Assessment of Water Quality in the Witwatersrand Basin using Inorganic Contaminants

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Abstract
This study evaluated the quality of the surface water resources in the East Rand. Multivariate statistical tools (principal component analysis and hierarchical cluster analysis) were used to investigate how mining and other factors negatively influence the surface water quality. The water quality index (WQI) was used to assess how suitable the water is for domestic use. The results obtained indicate that in addition to mining activities, sewage discharges and industrial effluents also have a negative effect in the surface water quality. Poor water quality from anthropogenic sources should be properly treated before being discharged into the surface water resources.

Keywords: mining, water quality index, principal component analysis, hierarchical cluster analysis

Introduction
Economically, South Africa has benefited greatly from mining, resulting in one of the major economic hubs (Johannesburg) in Africa to be developed from gold mining activities. However, this economic development left a polluted environment due to improper disposal of mine waste such as mine residues and acid mine drainage (AMD) (fig. 1).

Mining activities have a negative effect of deteriorating the water quality. This is a problem that is being faced in the Witwatersrand Goldfields of South Africa such that these can lead to shortage of usable water in the future (Humphries et al. 2017). Anthropogenic activities such as mining, industrial effluent and sewage discharge may result in an elevated levels of metals such as Fe, Al, Mn, Pb, Cu, Co, U, Zn (Humphries et al. 2017) and anions (such as SO_4, NH_3, NO_3) in the water bodies. Enrichment of such metals in the water leads to the water being unsuitable for domestic use as well other uses such as agriculture (Wang et al. 2017). Polluted water may pose a potential risk to human health and livestock or aquatic ecosystems (Giri and Singh 2013). Mines often deposited tailings close to water bodies such as the Blesbokspruit in the East Rand Goldfield,

***Figure 1** Mine dump in West Rand Goldfield generating acid seepage*

The Wonderfonteinspruit in the West Rand and the Russell Stream in the Central Rand. Therefore leaching of the potentially toxic elements could negatively affect the quality of surface water. It is therefore crucial to protect water resources from contamination, mostly by anthropogenic activities (Wang et al. 2017). This study evaluates the effect of mining on the current water quality resources in the East Rand Goldfield. Multivariate statistical tools and water quality index were used to assess the surface water quality and the effecting factors.

Methods

Study area

Water samples were collected in the East Rand of the Witwatersrand Goldfields in South Africa as shown in fig. 2.

Sample collection and preparation

A total of 19 sites in the East Rand were sampled for the inorganic chemistry analysis. Samples were collected using 100 ml polyethylene bottles. Duplicate samples at each site were collected for quality control. Samples to be analysed for cations were preserved by adding 3 drops of concentrated HNO_3. Both cation and anion samples were preserved at 4 °C before being analysed using inductively coupled plasma mass spectrometry (ICP-MS) and ion-chromatography (IC) respectively.

Water quality index

Surface water quality in the East Rand Goldfield was evaluated using a comprehensive water quality index (WQI) tool. This reflects the integrated effect of different water quality variables as shown in Equation 1 below (Meng et al. 2016).

$$\mathrm{WQI} = \sum\left[W_i \times \left(\frac{C_i}{S_i}\right)\right] \times 100 \qquad (1)$$

Where W_i = the weight of each parameter i and was obtained on the basis of the eigenvalues for each principal component

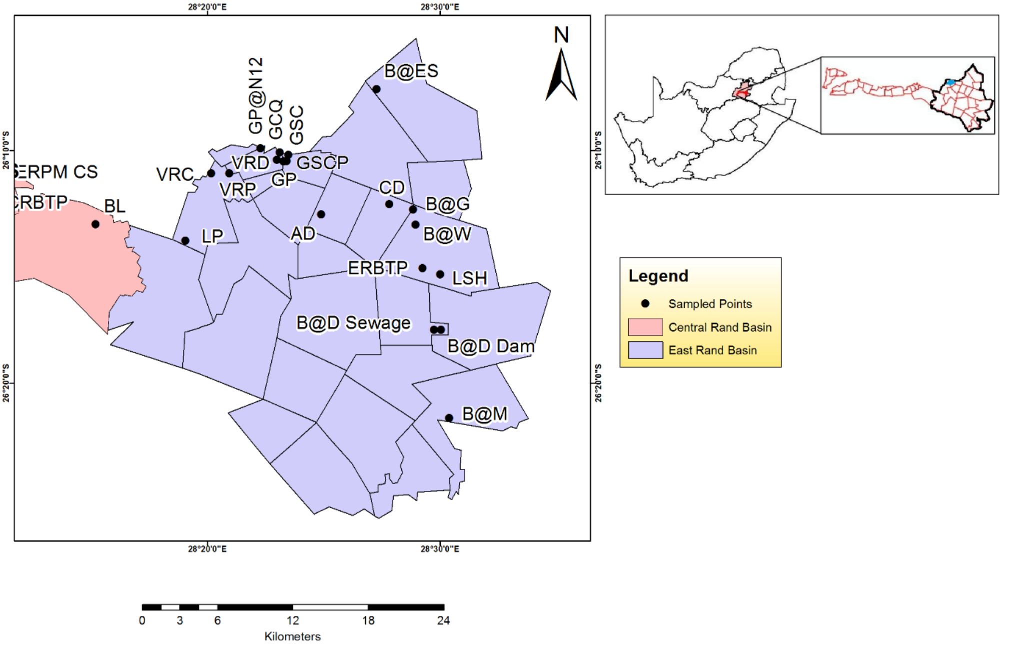

***Figure 2** The sampled points in the East Rand of the Witwatersrand Goldfields (Van Ryn Canal (VRC), Van Ryn Ponding (VRP), Van Ryn Downstream (VRD), Gravelotte Canal, (GC), Gravelotte ponding @N12 (GP@ N12), Gravelotte Sewage Canal (GSC), Gravelotte Sewage Canal Ponding (GSCP), Gravelotte outside Clay Quarry (GCQ) Gravelotte Ponding (GP), Leeupan (LP), Blesbokspruit at Esselen Street (B@ES), Blesbokspruit at Grootvlei (B@G), Blesbokspruit at Daggasfontein (B@D), Blesbokspruit at Marievale (B@M), Blesbokspruit at Welgedacht (B@W), Largo Sinkholes (LSH), Alexander Dam (AD) and Cowles Dam (CD)*

and factor loading for each parameter from the PCA results, and represents the relative importance of each water quality parameter for drinking purpose. C_i = concentration of the element in the water sample and S_i = drinking water limit obtained from South African water quality guideline and the World Health Organisation (DWAF 1996 and WHO 2011).

According to Meng et al. (2016), the WQI classify water into five categories: WQI < 50 means that the water is of excellent quality; 50 ≤ WQI < 100 means that the water is of good quality; 100 ≤ WQI < 200 means that the water is of poor quality; 200 ≤ WQI < 300 means that the water is of very poor quality and WQI ≥ 300 means that the water is of extremely poor quality.

Statistical analysis

Principal component analysis (PCA) and hierarchical cluster analysis (HCA) were used to investigate how mining and other factors influence the surface water quality in the basin. PCA places the principal components in a way that the ones contributing most in the variance of the dataset are classified as the first and the ones that contribute less are taken as the last principal components (Kura et al. 2013). HCA groups variables into clusters in terms of how closely related they are to each other and how different they are from the rest of the groups (Kura et al. 2013). Data processing was done using Microsoft Excel 2010 and the Statistical package for social sciences (IBM SPSS 22).

Results and discussion

Water quality assessment

Surface water quality was assessed by comparing the concentrations of all the parameters in the water with their respective drinking water standards according to DWAF (1996) and WHO (2011) as shown in tab. 1.

It was noted that NH^3 concentrations at sites B@D sewage, GSC, GSCP and GC are above the drinking water limits. Also, B@M, LSH and B@D dam and B@D sewage had concentrations that exceeded the drinking water quality standards for SO_4^{2-} and Fe respectively. Maximum permissible limit of sulfate in drinking water as described by WHO (2011) is 250 mg/L with high SO_4^{2-} concentrations in water potentially causing laxative effects (Annapoorna and Janardhana 2015). Conversely, >0.3 mg/L concentrations of iron gives water a bad taste and odour and it stains laundry (DWAF 1996 and WHO 2011). Levels of ammonia in drinking water should be below 1 mg/L (WHO, 2011) such that concentrations above may change the taste and odour of the water (DWAF 1996).

Table 1 *Drinking water quality limits (DWAF, 1996; WHO, 2011) and descriptive statistics for the parameters*

Parameter	limit	Min	Max	Parameter	limit	Min	Max
As	0.01	0.01	0.01	Li	2.50	0.01	0.04
B	2.40	0.01	0.42	Mg	150.00	5.06	46.25
Ba	0.70	0.01	0.07	Mn	0.10	0.03	2.18
K	12.00	4.43	16.40	Ni	0.07	0.01	0.03
Na	200.00	21.75	121.75	P	-	0.01	2.42
Sr	-	0.07	0.33	U	0.03	0.01	0.03
Ti	-	0.02	0.10	Ca	200.00	25.47	188.00
Zn	3.00	0.03	0.58	Cl	250.00	27.75	105.50
Al	0.1-0.2	0.10	0.17	SO_4^{2-}	250.00	14.50	**609.50**
Co	-	0.01	0.02	NO_{3^-}	11.00	0.05	7.85
Cu	2.00	0.01	0.01	F	1.50	0.20	0.58
Fe	0.30	0.04	**0.48**	NH_3	1.00	0.10	**23.00**
EC (µS/cm)	700.00	264.00	**1643.00**	Alkalinity	300.00	0.17	109.46
pH	9.20	7.50	9.00				

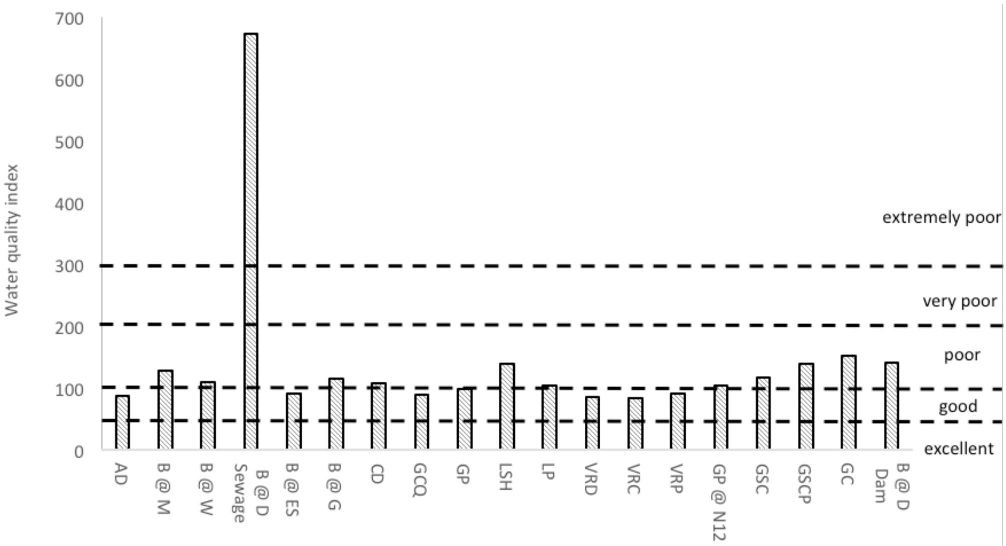

Figure 3 *WQI of the surface water collected in East Rand Golfields*

Water quality index

Weights (W_i) of each parameter were calculated on the PCA as shown in tab. 2. Using the W_i from tab. 2 and the limits obtained from South African water and WHO water guidelines, the WQI was calculated for the East Rand Goldfield. Results obtained are depicted in fig. 3.

Results in fig. 3 show that the water quality in East Rand Goldfields is generally poor with exception AD, B@ES, GCQ, VRC, VRP and VRD that showed a good water quality. B@ES is at the uppermost upstream of the Blesbokspruit, and the water samples did not seem to show substantial elevation in any ions. Similarly, water sampled at VRC, VRP and VRD, flows from Kleinfontein Lake, and is currently not vulnerable to contamination by sewage or mining activities. This is because the surface water in the Van Ryn area is diverted from the mining sites by a canal. Therefore all this water is potable and can be used for domestic purposes.

There are sites that displayed poor water quality (fig. 3) due to increasing concentrations of SO_4^{2-} and NH_3. Sites that displayed high NH_3 concentrations are B@D sewage, GC, GSCP and GSC because of either water mixed with sewage or direct sewage sampled for analysis. The presence of ammonia in the water may be from agricultural and industrial processes or sewage pollution (WHO 2011). LSH, B@D, and B@M showed an increase in SO_4^{2-} concentration. This can be a result of mining activities in the area since SO_4^{2-} rich mine water from the Eastern Basin Mine Water Treatment Plant is released to the Blesbokspruit after treatment and leachates from mine residues pollute water in this catchment. This water therefore pollutes Largo Sinkholes towards the downstream of the Blesbokspruit. Surface water quality deterioration was observed from midstream of the Blesbokspruit and this may also be influenced by mining activities since the spruit passes close to the gold mine tailings. Water in the CD and GP also showed deterioration in its quality because of sewage mixing that was happening in these areas.

Principal Component Analysis

Tab. 2 shows PCA results (variables, loading values and eigenvalues) as acquired from SPSS. This technique shows that SO_4^{2-}, Cl, Ca, Mg, Li, Ti and Na contributes a total variance of 33.5% in altering the surface water quality. Component 2 with a variance of 28.2% displayed Fe, Mn, NH_3, Cu, Co, Al and Zn to be the second highest contributing group to the water quality change. As obtained from the PCA results, metals and ions that appeared under PC1 and PC2 could be related

Table 2 PCA analysis and the calculated weights for the East Rand of the Wits Goldfields

PC	Eigenvalue	Relative eigenvalue	Variable	Loading value	Relative loading	Weight
1	9.06	0.40	B	0.52	0.05	0.02
			K	0.56	0.06	0.02
			Na	0.92	0.09	0.04
			Sr	0.71	0.07	0.03
			Ti	0.94	0.10	0.04
			Li	0.87	0.09	0.04
			Mg	0.88	0.09	0.04
			Ni	0.66	0.07	0.03
			EC	0.98	0.10	0.04
			Ca	0.94	0.10	0.04
			Cl	0.87	0.09	0.04
			SO_4^{2-}	0.90	0.09	0.04
			total	9.74	1.00	
2	7.6	0.34	Zn	0.95	0.12	0.04
			Al	0.87	0.11	0.04
			Co	0.95	0.12	0.04
			Cu	0.96	0.13	0.04
			Fe	0.82	0.11	0.04
			Mn	0.90	0.12	0.04
			Ni	0.56	0.07	0.03
			P	0.68	0.09	0.03
			NH_3	0.97	0.13	0.04
			total	7.65	1.00	
3	3.2	0.14	As	0.62	0.45	0.06
			Ba	0.74	0.55	0.08
			total	1.36	1.00	
4	2.7	0.12	U	0.52	1.00	0.06
total	22.56	1.00	**total**	0.52	1.00	0.94

to mining, industrial and sewage discharges. This is because these were assumed to be the most influencing anthropogenic sources to the surface water quality. However, concentrations of ions such as Ca and Mg could be related to weathering of the rocks that interacts with water along its flow path, in particular the dolomite which outcrops and suboutcrops extensively in the study area. Nonetheless, these ions do not have a negative effect to the water quality since their concentrations are within the drinking water standards.

Hierarchical cluster analysis

The dendrogram shows four groups as indicated by fig. 4. Group 1 is composed of sites that displayed good water quality as calculated by the WQI. This is the water that is not influenced negatively by the mining activities and can therefore be used for domestic purposes. Group 2 on the other hand shows sites that are highly contaminated by sewage since they showed an increase in NH_3. This water fell within the poor water quality as displayed by fig. 3.

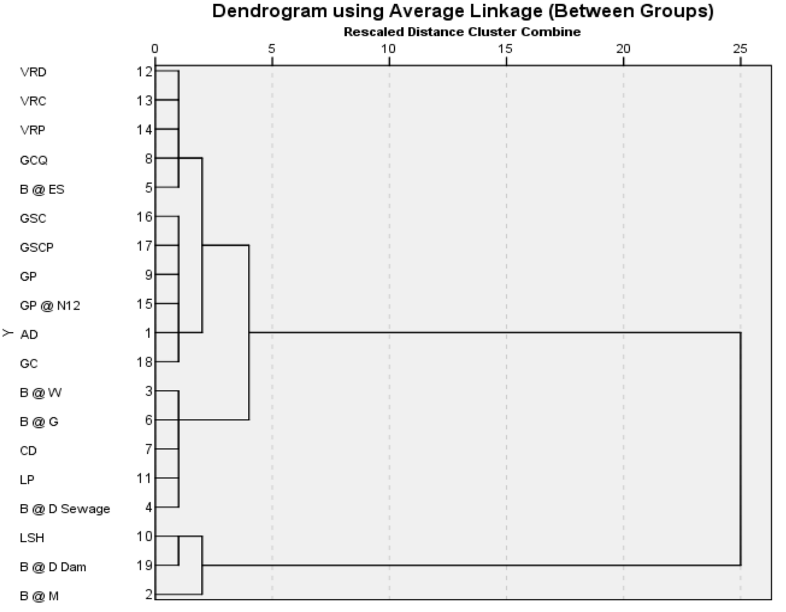

Figure 4 *Dendrogram constructed on agglomerative hierarchical clustering for 19 sites in the East Rand*

Sites that showed deterioration in their water quality were clustered together as group 3. Lastly, group 4 is composed of sites that displayed poor water quality because of their high SO_4^{2-} concentrations as a result of mining activities and industrial wastes. Contamination of these sites occurs from one site to the next along the river flowpath.

Conclusions

Multivariate statistical tools (PCA and HCA) and the WQI were used to investigate the main influences of surface water quality. This study indicates that mining activities, industrial effluents and sewage discharge around the East Rand Golfield have an effect in the surface water quality. This was noted from elevated concentrations of SO_4^{2-}, Fe and NH_3 in the water. PCA results also indicated that metals such as Al, Co, Cu, Mn as well as Cl and Ca had an effect in altering the water quality. However, as confirmed by the tools, there are other sources within the basin that still indicated good water quality signature for domestic use. The WQI results showed one site with extremely poor water quality due to contamination by sewage. To improve the surface water quality in this basin, tailing dumps that are next to the water bodies needs to be removed. Also, treatment plants should avoid discharging treated water back to the streams, unless it is of good quality. Lastly, proper sewage channels from human settlements must be installed to avoid raw sewage water mixing with surface water.

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