From Salt Balance to Contaminant Flux: Managing Water Quality Risk Using a Systems Approach

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ABSTRACT

We used a salt balance to describe contaminant transfer within a mine water system. The system included mine workings, mineral processing plants, water storages (both clean and dirty), and tailings storage facilities as components. Analysis of modelling results identified sub-systems associated with potential water quality risks. In particular, approximately 6 000 tonnes of dissolved salts associated with the tailings component could not be accounted for. Under the prevailing regulatory regime, this could be a significant water quality risk. However, the fragmented monitoring network and poorly characterised hydrogeology was not able to resolve the magnitude of the risk.

The cost of developing a tailings source term was significantly less than the cost of upgrading the groundwater monitoring network. Therefore, the tailings sub-system was characterised in detail. This involved collecting tailings process water and drain samples. We also collected tailings samples from various depths in the facility. Geochemical and hydraulic analysis of the tailings allowed an indicative source term to be developed. This quantified the contaminant flux through the tailings during deposition and after closure.

During the operational phase approximately 1 000 tonnes per year of dissolved salts actually leaves the tailings as seepage through the footprint. The residual salt mass leaves the tailings at the rate of approximately 250 tonnes per year once the tailings have desaturated.

The improved resolution of the tailings sub-system indicated that the tailings are a sink for dissolved salts in the mine water system. The fine particle size and low permeability of the tailings under compaction, is a natural mitigation that limits the rate of salt release. Therefore, the magnitude of the water quality risk was found to be moderate

Keywords: Salt balance, source term, tailings, water balance, drainage

INTRODUCTION

Two of the most important and fundamental tools of mine water management are water and salt balances (DWAF, 2006). Water distribution systems on mines are developed ad hoc in response to demand. Therefore, they include inherent inefficiencies, which lead to excessive water consumption and often unnecessary increases in dissolved solids. The goal of water and salt balances is to improve efficiency and water quality. However, the uncoordinated and independently led aspects of a mine water system overlap in a formidable way. As Ramo and St Clair (1998) put it: "it is like knitting with a tangled ball of yarn. It must be untangled before we try again to make the sweater".

The systems approach is a means of applying common sense (Ramo and St Clair, 1998). It is a tool for solving challenges in all spheres of human endeavour. Of course, the solutions typically involve interaction of previously self-directed groups of people and unprecedented flow of resources and information. Naturally, the solution is a considerable change from the present and past way of doing things.

A multi-disciplinary team has been assisting a South African platinum mining company in developing, refining and applying a detailed water balance. The team developed a water balance for a mine water system consisting of dozens of mine shafts and associated underground workings, multiple water storages (both clean and dirty), several mineral processing plants and associated tailings storage facilities (TSFs). The mining operation is located in the western limb of the Bushveld Igneous Complex. The team has "untangled the yarn" and assisted the mining company in "knitting a new sweater" out of their water distribution system. This paper describes one aspect of the work conducted. Specifically, it addresses the question of salt movement at TSFs.

METHODOLOGY

An annual water balance was developed for the operation by considering measured and estimated/calculated inflows and outflows from defined water management units (WMUs) according to the methodology of DWAF (2006). Each WMU is an individual sub-system of the larger mine water distribution system. To determine salt loads in circuit, chloride concentrations were obtained from four sources:

- The environmental monitoring programme, consisting of a database containing analytical results of samples collected from May 1995 to July 2012;
- Drinking water and service water quality analyses from March 2012 and June 2012;
- Tap water analyses from sampling conducted in May and June 2012; and
- Analyses from sampling conducted in June 2012.

Calculation of unmeasured chloride loads was conducted by determining the difference between input and output loads for each water management unit according to the methodology of DWAF (2006). Assuming that inputs equal outputs yielded the unmeasured chloride load by difference. Clearly, this is only valid for a chemical component that behaves conservatively within the mine water system.

Due to lack of data, seepage and interstitial water storage in TSFs were combined into one flow in the water balance. The salt mass balance calculated using water quality data and water balance flows revealed that the input salt load to most of the TSF sub-systems was greater than the output

load. To maintain salt mass balance a new output was added representing the salt load presumed to be lost in seepage (Figure 1).
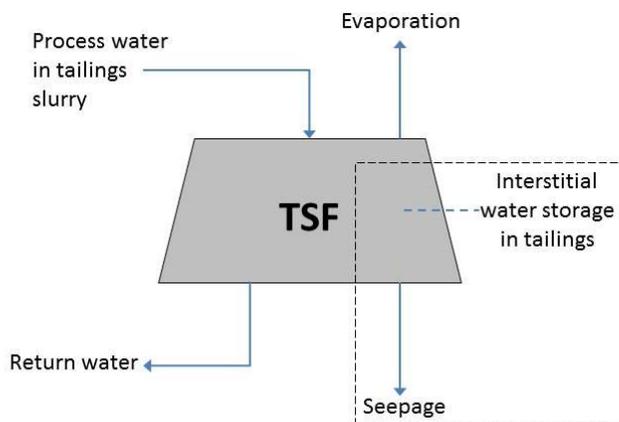
Figure 1 Schematic of the TSF water balance sub-system

The "seepage and interstitial" flow component was found to account for nearly half of chloride mass lost in the TSF sub-system (Table 1). However, the chloride mass of the seepage component could not be resolved from the available data. This was a question of considerable significance to the mining company. South African legislation makes it illegal to contaminate local water resources. Seepage from the TSFs could affect downstream water resources and potentially incur an environmental liability.

Table 1 Summary of water balance and calculated chloride mass balance for a selected TSF

Inputs	Flow (m³/a)	Cl mass (t/a)	Outputs	Flow (m³/a)	Cl mass (t/a)	% diff
Tailings slurry water from processing plants	3 670 038	1 703	Seepage, evaporation, interstitial losses	1 835 019	795	
			Return water	1 959 557	909	
Subtotals	**3 670 038**			**3 794 576**		3.3
		1 703			1 704	0.1

At the time, the mine was upgrading a fragmented water monitoring network and developing a more complete understanding of the local hydrogeology. Therefore, environmental monitoring data were unable to confirm the presence of a contaminant plume from the TSF, let alone its significance. Rather than incur the cost of additional monitoring wells, the mining company decided to establish a source term to resolve the seepage component of chloride losses from the TSF.

A source term describes the flux of contaminant mass emitted from a source. It is required for groundwater contaminant transport modelling and consists of a numerical description of the mass of contaminant emitted per unit time. The following tasks were conducted:

- Collect samples – augered from tailings, water samples
- Analyse samples – geotechnical characteristics, geochemical characteristics
- Develop source term from geochemical modelling of seepage quality coupled with estimates of seepage volume from the tailings

Sampling

Tailings samples were collected from auger holes bored into 12 locations on the top surface of the TSF using a portable, hydraulically-powered auger. Tailings samples were collected at 1.5 m intervals from each hole. Mixtures of tailings and distilled water at a ratio of 1:2 were made for each sample in the field and pH and EC measured using a calibrated Hanna HI98130 handheld meter. Twelve samples for laboratory analysis were selected based on the pH/EC profile results.

Water samples were collected from TSF drains 18, 32 and 54 on the perimeter of the TSF.

A drum was filled with slurry from a discharge point. The suspended tailings were allowed to settle and a sample of the tailings supernatant water was obtained. All water samples and the tailings supernatant were filtered by syringing the water through 0.45 μm polycarbonate membrane cartridges. A separate sub-sample for metals analysis was preserved with 2 mL of laboratory-grade nitric acid. All water samples were kept at 4°C from sampling to delivery at the laboratory. Samples were delivered to the laboratory the same day as collected.

Analysis

The analytical programme was conducted by a South African National Accreditation System (SANAS) certified laboratory.

Sixteen water samples were analysed including:
- Tailings drain samples (3)
- Tailings supernatant sample (1)
- Tailings sample leachates (12) obtained according to the modified ASTM D3987 method using deionised water at a liquid:solid ratio of 4:1.

All water samples were analysed for the following:
- Physico-chemical parameters (pH, Conductivity, Total dissolved solids (TDS), Alkalinity titration)
- Major anions (F, Cl, SO_4, NO_3)
- Cations (Na, K, Ca, Mg, Al, Fe, Mn, Cu, Pb, Zn, Cr, and others)

Twelve samples of tailings were analysed for the following:
- Mineral identification (by x-ray diffraction (XRD) or microscope petrography)
- Whole element analysis (by acid digestion and chemical analysis of the digest)
- Particle size distribution
- Saturated hydraulic conductivity
- Moisture content

Due to technical difficulties, unsaturated hydraulic conductivity was not measured. Generally, these results would inform numerical modelling of the long-term post-closure moisture content and seepage rate from the TSF. However, numerical seepage modelling was excluded from the scope of work due to time constraints.

Methodology

The analytical results were used to estimate tailings seepage quality during the operational phase of the TSF and post-closure. Interstitial water quality in the tailings during the operational phase, and hence seepage quality was estimated from the drain water quality. The post-closure seepage quality was estimated from the tailings leachates. PHREEQC (Parkhurst and Appelo 1999) was used to correct for dilution using the measured moisture content and mineralogy as inputs. Post-closure seepage rate were estimated from the saturated hydraulic conductivity results on the tailings samples.

RESULTS AND DISCUSSION

Water at Drain 18 appeared to be affected by local reducing conditions and is not considered to indicate the general quality of interstitial water in the tailings seepage (Table 2).

Table 2 Summary of water analysis results for the selected TSF

Parameter	DRAIN 18	DRAIN 54	DRAIN 32	SUPERNATANT
pH [s.u.]	10	8.1	8.1	7.4
EC [mS/m]	348	307	370	353
TDS	2400	2000	2600	2500
Alkalinity as $CaCO_3$	220	70	55	70
HCO_3	268.23	85.35	67.06	85.35
CO_3	66	0	0	0
Cl	564	530	481	352
NO_3	<0.1	6.5	<0.1	273
SO_4	1460	913	1440	835
F	0.26	<0.05	<0.05	0.09
Na	358	295	439	295
K	60	55	74	56
Ca	306	242	303	227
Mg	0.63	50	172	71
Al	0.27	<0.02	<0.02	<0.02
Fe	0.97	0.09	0.11	<0.05
Hg	0.0002	<0.0001	<0.0001	<0.0001

Chloride concentration in TSF seepage was estimated to be 433 mg/L based on the salt balance. This contrasts with the median chloride concentration of 506 mg/L in water from Drain 54 and Drain 32 (Table 2) and the chloride concentration of 352 mg/L in tailings supernatant. Equilibrium geochemical modelling of the water qualities indicates:

- Tailings supernatant is in equilibrium with calcium carbonate and aluminium hydroxide while being supersaturated with iron hydroxide.

- Water in contact with the tailings (Drain 54, Drain 32) becomes supersaturated with calcium carbonate, presumably from an increase in carbon dioxide partial pressure at depth in the tailings.
- Drain water is more concentrated than tailings supernatant and suggests a water loss of between 20% and 40% between the penstock pool and the drains.

Major ion proportions indicate that the supernatant and drain samples are compositionally similar (Figure 2). However, the compositions of the tailings leachates are significantly different (Figure 2 and Table 3).
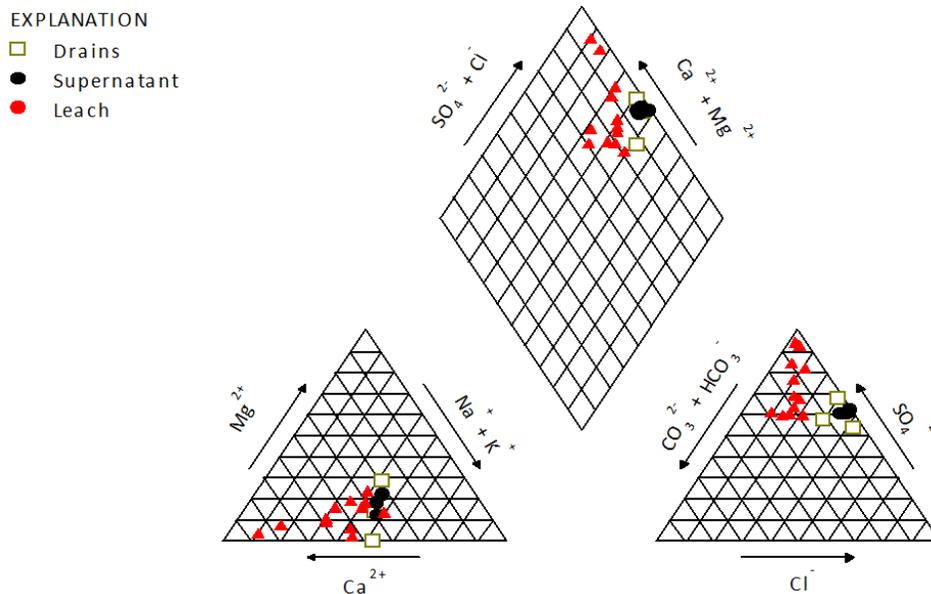
Figure 2 Piper diagram illustrating major ion composition of tailings leachates and water

Table 3 Summary of tailings leachate composition for the selected TSF

Parameter	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
pH	9.6	8.9	9.1	8.6	8.8	9	8.9	9.1	8.8	9.1	8.9	8.8
EC	27	30	22	114	40	22	31	19	34	22	35	134
TDS	132	150	104	844	250	134	178	88	202	114	192	1076
Alkalinity as $CaCO_3$	30	22	19	30	24	33	<12	27	30	27	33	43
HCO_3	20.3	22.6	17.1	31	25.2	33.5	12.0	26.4	32	25.8	34.1	41
CO_3	4.5	1.0	1.2	0.9	1.0	1.9	0.6	1.8	1.2	1.8	1.6	1.9
Cl	14	10	13	22	9.5	7.4	13	10	21	12	18	16
NO_3	<0.1	0.5	2.4	<0.1	3.2	5.9	2.5	<0.1	12.	1.4	<0.1	<0.1
SO_4	71	101	47	602	166	60	116	53	109	58	112	770
F	0.11	0.09	0.08	0.17	0.1	0.13	0.08	0.08	0.13	0.16	0.13	0.19
Na	15	15	12	26	16	9.1	11	7.1	17	11	18	20
K	3.9	5.3	6.4	15	6.8	4.1	6.1	3.3	8.5	5.2	7.8	14
Ca	18	15	10	135	32	13	24	13	20	12	24	189
Mg	0.39	5.6	2.2	7.8	2.7	3.1	2.4	2.3	4.3	3.2	1.6	3.6
Al	0.02	0.05	0.18	<0.02	<0.02	0.07	0.02	0.05	0.04	0.11	0.05	<0.02
Fe	0.09	0.08	0.22	<0.05	<0.05	0.06	<0.05	<0.05	0.06	0.11	<0.05	<0.05

Plagioclase, pyroxene, chromite are present in all samples which is consistent with the mineralogy of the platinum ore. Amphibole is also associated with the ore and is present in all but two samples.

Particle size distributions indicate that the tailings particles are in the range 0.001 mm to 0.85 mm (Figure 3). This classes the particles as silt or fine sand. The distribution for all samples is generally similar.
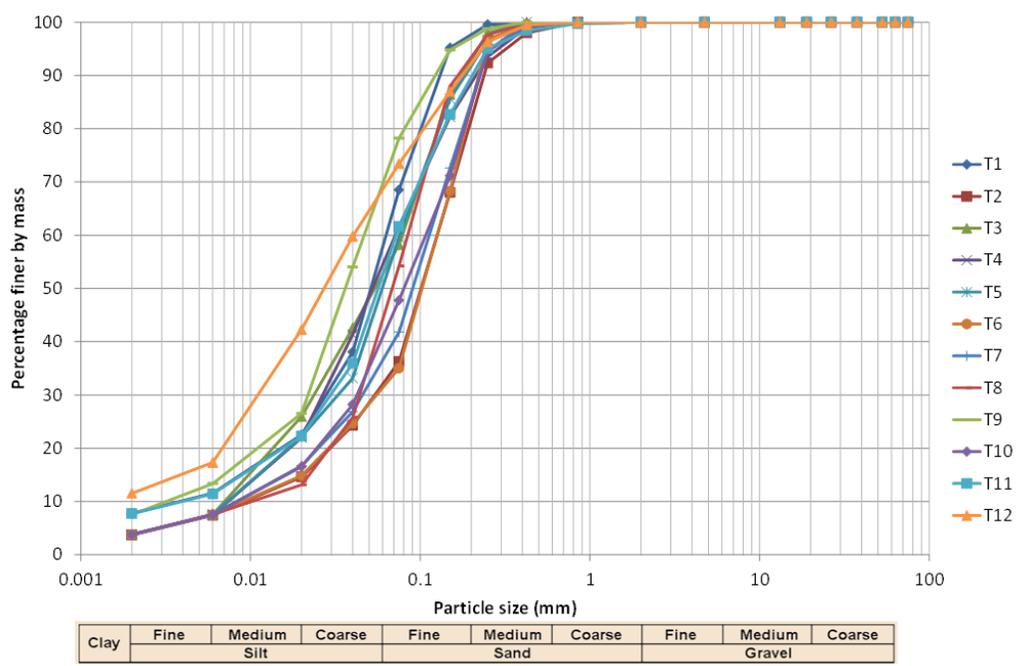
Figure 3 Tailings grain size

Saturated hydraulic conductivity of the tailings samples was directly measured by the laboratory at confining pressures of 50 kPa, 100 kPa, and 200 kPa. The median values were 1.15×10^{-7}, 5.85×10^{-8}, and 1.85×10^{-8} m/s respectively, showing a trend of decreasing hydraulic conductivity with increasing confining pressure. Median moisture content of the tailings samples was found to be 10%.

The TSF water balance indicates that seepage and interstitial losses in the tailings amount to 1 835 019 m^3 per year on average. Over a TSF footprint area of 119 ha this volume suggests that the effective hydraulic conductivity of the tailings is 5×10^{-8} m/s. This is consistent with the 10^{-8} to 10^{-7} m/s range in hydraulic conductivity expected in silt-sized material and is generally in agreement with the physical characterisation of the tailings conducted in this study.

Estimated confining pressure at the base of a 30 m column of saturated tailings ranges from 191 kPa to 272 Kpa with a median of 238 kPa. This is greater than the 200 kPa applied in the laboratory. Considering the trend of decreasing hydraulic conductivity with increasing confining pressure, a hydraulic conductivity of the order of 10^{-8} m/s or lower may prevail at the base of the tailings. Applied over the tailings footprint, this yields an annual seepage volume of 375 278 m^3.

After closure and draining of excess water, the tailings would eventually achieve equilibrium between the rate of rainfall recharge and moisture loss. Unsaturated conditions would prevail in the tailings and the actual rate of seepage through the footprint will be a function of tailings moisture content and the unsaturated hydraulic conductivity. As a rule of thumb, unsaturated hydraulic conductivity is one or more orders of magnitude less than saturated hydraulic conductivity. Therefore, for the selected TSF, unsaturated hydraulic conductivity would be at most 10^{-9} m/s. This yields an estimated post-closure seepage rate of less than about 37 528 m^3/year.

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The TSF drain water is an indicator of seepage quality during the operational phase of tailings deposition. The median chloride concentration of samples DRAIN32 and DRAIN54 is 506 mg/L.

The leach tests on tailings samples indicate the results of interaction between the tailings and water. Therefore, they are a starting point for assessing the results of rainfall infiltrating the tailings after closure. However, the liquid to solid ratio in the TSF after closure is likely to be considerably lower than the 4:1 ratio used in the leach tests. Based on the laboratory moisture results, a liquid to solid ratio of 1:10 appears more likely.

The geochemical modelling code PHREEQC (Parkhurst and Appelo 1999) was used to simulate the removal of water from the test leachates in contact with the minerals gibbsite, barite, calcite, chromite and hematite (**¡Error! No se encuentra el origen de la referencia.**). A CO_2 partial pressure of 10^{-2} atm was applied to simulate conditions deep in the tailings.

Table 4 Summary of modelled post-closure seepage quality for the selected TSF

Parameter	Min	Median	Max
pH [s.u.]	6.8	7.2	7.4
Total dissolved solids	4 203	7 187	32 386
Alkalinity as $CaCO_3$	101	218	349
HCO_3	75	197	324
CO_3	0.05	0.33	0.87
Cl	308	540	915
NO_3	12	168	2 184
SO_4	1 490	3 051	12 557
F	1.80	3.37	5.51
Na	295	623	1 080
K	1 086	2 071	10 951
Ca	111	371	7 146
Mg	16	120	324
Al	0.56	0.88	1.32
Fe	nd	nd	nd

Graphical representation of the time varying seepage rate and seepage quality (as chloride concentration) from the TSF footprint is shown in Figure 4. The product of these two quantities yields the mass of chloride entering the groundwater system beneath the tailings. The duration of

the operational phase has been assumed to be 20 years, followed by approximately 20 years of dewatering.

Based on the outcome of this assessment, the chloride mass entering the groundwater is 190 tonnes/year during the operational phase. This decreases to 20 tonnes/year after closure (Figure 4). This contrasts with the combined seepage and interstitial estimates of 795 tonnes per year from the salt balance.
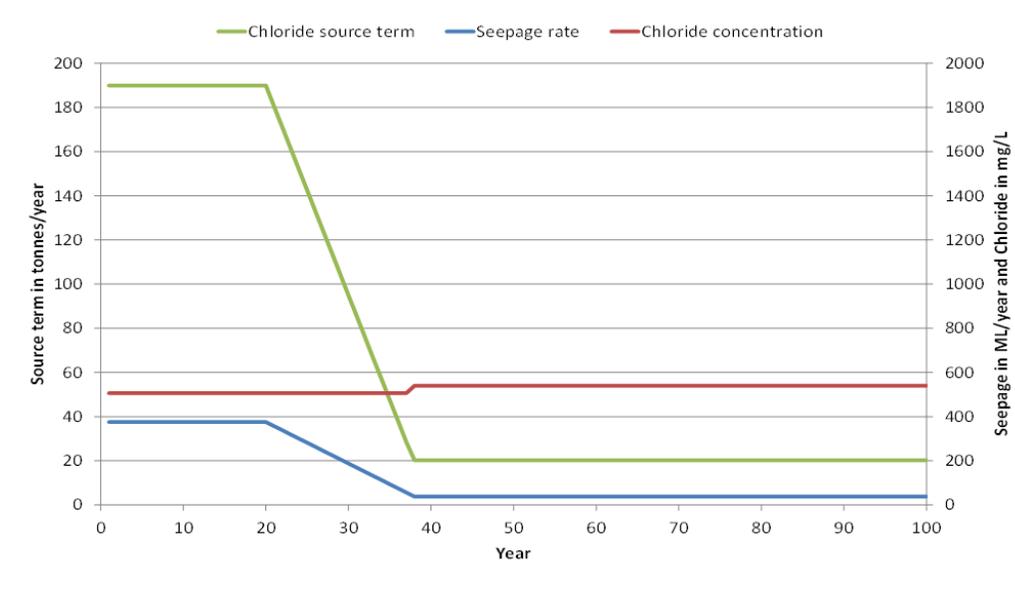
Figure 4 Source term for the selected TSF

CONCLUSION

Physical characterisation of tailings material from the selected TSF has allowed seepage through the TSF footprint to be estimated. This was calculated as 37 528 m³/year during the operational phase, decreasing to 3 753 m³/year after the tailings have desaturated post-closure.

Tailings seepage quality during post-closure can be geochemically modelled from drain water quality and leach test results. Considering the mineral assemblage in the tailings and the tailings moisture content, chloride concentrations vary from 506 mg/L during the operational phase to 540 mg/L after closure.

The source term combining the seepage rate and seepage quality indicates that the tailings are a sink for dissolved salts. During the operational phase 5 960 tonnes per year of dissolved solids are placed on the selected TSF. However, 1 117 tonnes per year actually leaves the tailings as seepage through the footprint. The residual salt mass leaves the tailings at the rate of approximately 262 tonnes per year once the tailings have desaturated. The fine particle size and low permeability of the tailings under compaction, is a natural mitigation which limits the rate of salt release.

Closer analysis of the TSF sub-system resolved water balance outputs from the mine water distribution system.

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