A reduction in mining and industrial effluents in the Blesbokspruit Ramsar wetland, South Africa: Has the quality of the surface water in the wetland improved?

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ABSTRACT

The Blesbokspruit Wetland, 40 km southeast of Johannesburg, South Africa, was listed as a Ramsar Wetland of International Importance in 1986. Following discharges of mine-waters in the mid-1990s, the wetland no longer complied with the Ramsar criteria. This paper reports on historical trends in surface water quality of the Blesbokspruit, as a step towards restoration to Ramsar status. Monthly water quality data (SO_4, Na, Cl and Mg concentrations, pH and EC values), from January 2000 to December 2011, were obtained from Rand Water for sites at: the stream inflow, just after the discharge point of pumped underground mine-water from Grootvlei mine, and the stream outflow point. The major ions were grouped into two distinct time-variation patterns (SO_4-Mg) and (Na-Cl). Despite extensive reports that the wetland had an acid mine drainage problem, the pH values over an 11-year period were constrained within a range of 6.7 to 8.8. In 2011, following the cessation of underground mine-water pumping operations, mineralisation of the Blesbokspruit showed a large stepwise reduction, in contrast to a slowly decreasing trend over the previous 10 years, in both the SO_4-Mg and Na-Cl groups, and EC. The stepwise reduction suggests that the pulping plant within the paper mill, a major source of Na-Cl rich effluent, had ceased operations coincidentally with the cessation of underground water discharges. This contradicts previous findings that underground mine-water discharge was the principal contributor to contamination of the Blesbokspruit Wetland. So, while the Blesbokspruit may have had a high mineralisation problem, this was not simply an acid mine drainage problem, but a combination of the effects of mining and industry.

Keywords: acid mine drainage, underground mine-water, Blesbokspruit, Montreux Record, Grootvlei Mine, water quality, circumneutral, Ramsar

INTRODUCTION

> *Dewatering of mine shafts contributes large quantities of poor quality water to the Blesbokspruit. Fish kills have occurred due to the presence of a red iron precipitate in the discharged water….The site has been listed on the Montreux Record due to upstream and adjacent activities, which threaten the ecological nature of the site.*
> South African Wetlands Conservation Programme (1999)

Approximately 40 km south-east of Johannesburg, between 26° 12'S – 26° 23'S latitude and 28° 29' – 28° 32'E longitude, is the Blesbokspruit Wetland, designated by the Ramsar Convention as a Wetland of International Importance (Haskins and Compaan, 1998; Ekurhuleni Municipality, 2008). This wetland is one of the largest in Southern Africa, and the only Ramsar site in Gauteng Province, covering an area of 1 858 ha in the Ekurhuleni Metropolitan Municipality, at an altitude of 1 585 m amsl (AngloGold Ashanti, 2004; Ekurhuleni Municipality, 2008; Du Plessis et al., 2014). The Blesbokspruit Wetland is surrounded by 5 towns in the East Rand region – Springs, Boksburg, Benoni, Brakpan and Nigel – making this wetland an important ecosystem within a highly urbanised economic hub. The wetland serves as a buffer for the water entering the Vaal River, the main source of water for Gauteng's socio-economic activities (Eastern Basin Blesbokspruit Catchment Task Team, 2006; Hoare et al., 2008; Du Plessis et al., 2014).

The Blesbokspruit Wetland was first recognised as a Ramsar Wetland of International Importance in 1986 because of the important wildlife, especially waterfowl, it supported during its accreditation period (De Wet et al., 1990; Dini, 1999; Birdlife South Africa, 1998; South African Wetlands Conservation Programme, 1999; AngloGold Ashanti, 2004). The Blesbokspruit Wetland became severely degraded when mine-water discharges were permitted, starting in 1995, to prevent flooding of the underground East Rand hydrological compartment, linking several operating and decommissioned gold mines. Water in the Blesbokspruit Wetland became highly saline and acidic (Scott, 1995; Wood and Reddy, 1998; Van Wyk and Munnik, 1998; Thorius, 2004; Schoeman and Steyn, 2001; Jones and Wagener, 2011; Nyeleti Network for Built Environment, 2011). The Blesbokspruit Wetland was then declared ecologically degraded, and in 1996 this Ramsar site was included in the Montreux Record, a register which lists potentially threatened or degraded Ramsar sites that are no longer in compliance with criteria of the Ramsar Convention (South African Wetlands Conservation Programme, 1998; Ramsar Convention Secretariat, 2007; Adair et al., 2012; Durand, 2012; De Wet and Sidu, 2013; Du Plessis et al., 2014).

Because of past and ongoing secondary salinity and acidic waters threats, continuous monitoring and improvement of surface water quality became conditions for reinstatement of the Blesbokspruit to international Ramsar status (Ramsar

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Convention Secretariat, 1996; Dini, 1999; Kotze, 2000; Richards, 2001; Collins, 2005; Mulungufhala, 2008; Liefferink and Van Eeden, 2010; Macfarlane and Muller, 2011; Coughlan, 2013). Secondary salinity is a widespread phenomenon that affects inland freshwater systems, including wetlands (Kerekes et al., 1986; Cortecci et al., 2002; Nielsen et al., 2003; Clark et al., 2006). Increasing salinity in inland wetlands poses the problem of unsustainable use of natural resources, with many environmental and socioeconomic repercussions (Williams, 2001; Schuyt and Brander, 2004; Australian Department of Environment and Conservation, 2012). More importantly, the ecological character of freshwater wetlands becomes compromised, with a progressive deterioration in their abiotic and biotic features (James et al., 2003; Castañeda and Herrero, 2008).

Since the Grootvlei Mine incidents in the mid-1990s, acid mine drainage in the Blesbokspruit Wetland has been monitored and addressed by relevant authorities, the management of Grootvlei Mine and other stakeholders within the Blesbokspruit catchment (Scott, 1995; South African Wetlands Conservation Programme, 1999; Eastern Basin Blesbokspruit Catchment Task Team, 2006; Ryan, 2009; South African National Assembly, 2009; Macfarlane and Muller, 2011; Department of Water Affairs, 2013). As part of acid mine drainage management measures, Grootvlei Mine was mandated to install underground mine-water treatment plants and comply with its water use licence requirements (Wood and Reddy, 1998; Van Wyk and Munnik, 1998; Bowell, 2000; Schoeman and Steyn, 2001; Van der Merwe and Lea, 2003; Lea et al., 2003; Durand, 2012). However, because of management and technical problems, Grootvlei Mine was unable to comply with its water use permit in relation to underground mine-water discharges into the Blesbokspruit Wetland. With another change of ownership, Grootvlei Mine faced financial difficulties, which contributed to the complete cessation of underground mine-water discharge in December 2010 (Van der Merwe and Lea, 2003; Naidoo, 2009; Saving Water SA, 2010; De Wet and Sidu, 2013). The year 2011 was thus another transition point in the history of underground mine-water pumping operations in the Blesbokspruit Wetland, with the complete shutdown of Grootvlei Mine (Durand, 2012; De Wet and Sidu, 2013; Department of Water Affairs, 2013). In parallel, during the year 2011, the pulping plant at Sappi Enstra paper mill in Springs was decommissioned and was no longer discharging waters high in dissolved salts into the Blesbokspruit water system (Sappi, 2011).

The importance of this study is that a progressive improvement in the surface water quality of the Blesbokspruit Wetland could motivate the Department of Environmental Affairs to apply for the delisting of this Ramsar site from the Montreux Record (Ramsar Convention Secretariat, 1996; Macfarlane and Muller, 2011). This would be possible if there were a consistent reduction in salt levels or ionic concentrations as well as no acidic waters running through the Blesbokspruit Wetland (Ramsar Convention Secretariat, 1996; South African Wetlands Conservation Programme, 1999; Ramsar, 2012). Achieving desirable water conditions in Ramsar terms could help South Africa, a pioneer Ramsar Contracting Party, recover from the socio-political and environmental criticisms associated with the degradation of the only Ramsar site in Gauteng Province (Barker, 1995; Haskins and Compaan, 1998; South African Wetlands Conservation Programme, 1998; South African National Assembly, 2009; Macfarlane and Muller, 2011; Durand, 2012).

As a water-scarce country, South Africa needs to wisely use its existing water resources, which include the Blesbokspruit Wetland (Uys, 2004; Ekurhuleni Metropolitan Municipality, 2008; Du Plessis et al., 2014). The Blesbokspruit Wetland is an important source of water for irrigation, livestock, sociocultural, recreational, domestic and industrial activities as well as sustaining aquatic biota within highly urbanised and industrial surroundings (South African Wetlands Conservation Programme, 1999; Van der Merwe, 2003; Thorius, 2004; Naledzi Environmental Consultants, 2007; Ekurhuleni Municipality, 2008; Macfarlane and Muller, 2011). On these grounds, water resources, like the Blesbokspruit Wetland, should be protected from any pollution and degradation because they contribute to the sociocultural and economic upliftment of the country (National Water Act (Act No. 36 of 1998); Collins, 2005; Mulungufhala, 2008; Du Plessis et al., 2014).

This study sets out to provide an updated assessment of progress towards re-establishing the suitability of the surface water in the Blesbokspruit Wetland for a possible removal from the Montreux Record by assessing historical trends in surface water quality. Despite the large outcry about possible acid mine drainage in the Blesbokspruit Wetland, there has not been a previously published interpretation of the available water quality record generated through the continuing sampling activities of Rand Water.

METHODS

Monitoring sites and sampling

The Blesbokspruit Wetland forms part of the Blesbokspruit catchment, a locality which falls within the Upper Vaal Catchment Management Area section C21E (Hoare et al., 2008). Water resources in this catchment are the responsibility of the Department of Water and Sanitation and Rand Water (a parastatal company) (Blesbokspruit Forum, 2003; De Fontaine, 2012; DWS, 2015). Rand Water established a monitoring network in the Blesbokspruit as far back as 1975, with sites ranging from B1 to B17 (De Fontaine, 2012). For this paper, monthly historical water quality records from 2000 to 2011 for 3 monitoring sites within the Blesbokspruit Wetland have been examined: (i) Site B5 at the stream inflow to the wetland; (ii) Site B16 just after the discharge point of pumped underground mine-water at Grootvlei Mine Shaft No. 3; and (iii) Site B11 at the stream outflow from the designated wetland area (Fig. 1). The sampling locations are shown in Fig. 1, with the positions of gold mines and tailings storage facilities that may affect surface water quality (Table 1). The area surrounding the wetland is more than 45% urbanised, with agricultural lands, tailing dams, and industrial land use comprising the remainder (AngloGold Ashanti, 2004; Du Plessis et al., 2014).

Sampling and analytical methods

The dataset obtained from Rand Water consisted of fortnightly monitored water quality parameters from January 2000 to December 2011. Water parameters that might be associated with the reported dissolved salt concentration and acidity in the Blesbokspruit Wetland were selected: Na, SO_4, Cl, Mg, EC and pH. The selected parameters had few missing values, and concentrations for the selected chemical species were generally above detection limits. The concentrations of several chemical species were omitted because they were only intermittently above detection limits and thus are not suitable for time-series

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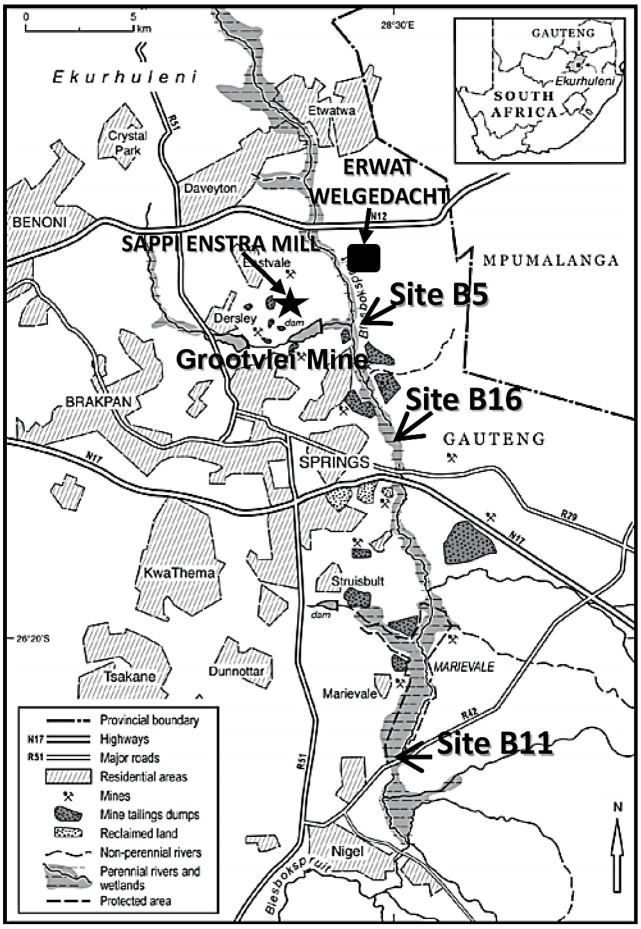

Figure 1

Sampling points (arrows) along the Blesbokspruit Wetland: Site B5 – inflow point; Site B16 – underground water discharge point; Site B11 – outflow point: and upstream industrial/mining water pollution sources ERWAT wastewater treatment plant, Sappi Enstra paper mill and Grootvlei Gold Mine (Ambani, 2013)

TABLE 1
The upper, middle and lower water monitoring sites in the Blesbokspruit Wetland, with surrounding activities and land use as possible sources of water pollutants

Site	Coordinates	Description and pollution influence
B5	28°28'48.22''E 26°12'52.63''S	Site located at the inflow of Blesbokspruit Wetland — receives runoff/ outflow from upstream water users/ land use, such as ERWAT's Welgedacht and McComb sewerage works, Welgedacht road, Geduld Mine tailings dam, Cowles Dam, Sappi Enstra paper mill, and residential areas
B16	28°30'4.42''E 26°15'31.17''S	Site located within the wetland, downstream of Grootvlei Mine Shaft No. 3 discharge point of pumped underground water (1995–2010). Receives major flow from inlet point (B5), plus runoff/ outflow from a minor unnamed tributary flowing in from the west.
B11	28°29'50.25''E 26°23'25.99''S	Located at the outflow of Blesbokspruit Wetland, within the Marievale Bird Sanctuary. Receives runoff/ outflow from upstream (B5 and B16), plus runoff from gold mine tailings located on both sides of the main water channel downstream of B16 and residential areas.

analysis. This includes parameters, such as calcium and alkalinity, that are important when characterising acid mine drainage. The sampling procedure, preservation, transportation and analysis of the water samples by Rand Water technicians followed standard methods and protocols (Rand Water, 2012).

Data treatment

For further analyses, the dataset was cleaned – values outside physical limits and below analytical detection limits were labelled as missing values. These 11-year series had ~1 300 records for each parameter at each sampling locality. For years when samples were collected fortnightly, the two values were combined into monthly averages. In later years, the sampling frequency was reduced to monthly sampling. Initial inspection of the inter-annual variations showed a distinct discontinuity in concentrations at the end of 2010. This date coincided with the documented cessation of pumping of underground water and discharge into the Blesbokspruit. Accordingly, the records were then divided into two distinct periods, i.e., water quality data collected during years 2000 to 2010; and that collected from January to December 2011. Records from the three sites were used to establish spatial gradients along the course of stream flow, and monthly and seasonal changes over the two distinct periods. Spatial gradients and seasonal variations were represented in graphs of monthly averages at each of the three sites, for each chemical or physical parameter. Descriptive statistics were applied to the water quality data to test the significance in changes of ionic concentrations, conductivity and pH in the Blesbokspruit Wetland between the two periods (during continuous underground pumping 2000–2010; and 2011 after cessation of pumping).

RESULTS AND DISCUSSION

Major ionic species in waters of the Blesbokspruit Wetland include Na, Cl, Mg and SO_4, which were regularly well above the detection limits (Tables 2 to 6). The monthly mean ionic concentrations showed distinct spatial gradients and seasonal variations (Figs 2 to 5).

Spatial gradients and source of elevated sulphate and magnesium concentrations

Over the period 2000–2010, sulphate (SO_4) and magnesium (Mg) concentrations followed similar spatial patterns (Figs 2a, 2b, 2e and 2f). At the inlet site B5, SO_4 and Mg concentrations were low, then increased by a factor of 4.5 (SO_4) and 3.1 (Mg) at the mine-water discharge point B16, and sustained high levels at the outlet B11 (Table 2 – spatial increment ratio). This increase at the downstream sites is consistent with Mg and SO_4 mineralisation from underground mine-water pumping operations at Grootvlei Mine Shaft No. 3.

By contrast, the year 2011 showed a minor spatial variation in SO_4 and Mg concentrations, with concentrations at the discharge and outlet points being reduced by a factor of 2.1 (Mg) to 3.2 (SO_4) compared to previous years (Table 2 – spatial increment ratio and Figs 2c, 2d, 2e and 2f). The inlet B5 still had the lowest overall SO_4 and Mg concentrations compared to the downstream sites B16 and B11. The distinct spatial gradients of SO_4 and Mg concentrations of earlier years did not show in 2011, since the pumping of underground mine-water at B16 stopped at the end of 2010.

SO_4 and Mg concentrations showed a different level of variability from their respective means over the period 2000–2010

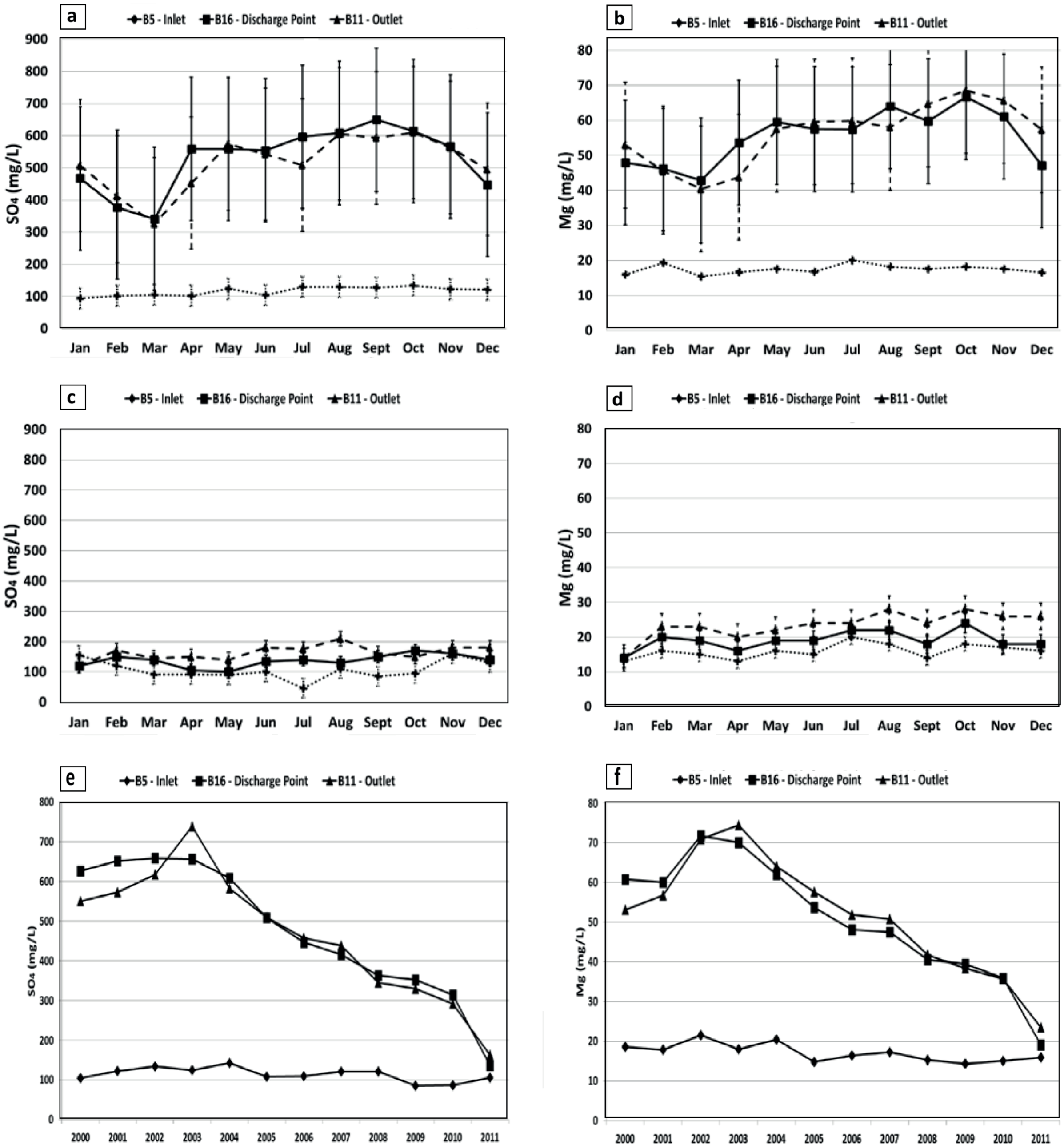

Figure 2

Spatial and seasonal concentrations at inlet, discharge and outlet sampling points of: monthly average (a) SO4 and (b) Mg from 2000 to 2010; (c) SO_4 for 2011; and (d) Mg for 2011. Annual average (e) SO_4 and (f) Mg, from 2000 to 2011. Error bars indicate monthly standard deviation over both periods (2000–2010 and 2011).

at the different sampling points (Table 2 and Figs 2a and 2b). At the inlet B5, the ranges for SO_4 and Mg concentrations were less pronounced, and their standard deviations showed little variability from their means compared to values for the mine discharge point B16 and the outlet B11 (Table 2). This implies that Mg and SO_4 contamination was the result of discharge of underground mine-water enriched with Mg and SO_4 rather than upstream activities during the period 2000–2010. By contrast, in 2011, the differences in the ranges and variability in Mg and SO_4 concentrations were significantly reduced at the downstream sites B16 and B11, while at the inlet, B5, these values did not change significantly (Table 2 and Figs 2e and 2f).

Seasonal variations in SO_4 and Mg concentrations

Seasonally, over the period 2000–2010, SO_4 and Mg concentrations at the two downstream sites were at the highest levels during the dry season (May through October), with reduced dilution in the absence of rain and surface runoff. In contrast, concentrations start decreasing with the onset of the rainy season (October) and reach the lowest values in March, especially for the downstream sites receiving SO_4 and Mg-rich waters from the underground works (Figs 2a and 2b). At the inlet (Site B5), there are no obvious seasonal variations of SO_4 and Mg. By contrast, in 2011, the previous seasonal variations were lacking

TABLE 2
Descriptive statistics for SO_4 and Mg concentrations for the periods 2000–2010 and 2011. The B16 discharge point is after the discharge point of underground mine-water

	SO_4 (mg/ℓ)						Mg (mg/ℓ)					
	2000–2010 *n* = 132			2011 *n* = 12			2000–2010 *n* = 132			2011 *n* = 12		
	B5 Inlet	B16 Discharge	B11 Outlet	B5 Inlet	B16 Discharge	B11 Outlet	B5 Inlet	B16 Discharge	B11 Outlet	B5 Inlet	B16 Discharge	B11 Outlet
Mean	114	510	496	106	137	163	17	54	54	16	19	24
Median	110	460	468	98	140	165	17	51	53	16	19	24
Std. dev.	33	220	206	32	21	24	4.1	18	18	2.1	2.7	3.8
Rel. std dev.	29%	44%	42%	30%	15%	15%	24%	33%	33%	13%	14%	16%
Std. error	2	20	18	9	6	7	0.4	1.6	1.6	0.6	0. 8	1.1
Minimum	54	53	100	46	100	120	11	17	10	13	14	14
Maximum	280	1 460	1 350	160	170	210	36	135	97	20	24	28
Spatial increment ratio (relative to inlet)	1.0	4.5	4.3	1.0	1.3	1.5	1.0	3.1	3.1	1.0	1.2	1.5

at the downstream sites, while the inlet maintained the previous lack of seasonality (Figs 2c and 2d).

The combined results of both periods confirm that, in the absence of underground mine-water discharge operations at Grootvlei Mine Shaft No. 3, SO_4 and Mg concentrations revert to values similar to concentrations at the inlet to the wetland. The concentrations at downstream sites are reduced by factors 2.8 to 3.2 for SO_4, and by 1.6 to 2.1 for Mg (Figs 2e and 2f).

In summary, elevated SO_4 and Mg concentrations in the Blesbokspruit Wetland (from the discharge point B16 to the outlet B11) were a direct result of the discharge of underground mine-water, high in mineral content, until the pumping activities ceased in December 2010. This fluctuation could be explained by the seasonal and inter-annual discharges of SO_4 and Mg salts by Grootvlei Mine (as portrayed by SO_4 and Mg concentration values at the discharge point Site B16). This explains why, when water exited the Blesbokspruit Wetland at the outlet B11, SO_4 and Mg concentration values were still comparatively high in both the rainy and dry seasons for the period 2000–2010, implying that external factors such as geology contribute to pre-existing sulphate and magnesium minerals (Harrison, 1958; DWA, 2013; Nordstrom et al., 2015). Nevertheless, after December 2010 (and the cessation of the pumping operations at Grootvlei Mine), SO_4 and Mg concentrations downstream of the inlet B5 at the Blesbokspruit Wetland decreased significantly, even if they were still marginally higher than concentrations at the inlet.

Spatial gradients and source of elevated sodium and chloride concentrations

Over the period 2000–2010, spatial trends in sodium (Na) and chloride (Cl) concentrations were flat. At the inlet B5, Na and Cl concentrations were already high compared to contents in fresh surface water, but similar to concentrations at the discharge point B16 and outlet B11 (Figs 3a, 3b, 3e and 3f; and Table 3). A step increase, similar to that observed for SO_4 and Mg concentrations at the discharge point, is entirely absent. This implies that Na and Cl primarily originated from an upstream source before entering the Blesbokspruit Wetland at B5, and that the underground discharged mine-water did not add to these species. The presence of Na and Cl contamination could be associated with upstream industries, such as a pulp and paper mill, wastewater plant, abandoned coal mines or gold mine tailings.

In 2011, Na and Cl concentrations showed decreases at all three locations (Table 3 and Figs 3c and 3d). However, the fractional reductions for Na and Cl were smaller than for SO_4 and Mg. Similar to the 2000–2010 period, there are no obvious spatial gradients for 2011 (spatial increment ratios, last line of Table 3), in contrast to the spatial changes in SO_4 and Mg for both periods.

When comparing the two periods, there are two notable changes: (i) the absolute concentrations of both Na and Cl reduced by x1.6 on average over the three locations; and (ii) these reductions contrasted with the larger reductions for SO_4 (x3.0) and Mg (x1.8) at the downstream sites. The spatial variations and the comparable magnitude of reduction in concentrations at all three sites confirm that Na and Cl contamination found in the Blesbokspruit Wetland did not originate primarily from underground mine-water discharges, rather from upstream industries and land use. Nevertheless, the coincident reduction of Na and Cl from 2010 to 2011 does require a separate explanation.

The separation of the dataset into two periods was based on the stepwise reduction of SO_4 and Mg that occurred at the end of 2010, coinciding with the well-publicised cessation of underground mine-water pumping operations. During the course of this investigation, it was discovered that Sappi Enstra, located in the Springs industrial area upstream of Blesbokspruit, had simultaneously but coincidentally decommissioned their pulping plant at the end of 2010. The discharges from pulping plants contain elevated concentrations of Na and Cl. However, industries are not legally obligated to treat Na- and Cl-rich waters prior to discharge, nor to report on quantities of such discharges (SRK, 1990). Thus, despite the paper company being a regular participant in the Blesbokspruit Forum over the decade, the Na and Cl concentrations in the Blesbokspruit had not been associated with upstream industrial discharges. This circumstantial evidence is in line with previous research on low alkalinity caused by industrial and mining effluents. In water resources such as the Blesbokspruit Wetland, acid mine drainage does not result in low pH because the solubility and/or precipitation of certain heavy metals increase the water pH (Harrison, 1958; Van der Merwe et al., 1990). This explains why

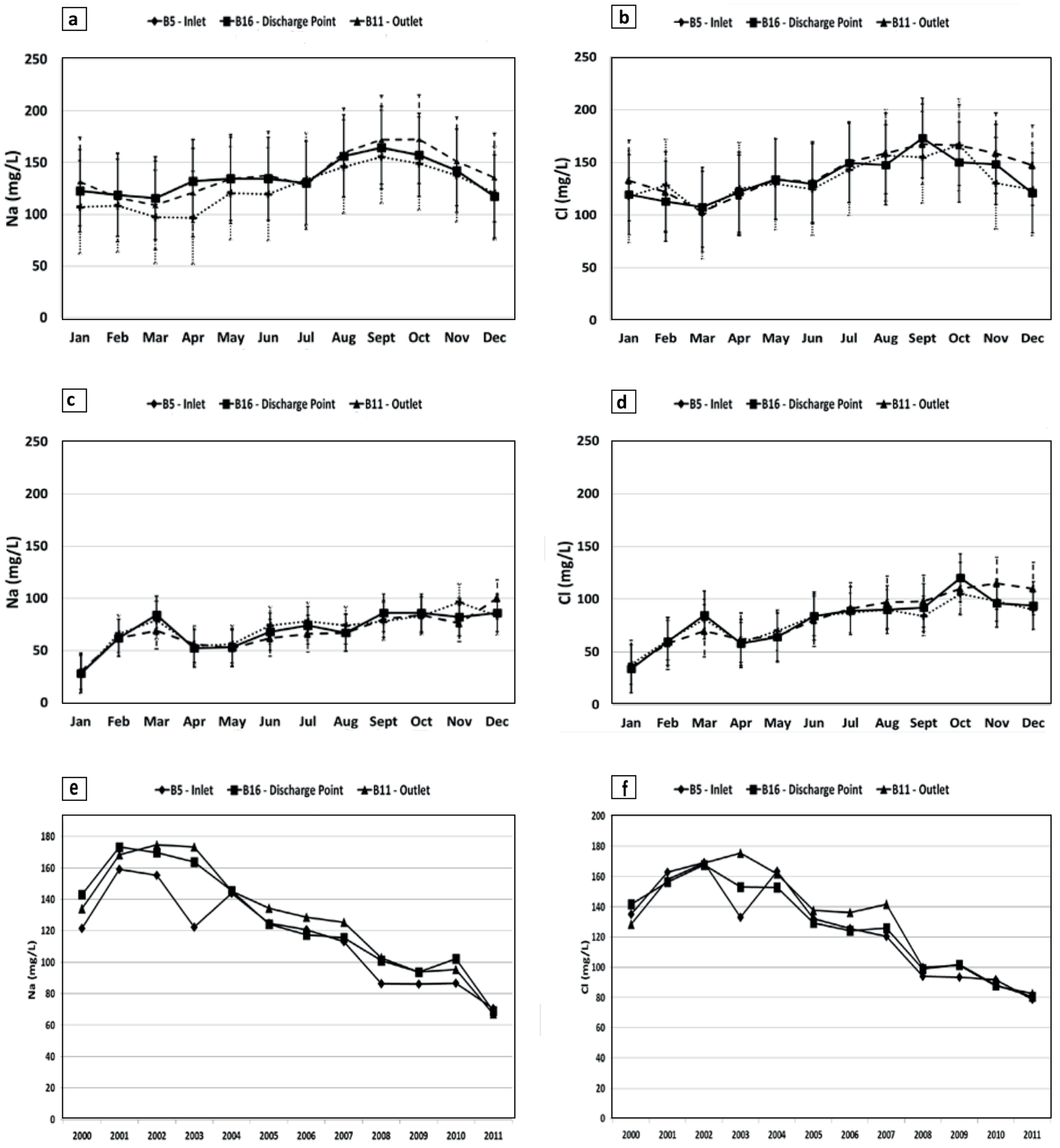

Figure 3

Spatial and seasonal concentrations at inlet, discharge and outlet sampling points: monthly average (a) Na and (b) Cl, from 2000 to 2010; and (c) Na for 2011; (d) Cl for 2011. Annual average (e) Na and (f) Cl, from 2000 to 2011. Error bars indicate monthly standard deviation over both periods (2000–2010 and 2011).

the high mineralisation of this water from Na, Cl, SO_4 and Mg discharges is not an exclusively low-pH acid mine drainage problem.

Seasonal variations in sodium and chloride concentrations

There were some seasonal variations in Na and Cl concentrations at the three locations during the period 2000–2010 (Figs 3a and 3b). During the dry months, Na and Cl concentrations gradually increased until the commencement of the rainy season in October, after which concentrations decreased through March with the dilution of Na and Cl by rainwater and runoffs into the Blesbokspruit Wetland. By contrast, in 2011, the previous Na and Cl seasonal variations were not that pronounced at the three sites (Figs 3c and 3d).

The combined results of both periods confirm that Na and Cl concentrations emanated from upstream sources before entering the Blesbokspruit Wetland. This was verified by the negligible spatial increment ratio of Na and Cl concentrations from the inlet B5 to the downstream sites. Subsequently, with the cessation of pumping discharges from Grootvlei Mine and the decommissioning of the pulping plant at the Sappi Enstra paper mill, Na and Cl levels in the Blesbokspruit Wetland decreased.

TABLE 3 Descriptive statistics for sodium and chloride concentrations for the periods 2000–2010 and 2011												
	Na (mg/ℓ)						Cl (mg/ℓ)					
	2000–2010 *n* = 132			2011 *n* = 12			2000–2010 *n* = 132			2011 *n* = 12		
	B5 Inlet	B16 Discharge	B11 Outlet	B5 Inlet	B16 Discharge	B11 Outlet	B5 Inlet	B16 Discharge	B11 Outlet	B5 Inlet	B16 Discharge	B11 Outlet
Mean	120	132	134	71	69	67	128	130	136	79	81	83
Median	110	128	130	76	71	67	125	125	135	84	87	86
Std. dev.	45	40	43	18	18	18	44	38	38	19	23	25
Rel. std. dev.	38%	30%	32%	25%	26%	26%	34%	29%	28%	24%	28%	30%
Std. error	4	4	4	5	5	5	4	4	3	5	7	7
Minimum	27	33	34	27	28	30	38	40	43	38	34	36
Maximum	360	250	250	96	86	100	283	333	220	105	120	115
Spatial increment ratio (relative to inlet)	1.0	1.1	1.1	1.0	1.0	0.9	1.0	1.0	1.1	1.0	1.0	1.0

TABLE 4 Descriptive statistics for electrical conductivity for the periods 2000–2010 and 2011						
	EC (mS/m)					
	2000–2010 *n* = 132			2011 *n* = 12		
	B5 Inlet	B16 Discharge	B11 Outlet	B5 Inlet	B16 Discharge	B11 Outlet
Mean	104	173	175	75	81	88
Median	103	170	176	78	84	86
Std. dev.	25	45	45	12	14	17
Rel. std. dev.	24%	26%	26%	16%	18%	19%
Std. error	2	4	4	3	4	5
Minimum	49	59	65	54	53	56
Maximum	188	285	270	92	100	110
Spatial increment ratio (relative to inlet)	1.00	1.65	1.67	1.00	1.08	1.17

Spatial gradients and source of elevated electrical conductivity

Similar to the spatial patterns of Mg and SO_4 over the period 2000–2010, there was a step increase (factor x1.7) in electrical conductivity (EC) values at the discharge point B16, with this value sustained to the outlet B11 (Table 4 and Figs 4a and c). The enhanced EC coincided with the step increases in Mg and SO_4 contamination (Figs 2a and 2b). This implies that underground mine-water also affected the EC of the water in the Blesbokspruit Wetland. By contrast, in 2011, the previous spatial gradients were not visible, as EC values became uniform from the inlet through the discharge point to the outlet (Tables 4 and 5, Figs 4b and 4c).

By contrast, for the year 2011, as with Na and Cl concentrations, EC values at the three locations showed minimal variability and were within smaller ranges than previous years (Table 4, Figs 4b and 4c). In the absence of other sources of effluents upstream, possibly the Sappi Enstra pulping plant, EC values had decreased, as expected, with the overall drop in the major ion concentrations.

Seasonal variations in electrical conductivity

In parallel to seasonal variations in Mg, SO_4, Na and Cl concentrations for the period 2000–2010, EC also showed lower values during the rainy period and higher values during the dry season (Fig. 4a). In 2011, the seasonal patterns of EC were similar to the seasonal variations of Na and Cl, indicating the now dominant influence of these species rather than SO_4 and Mg (Fig. 4b).

In summary, because of the high concentrations of ions in the water (Tables 4 and 5), EC values tended to be high, from the inlet B5, through the discharge point B16 to the outlet B11, over the period 2000–2010 compared to the year 2011. The reductions in ionic concentrations between both periods contributed to the decrease in the water conductivity (EC), with the inlet B5 showing major reductions in Na and Cl concentrations while the downstream sites had significant decreases in all ionic concentrations (Table 5). The seasonal patterns suggest the influence that rainfall has on the ionic concentration through dilution.

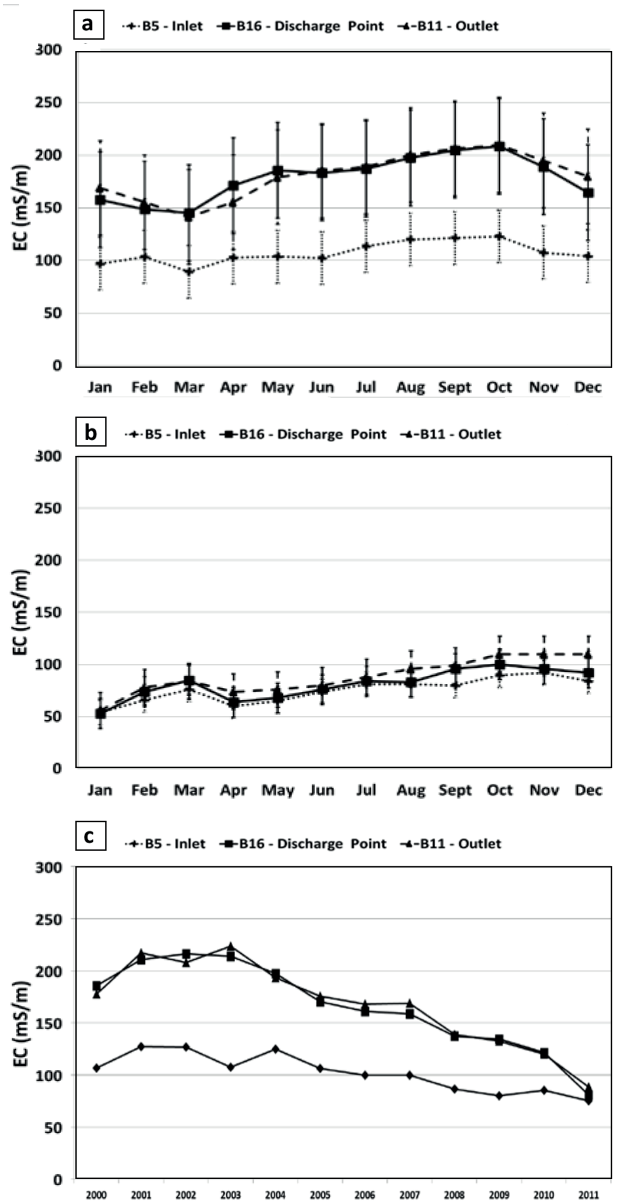

Figure 4

Spatial and seasonal values at inlet, discharge and outlet sampling points of: (a) monthly average electrical conductivity from 2000 to 2010; and (b) for 2011; and (c) annual average electrical conductivity (EC), from 2000 to 2011. Error bars indicate monthly standard deviation over both periods (2000–2010 and 2011).

Spatial gradients and seasonal variations in pH

Despite elevated Mg, SO_4, Na and Cl values, pH tended to be circumneutral to slightly basic, i.e., ranging from 6.7 to 8.8 (B5 to B11), for all the sampling locations over the period 2000–2010 (Fig. 5a). Spatially, the inlet B5, upstream of the Blesbokspruit Wetland, tended to be circumneutral (mean monthly pH = 7.9) in comparison with the downstream sites B16 and B11 (mean annual pH = 8.0 and 8.2, respectively) (Fig. 5c). The annual variation in pH was not highly seasonal, reflecting the combined effects of naturally alkaline geology and the treatment of mine effluent, by liming and other methods (Harrison, 1958; Scott, 1995; Wood and Reddy, 1998; Van Wyk and Munnik, 1998; South African Wetlands Conservation Programme, 1999; Bowell, 2000; Schoeman and Steyn, 2001; Van der Merwe and Lea, 2003; Lea et al., 2003; Tonkin, 2005; Eastern Basin Blesbokspruit Catchment Task Team, 2006; South African National Assembly, 2009; Madzivire et al., 2011; Durand, 2012; DWA, 2013).

In 2011, with no additional underground mine-water being discharged into the Blesbokspruit Wetland, pH values tended towards neutrality (7.2–8.2) as the water flowed from the inlet B5 to the site close to Grootvlei Mine Shaft 3 (B16) (Figs 5b and 5c). Samples from downstream site B11 had higher pH values – above 8.2. Overall, there was no distinct seasonal pattern in pH readings, even when Grootvlei Mine was no longer operational. Overall pH results showed little variability from the mean at different locations and across the seasons, implying that there is effective buffering of the pH of the water in the Blesbokspruit Wetland despite the accumulation or dilution of dissolved salts in its system (Table 6).

pH values represent a fundamental issue in terms of the conventional understanding of water discharge from the underground workings, widely referred to as 'acid mine drainage' (Bowell, 2000; Durand, 2012; Nordstrom et al., 2015). As

TABLE 5
Period average ion concentrations and conductivity over the periods 2000–2010 and 2011

Monitoring Location	Ion / EC	A: 2000–2010	B: 2011	Change: (B – A)	Percentage Change: (A – B) / A
B5 - Inlet	SO_4 (mg/ℓ)	117	106	11	−9%
	Mg (mg/ℓ)	18	16	2	−11%
	Na (mg/ℓ)	125	71	54	−43%
	Cl (mg/ℓ)	134	79	55	−41%
	EC (mS/m)	**108**	**75**	**33**	**−31%**
B16 - Discharge	SO_4 (mg/ℓ)	530	137	393	−74%
	Mg (mg/ℓ)	56	19	37	−66%
	Na (mg/ℓ)	136	69	67	−49%
	Cl (mg/ℓ)	135	81	54	−40%
	EC (mS/m)	**179**	**81**	**98**	**−55%**
B11 - Outlet	SO_4 (mg/ℓ)	517	163	354	−68%
	Mg (mg/ℓ)	56	24	32	−57%
	Na (mg/ℓ)	139	67	72	−52%
	Cl (mg/ℓ)	142	83	59	−42%
	EC (mS/m)	**181**	**88**	**93**	**−51%**

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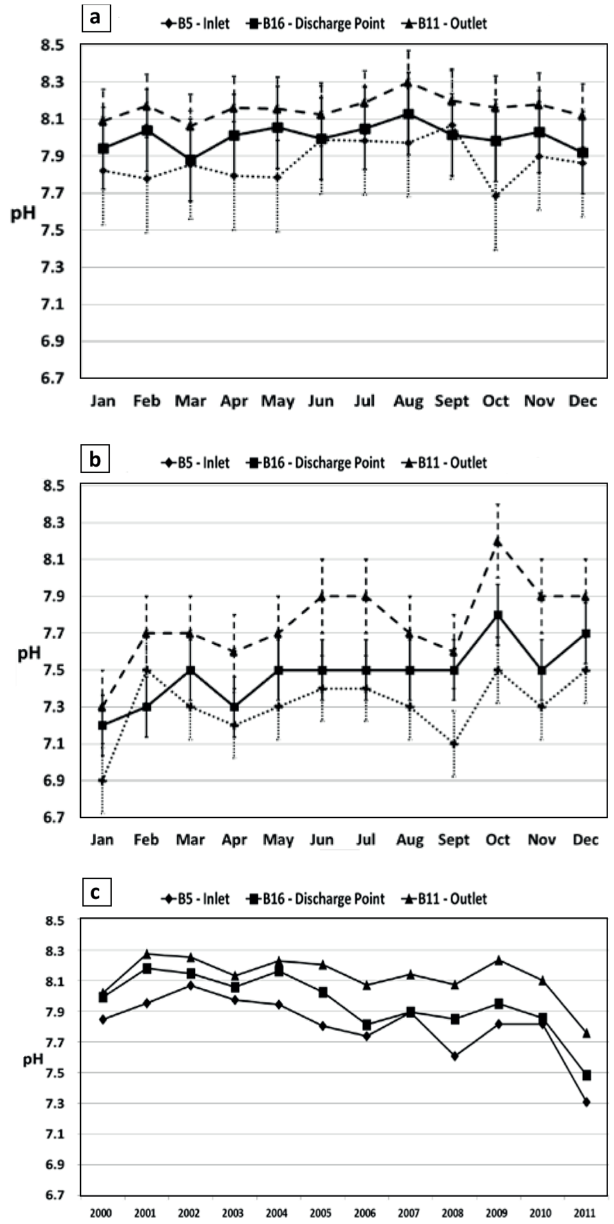

Figure 5

Spatial and seasonal variations in monthly average pH measurements (a) from 2000 to 2010; and (b) during 2011; and (c) annual average pH from 2000 to 2011. Error bars indicate monthly standard deviation over each period (2000–2010 and 2011)

the sampling point B16 is located only a few metres downstream of the discharge point of the underground water, and as this water has a high Mg and SO_4 imprint, the conventional understanding would be that this water is mildly acidic (Nordstrom et al., 2015). However, since the 1990s the underground water has usually been treated, partially or fully, before being discharged into the wetland (Bowell, 2000; Durand, 2012) – the expectation would be for pH levels to become neutral to alkaline (Nordstrom et al., 2015). In fact, the pH values of the mine discharge water were neutral to slightly alkaline over the entire period 2000 to 2011 (Fig. 5c). The jump in EC at Site B16 may have reflected an increase of mineralisation but this was not accompanied by lowered pH values. In addition to the buffering properties of existing dolomitic rocks, the different treatments for increasing pH for effluents and tailings included, inter alia, desalinisation plants and the use of chemical treatments, including lime and desulphurisation (Bowell, 2000; Durand, 2012; DWA, 2013). Clearly, the water quality issue with the Blesbokspruit Wetland is one of high mineralisation and neutral pH, more correctly referred to as circumneutral mineralisation (Madzivire et al., 2011; DWA, 2013; Nordstrom et al., 2015).

CONCLUSIONS

This study provides evidence that surface water quality for the period 2000 to 2011 (for parameters pH, EC, SO_4, Na, Cl and Mg) followed distinct spatial patterns from the inlet, past the underground mine-water discharge point to the outlet of the Blesbokspruit Wetland. The mineralisation grouped ion species into two distinct patterns of spatial and time variation. The first grouping links SO_4 and Mg, and the second Na and Cl. Taking the literal sense of 'acid mine drainage' as implying lowered pH values, the findings of this paper are paradoxical, in that the pH values remained uniformly constrained within a narrow range of pH 6.7 to 8.5 – circumneutral values. Within the broader sense of water chemistry, the term AMD also encompasses high levels of mineralisation resulting from acid dissolution of minerals. The results of this paper reveal that, even in this broader sense, only part of the mineralisation is attributable to AMD processes. A substantial portion of the mineralisation is in the form of Na and Cl, at much higher concentrations than could be accounted for from natural processes. The origin is presumed to be an upstream industrial source, tentatively identified as discharge from a paper pulping plant, based on circumstantial evidence. Seasonally, the highest concentrations in ionic species occurred during the dry months when there was no surface rainwater runoff to dilute contaminated discharges.

TABLE 6
Descriptive statistics results for pH for the periods 2000–2010 and 2011

	pH					
	2000–2010 *n* = 132			2011 *n* = 12		
	B5 Inlet	B16 Discharge	B11 Outlet	B5 Inlet	B16 Discharge	B11 Outlet
Mean	7.9	8.0	8.2	7.3	7.5	7.8
Median	7.9	8.0	8.2	7.3	7.5	7.7
Std. dev.	0.3	0.2	0.2	0.2	0.2	0.2
Rel. std. dev.	4%	3%	2%	2%	2%	3%
Std. Error	0.03	0.02	0.01	0.05	0.05	0.06
Minimum	6.7	7.5	7.8	6.9	7.2	7.3
Maximum	8.6	8.7	8.8	7.5	7.8	8.2
Spatial increment ratio (relative to inlet)	1.00	1.01	1.04	1.00	1.03	1.07

However, in 2011, following the cessation of underground mine-water pumping operations at Grootvlei Mine, the mineralisation of the surface waters in Blesbokspruit revealed a large step-wise reduction compared to the slowly decreasing trends over the previous 10 years, in both the SO_4-Mg and Na-Cl groups. Such contrast during the two periods in the ion concentrations and associated EC appeared to confirm that the mineralisation of the Blesbokspruit Wetland was induced by underground mine-water discharges at Grootvlei Mine. However, from the spatial and temporal trends, it was established that upstream sources were the major contributors to the sodium and chloride ion burdens entering the Blesbokspruit wetland. Upstream industries include the paper pulping plant and a sewage treatment plant. Although compositional data on discharges from the pulping plant are not reported in this study, knowledge of the process identifies Na and Cl as major impurities in discharge water. Furthermore, the coincidence of a sharp and permanent drop in the Na and Cl concentrations coinciding with the cessation of operation of this plant at the end of 2010 supports this conclusion. It was coincidence that this event happened at the same time as cessation of underground water discharges from Grootvlei Mine.

This new evidence contradicts previous findings that have identified underground mine-water discharge as the only contributor to high mineralisation in the waters of the Blesbokspruit Wetland. Despite all the public and institutional complaints about high ion levels and acidic waters in the Blesbokspruit, there had been no previous report that upstream industrial effluents were a substantial and equal contributor to the high ionic concentrations recorded in the Blesbokspruit Wetland. The paradox of a wetland contaminated by acid mine drainage, but showing consistently neutral pH values is resolved. The water quality issue with the Blesbokspruit Wetland is one of high mineralisation rather than low pH (high acidity), since the surface water pH was circumneutral, both during the pumping of underground mine-water, and after cessation of such operations at Grootvlei Mine Shaft No. 3. Nevertheless, from December 2010 to January 2011, there was a large stepwise reduction in mineralised waters from upstream industries and mining – coinciding with the decommissioning of the pulping plant and termination of pumping operations at Grootvlei Mine by the end of 2010. Based on the overall improvement of surface water quality in the Blesbokspruit Wetland, there is hope for its reinstatement as a designated Ramsar Wetland of International Importance.

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