a critical role in monitoring water quality in the catchment, periodically (bi-weekly). It is recommended that the authorities consider the use of online water quality monitoring detection systems in addition to the existing manual system in order to detect failures as and when they occur and improve turnaround time in resolving them.
5. It can be concluded that deterioration in raw water quality will have an adverse financial impact on the municipality, as sophisticated technologies or increase in chemical usage may be required to eliminate contaminants. The deteriorating water quality has adverse health effects if municipal treatment processes are unable to eliminate contamination. It also has negative aesthetic effects which may be objectionable, depending on the level of contamination.
6. This study used the process control index C_{pk} as a generic measure that can be applied to track water quality. It is recommended that stakeholders use generic indices to develop amber and red lights for water quality and hence promote action. This should help simplify process control since actual limits do not have to be memorised by staff; instead, traffic light signals can be programmed and calibrated periodically.

It can be recommended that additional studies are required to be undertaken to better understand the sources of pollution throughout the catchment. These could cover: hydrogeological modelling to understand contaminated groundwater flows, assessments of bank erosion, agricultural runoff assessment, identifying dust sources, and developing and piloting treatment methods.

REFERENCES

- Adeleke, R.A., Bezuidenhout, C.C., 2011. Integrated Water Resources Management (IWRM) in South Africa - challenges of microbiology quality of water resources. African Journal of Science, Technology, Innovation and Development. 4, 55-64
- Akcil, A., Koldas, S., 2006. Acid mine drainage (AMD): causes, treatment and case studies. Journal of Cleaner Production. 12, 1139-1145
- Baptista, C., Santos, L., 2016. Water quality monitoring in the Paul do Boquilobo Biosphere Reserve. Physics and Chemistry of the Earth, Parts A/B/C, 180-187
- Behmel, S., Damour, M., Ludwig, R., Rodriguez, M., 2016. Water quality monitoring strategies—A review and future perspectives. Science of the Total Environment. 1312-1329

Brown, S.A.P., 1993. The Witbank Dam catchment. Retrieved 2017/03/01. http://www.who.int/water_sanitation_health/resourcesquality/wpccasestudy5.pdf

Department of Water Affairs, 2011a. Development of reconciliation strategy for the Olifants River water supply system. Pretoria

Department of Water Affairs, 2011b. Water requirements and water resource report. Pretoria

Department of Water Affairs, 2012. Witbank and Middelburg Dam catchments managed release of saline mine water: 2006/2007 to 2010/2011 hydrological years. Pretoria

Department of Water Affairs and Forestry, 1996. South African water quality guidelines. Agricultural use: irrigation, 4. Pretoria

Department of Water Affairs and Forestry, 1996a. South African water quality guidelines. Agricultural use: livestock watering, 5. Pretoria.

Department of Water Affairs and Forestry, 1996b. South African water quality guidelines. Domestic use, 1. Pretoria

Department of Water Affairs and Forestry, 1996c. South African water quality guidelines. Industrial use, 3. Pretoria

De Villiers, S., Mkwelo, S., 2009. Has monitoring failed the Olifants River, Mpumalanga? Water SA. 35, 671-676

Gao, L., Bryan, B.A., Liu, J., Li, W., Chen, Y., Liu, R., Barret, D., 2017. Managing too little and too much water: robust mine-water management strategies under variable climate and mine condition. Journal of Cleaner Production. 162, 1009-1020

IMIESA. 2010. The facts about AMD : acid mine drainage. IMIESA 35, 52-53.

Jadhav, S.V., Marathe, K.V., Rathod, V.K., 2016. A pilot scale concurrent removal of fluoride, arsenic, sulfate and nitrate by using nanofiltration: Competing ion interaction and modelling approach. Journal of Water Process Engineering. 13, 153-167

Khan, S., Shahanza, M., Jehan, N., Rehman, S., Shah, M.T., Din, I., 2013. Drinking water quality and human health risk in Charsadda district, Pakistan. Journal of Cleaner Production. 60, 93-101

Kefeni, K.K., Msagati, T.A.M., Mamba, B.B., 2017. Acid mine drainage: Prevention, treatment options, and resource recovery: A review. Journal of Cleaner Production. 151, 475-493

Li, H., Yang, Z., Liu, G., Casazza, M., Yin, X., 2017. Analyzing virtual water pollution transfer embodied in economic activities based on gray water footprint: A case study. Journal of Cleaner Production. 161, 1064-1073

Maree, J., Mujuru, M., Bologo, V., Daniels, N., Mpholoane, D., 2013. Neutralisation treatment of AMD at affordable cost. Water SA. 2, 245-250

Montgomery, D.C., 2007. Introduction to statistical quality control. John Wiley & Sons, New York.

Mulopo, J., 2015. Continuous pilot scale assessment of the alkaline barium calcium desalination process for acid mine drainage treatment. Journal of Environmental Chemical Engineering. 2, 1295-1302

NIST/Sematech Engineering Statistics Handbook. What is process capability? National Institute of Standards and Technology. Retrieved 2017/03/01. <http://www.itl.nist.gov/div898/handbook/pmc/section1/pmc16.htm>.

Nkhonjera, G.K., 2017. Understanding the impact of climate change on the dwindling water resources of South Africa, focusing mainly on Olifants River basin: A review. Environmental Science and Policy. 71, 19-29

Northey, S.A., Mudd, G.M., Saarivuori, E., 2016. Water footprinting and mining: Where are the limitations and opportunities? Journal of Cleaner Production. 135, 1098-1116

Regmi, G., Indraratna, B., Nghiem, L.D., 2009. Long-term performance of a permeable reactive barrier in acid sulphate soil terrain. Water, Air, & Soil Pollution: Focus. 9(5-6), 409-419.

South African National Standard 241-1:2015 Drinking water, Part 1: Microbiological, physical, aesthetic and chemical determinants. 241-2:2015 drinking water, Part 2: Application of SANS 241-1. SABS, Pretoria

Salem, M.G., Amin, E., 2012. Enhanced removal of dissolved iron and manganese from nonconventional water resources in Delta District, Egypt. Energy Procedia, 983-993

Van Zyl, H., Maree, J., Van Niekerk, A., Van Tonder, G., Naidoo, C., 2001. Collection, treatment and re-use of mine water in the Olifants River Catchment. Journal South African Institute of Mining and Metallurgy. 101, 41-46

Figure 1
[Click here to download high resolution image](#)

Figure 2
[Click here to download high resolution image](#)

Figure 3
[Click here to download high resolution image](#)

Figure 4
[Click here to download high resolution image](#)

Figure 5
[Click here to download high resolution image](#)

Figure 6
[Click here to download high resolution image](#)

Figure 7
[Click here to download high resolution image](#)

Figure 8
[Click here to download high resolution image](#)

Figure 9
[Click here to download high resolution image](#)

Figure 10
[Click here to download high resolution image](#)

Figure 11

[Click here to download high resolution image](#)

Revised Paper highlights

1. Importance: A new study covering surface and dam water mineral footprints in a mining region
2. Approach: Comprehensive multi-year study of water quality over dam catchment areas
3. Adventure: Process capability index as a generic measure for water quality monitoring
4. Impact: Critical warning that total dissolved salts are expected to increase beyond safe acceptable levels

Journal of Cleaner Production

Date: October 2017

Re: Reference paper no JCLEPRO-D-17-01711R3 (Water Quality in a Mining and Water-stressed Region)

Thank you for the response and reviewers feedback on the referred paper which was submitted for consideration and possible publication in the Journal of Cleaner Production. The table below provides the authors' feedback for each of the comments from the reviewers.

I hope you find this is order to reconsider the amended paper.

Ref. No.: JCLEPRO-D-17-01711R3

Title: Water Quality in a Mining and Water-stressed Region

Reviewer 1 comments	Responses
1) The authors should be commended for substantially improving the article through the review process. The article addresses an important water quality issue for the local region, which has flow on effects for community health. So on those grounds the article has merit. I see no further issue with the technical or quantitative aspects of the article. So my comments on the revised manuscript will be relatively limited.	Thank you.
(2) The first two paragraphs of introduction feel somewhat muddled and lacking a clear narrative. I would suggest having a think about what you clearly want to communicate to set the context for the study. The third and fourth paragraphs are much better. Also section 1.2 and 1.3 are much more focused, and the overall writing style from section 2 onwards is much better.	The revised and re-organised introduction text is left in dark blue font.
(3) [Page 2, Line 22] I would suggest 'with adverse affects ON the raw water quality', rather than 'IN the raw water quality'.	Done.
(4) [Page 12, Line 55] Change 'The could cover' to 'These could cover'.	Done.
(5) Figure 1 has been improved by the inclusion of the monitoring points. Due to this, Figure 3 now seems unnecessary as it is effectively a duplication of Figure 1 with less detail.	Done.