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TECHNICAL ARTICLE

Field Study of the Chemical and Physical Stability of Highly Sulphide-Rich Tailings Stored Under a Shallow Water Cover

Akué Sylvette Awoh · Mamert Mbonimpa · Bruno Bussière

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Abstract Highly sulfide-rich (approximately 83 % pyrite), potentially acid-generating mine tailings were subaqueously deposited in the Don Rouyn old quarry pit from 1997 to 2000. The site covers approximately 7 ha near Rouyn-Noranda, Quebec. Various in situ measurements and laboratory tests were performed during the summer and autumn of 2008, 2009, and 2010 to: characterize tailings samples; monitor water quality in the final effluent, shallow water cover, and groundwater around the pit, and; study tailings erosion and resuspension. In situ measurements included the vertical profile and spatial distribution of pH, temperature, dissolved oxygen, electric conductivity, and redox potential. Suspended tailings, wind speed, and direction were monitored. Groundwater, cover water, and final effluent water samples were chemically analyzed and suspended sediment concentrations (SSCs) was determined. Physical, mineralogical, and chemical tailings properties were also determined. Results show that the quality of the groundwater, cover, and effluent waters complied with Canadian and Quebec regulations. SSCs were also within regulation limits. No association was found between SSC and hydrodynamic conditions (wind speed, fetch, etc.). Although theoretical calculations indicated a critical wind speed of at least 10 m/s for tailings resuspension, suspended sediment was observed for wind speeds at <10 m/s.

A. S. Awoh (✉) · M. Mbonimpa · B. Bussière
Research Institute on Mines and the Environment,
UQAT, Rouyn-Noranda, QC J9X 5E4, Canada
e-mail: akue-sylvette.awoh@uqat.ca

A. S. Awoh · M. Mbonimpa · B. Bussière
Industrial NSERC-Polytechnique-UQAT Chair, Environment and Mine Waste Management, Rouyn-Noranda, Canada

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Introduction

The main environmental challenge related to sulphide-rich tailings is the generation of acid mine drainage (AMD). AMD is generated naturally when sulphide minerals, such as those contained in sulphide-rich tailings and waste rocks, are exposed to air and water (Aubertin et al. 2002). One method to prevent AMD production is to reduce the oxygen supply to the tailings; oxygen barriers are recognized as the most effective approach to control AMD in humid climates. The application of a shallow water cover, created by subaqueous deposition of the tailings, is one such technique (MEND 2001). A shallow water cover limits the oxygen supply to the underlying tailings because the diffusion coefficient of oxygen is 10,000 times lower in water than in air. However, a shallow water cover is a complex and dynamic system subject to several factors, including oxygen transport, tailings erosion, resuspension, and water exchange with the surrounding environment (Li et al. 1997). These may affect the effectiveness and the water quality of the cover and the groundwater. When the dissolved oxygen concentration in a shallow pond approaches saturation, increased resuspension can lead to oxidation of the resuspended tailings, which in turn results in the release of sulfates, acids, and metals, as observed in both laboratory and field studies (Catalan and Yanful 2002; Yanful et al. 2000). Several researchers have developed design tools for shallow water covers based on the interaction between wind speed and shear stress that induces resuspension (Adu-Wusu et al. 2001; Kachhwal et al. 2010;

Mian and Yanful 2004, 2007; Mian et al. 2007; Peacey and Yanful 2003; Yanful and Catalan 2002).

The above-mentioned studies are based on concepts described in the Shore Protection Manual of the US Army Coastal Engineering Research Center (CERC 1984) and the Coastal Engineering Manual (CEM) of the US Army Coastal Engineering Research Center (CERC 2002). These concepts were applied to shallow water covers with different dimensions: the 96 ha Louvicourt site located 25 km east of Val d'Or (Quebec, Canada) (Vigneault et al. 2007), the 115 ha Shebandowan site located 100 km northwest of Thunder Bay (Ontario, Canada) (Kachhwal and Yanful 2010; Kachhwal et al. 2010), the 192 ha Quirke Waste Management Area in Ontario (Canada) (Adu-Wusu et al. 2001), the 215 ha Heath Steele site located 60 km northwest of Newcastle (New Brunswick, Canada; Mian and Yanful 2004), and the 110 ha Stekenjokk site in Sweden (Holmström and Öhlander 1999). As very few studies have examined small sites, the question arises: are the concepts proposed by CERC (1984, 2002) applicable to such sites?

From a design perspective, the water depth is generally optimized to minimize tailings resuspension, which can affect overall water quality. Field measured data on sediment suspended concentrations (SSCs) at several sites in Canada have shown that resuspension cannot be eliminated, even with a deep (up to 2 m) water cover (Adu-Wusu et al. 2001; Catalan and Yanful 2002). It is however important that the sediment and other metal concentrations remain within regulatory limits. The water quality depends on the sulphide content of the tailings. The pyrite content was about 30–50 % at the Louvicourt sites (Li et al. 1997) and about 35 % at the Stekenjokk site (Holmström and Öhlander 1999). Few data are available on flooded tailings containing higher percentages of sulphide minerals.

The water cover at the Don Rouyn site meets the above-mentioned conditions: a relatively small site with highly sulphide-rich tailings (about 83 % pyrite). The site is a former open pit that has been completely enclosed by rock walls with irregular contours. This is a particular feature, as most shallow water covers are formed by engineered dykes.

The purpose of this study was to assess the effectiveness of the shallow water cover at the Don Rouyn site in limiting AMD generation. Specifically, this study focused on the chemical and physical stability of highly sulphide-rich tailings in the shallow water cover and the groundwater quality around the site. To do so, field monitoring was performed from June to October of 2008, 2009, and 2010. The purpose was to conduct physicochemical characterization of the cover water and the groundwater around the site and to measure wind speed and suspended sediment concentrations (SSCs). Physical, mineralogical, and chemical analyses of the tailings and chemical analyses of cover and ground water samples were also conducted in the laboratory. Results are presented and discussed.

History and Description of the Study Site

The Don Rouyn site is located 4 km west of Rouyn-Noranda (QC, Canada) and north of Route 117, where a porphyry copper deposit was intermittently open-pit mined from 1959 to 1980 (GEOCON 1997a). Once the mineral reserves were depleted, the pit was flooded, covering an area of 7.7 ha within a 20.68 ha drainage basin. From 1997 to 2000, the Don Rouyn pit was used to store tailings from the Gallen Mine under water. The Gallen Mine was a volcanogenic massive sulfide ore deposit, with 4.95 % Zn, 0.18 % Cu, 42.36 g/t Ag, and 1.185 g/t Au. It was operated in phases from 1955 to 2000 (Beaud 2005). A volume of 700,000 m^3 of Gallen tailings was deposited underwater at a pH between 10.5 and 11.5. Currently, the water elevation relative to mean sea level is maintained at 308.5 m by a weir built in a channel to discharge the water into the environment.

The design water depth (h) was only 1 m (GEOCON 1997a), which is relatively shallow. The depth of the water cover between the weir crest level and the tailings surface was measured in July, 2005 (Fig. 1). The maximum, average, median, and minimum depths of the water cover from the weir crest level to the tailings surface are 2.81, 1.23, 1.16 and 0.81 m, respectively (Beaud 2005; Mbonimpa et al. 2008).

Due to the small area of the shallow water cover at the Don Rouyn site, the fetch is also small, which can reduce the effect of hydrodynamic mechanisms. This site also differs from other sites in the sulphide content of the tailings; tailings sampled 2 years before subaqueous tailings disposal ended showed a pyrite content up to about 76 % (Catalan 1998). Recent analyses conducted on four samples taken near the water–tailings interface in summer 2005 showed a pyrite content from 86 to 96 %, for an average of 91 % (Mbonimpa et al. 2008). The Xstrata Copper Horne Smelter, which was responsible for site management, occasionally added lime milk to buffer the water and control a small seasonal increase in Zn concentration in the effluent until 2005.

Six monitoring wells were installed around the Don Rouyn pit in 1997. At the time of this study, five wells, identified as F1, F2, F3, F5, and F6, were operational (Fig. 2). Well F4 was destroyed due to aggregate operations around the site. Two piezometers each were installed in wells F1, F2, F3, and F6. In each case, the filter tip placed in the near-surface fractured bedrock was identified as S (e.g. F1-S). The filter tip of the second piezometer was installed deeper into the bedrock and was identified as D (e.g. F1-D) (GEOCON 1997a). In borehole F5, only one deep monitoring well was placed in the bedrock. Wells F3 and F5 cross a fill made of silt, sand gravel, and crushed stone until reaching bedrock. Wells F1, F2, and F6 were driven through

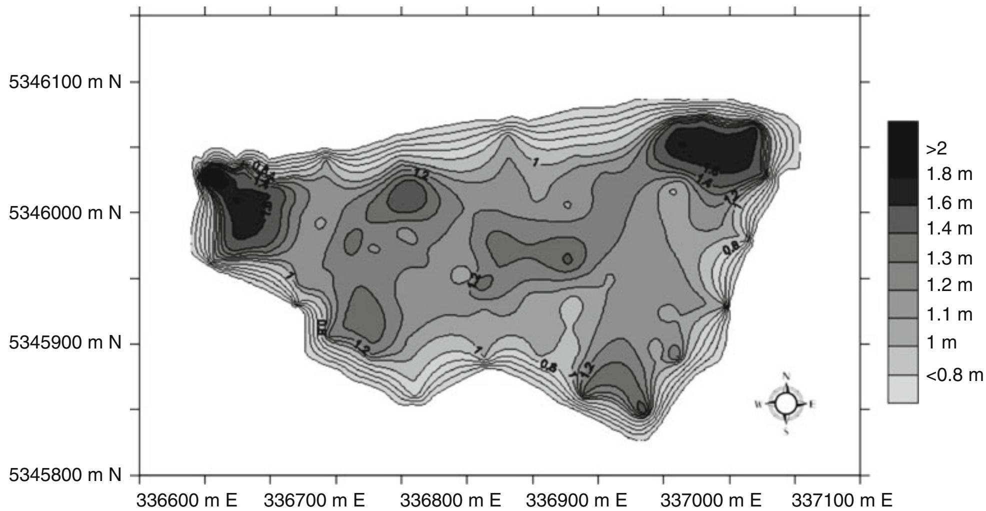

Fig. 1 Surface contours of water depth h between the weir crest level and the tailings surface determined in July 2005 in NAD 83, MTN Zone 10 coordinates with m *N* meters North and m *E* meters East (Beaud 2005)

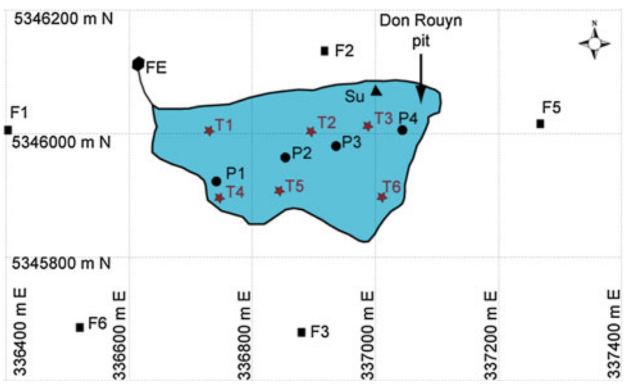

Fig. 2 Location of boreholes (F1–F6), tailings sampling stations (T1–T6), final effluent (FE) stations (P1–P4) for cover water sampling, and station Su for continuous measurement of suspended sediment concentration (in NAD 83, MTN Zone 10 coordinates). m *N* meter North, m *E* meter East

black organic soil, clay, till, and sand deposits until reaching bedrock. Each piezometer consists of a PVC 25 mm in diameter (GEOCON 1997a). A Waterra pumping system, consisting of an HDPE tube and a ball valve, was installed in each piezometer. A more detailed description of the monitoring wells is presented in Awoh (2012).

Materials and Methods

Tailings Sampling and Characterization

Tailings from beneath the shallow water cover at the Don Rouyn site were sampled at six stations T1–T6, as shown in Fig. 2. At each station, a tailings sample was taken from a boat using a bottom sediment sampling dredge. Samples were collected up to a depth of about 20 cm in the tailings. Each sample was poured into a separate bucket and covered with water from near the boat to prevent oxidation.

In the laboratory, the six samples were homogenized underwater in a large barrel to obtain a single homogeneous mixture of representative tailings from the Don Rouyn site. Two tailings samples were removed from the mixture for physical, mineralogical, and chemical characterization.

Particle size was obtained using a Malvern Mastersizer laser particle size analyzer, which provides a volume size distribution for diameters from 0.05 to 900 µm. Further details on the techniques of grain-size distribution measurements are given by Merkus (2009). The relative density of the tailings was determined using a Micromeritics Accupyc 1330 helium pycnometer (±0.03 % accuracy).

Elemental analysis of tailings solids involved complete digestion in $HNO_3/Br_2/HF/HCl$ followed by inductively coupled plasma and atomic emission spectroscopy (ICP-AES, Perkin-Elmer, relative precision of ±5 %; Villeneuve 2004). Materials used to verified accuracy were certified by the Canadian Certified Reference Materials Project (CCRMP).

The X-ray diffraction (XRD) data for the mineralogical characterisation of the solids was determined using the quantitative Rietveld method (relative precision of ±0.5 %) with TOPAS software (Young 1995). The tailings were also examined by a scanning electron microscope (SEM) (Hitachi S-3500N) equipped with an energy dispersive spectrometer (Silicon Drift Detector, Oxford X-Max 20 mm^2) with INCA software (450 Energy). The detection limit is approximately 1 % (Çubukçu et al. 2006). The polished sections were first prepared and observed under an optical microscope (model Nikon optiphot2 Pol). Afterwards, the SEM images obtained were analyzed with a Hitachi S-3500N spectrometer energy dispersive X-ray (EDS).

Water Sampling and Analysis

Water samples of the shallow water cover final effluent (FE) were taken from the weir (Fig. 2) in a 1 L high density polyethylene (HDPE) bottle (fully filled), which was acid washed prior to use. The water samples were quickly (within less than 2 h) brought to the laboratory and filtered through 0.45 µm nylon filter and then acidified with nitric acid to 2 % v/v HNO_3 (2 % HNO_3 to 100 mL of filtered water) prior to laboratory analysis. The acid quality met the requirements of the American Chemical Society. The temperature of the water flowing over the weir was previously measured in situ.

In the shallow water cover, four sampling stations (P1–P4) were selected on the east–west axis (Fig. 2) where the depth of the shallow water cover was <2 m. At each station, a temperature and dissolved oxygen (DO) profile was determined using an Ecosense® polarographic electrode DO200 (relative precision of ±2 %), provided by YSI Environmental. Manual calibration was performed in the field according to the local atmospheric pressure immediately before measuring. One water sample was collected directly near the surface of the shallow water cover by dipping a 1 L HDPE bottle into the water. Another sample was collected as close as possible to the tailings–water interface using a 2.2 L clear acrylic Alpha sampler; this water was immediately transferred into acid-washed HDPE bottles. This sample was used for physicochemical and chemical analyses and to determine the suspended sediment concentration (SSC) in the laboratory.

For groundwater sampling, water was pumped into each piezometer using the low-flow (minimal drawdown) method at 0.1–0.5 L/min (ASTM D6771-02 2002) until the physicochemical properties (T, pH, and electrical conductivity) become stable (MDDEP 2011). One litre of water was then collected in an acid-washed HDPE bottle.

The pH was measured with a relative precision of ±0.01 pH unit using a bench top pH/ISE meter, Orion model 920A, equipped with an Orion Triode electrode for pH with automatic temperature compensation. The Eh was measured with a Pt/Ag/AgCl-combined electrode (relative precision of ±0.2 mV), then corrected for a normal hydrogen electrode. The electrical conductivity (EC) was measured with OAKTON Acorn Series CON 6 conductivity meter with two platinum electrodes (precision of ±0.5 %).

All water samples were filtered through a Fisher Scientific nylon filter with a 0.45 µm pore diameter. Samples were then acidified to 2 % v/v HNO_3 to prevent metal oxidation. Samples were then analyzed by ICP-AES (a relative precision of 5 % evaluated by Villeneuve 2004). Sulfate content was also calculated from the concentration of total sulfur (S) using the ratio of molecular weights. In this case, it is assumed that all sulfur was in the sulfate form.

In addition to the physicochemical and chemical analyses, water samples from the two sampling campaigns in 2010 were sent to an outside laboratory (MultiLab, Rouyn-Noranda) for analysis of bicarbonate, carbonate, chloride, potassium, and sodium. The data were used to determine the water hydrochemical facies.

Wind Speed and Direction Measurement

A microanemometer (part of an HOBO Micro Station) equipped with a data recorder was installed at the Don Rouyn site to measure hourly wind speed and direction. Wind speed and direction were measured every 2 s, from which the hourly average speed and direction was determined and recorded. Hourly gust speed, i.e. maximum wind speed observed during the 1 h measurement period, was also recorded. Before the anemometer was installed at the Don Rouyn site, it was previously installed on the same lot at the weather station at Rouyn (call No.: WUY) for a period of 8 days as a reliability check, i.e. to verify whether the two stations measure the same wind speed and direction. WUY data were extracted from the National Climate Archives of Environment Canada (Environment Canada 2008). The WUY weather station, owned by the Xstrata Copper Horne Smelter, is located 2.5 km from the Don Rouyn site. The anemometer was installed at a height of 10 m above the ground and the microanemometer was installed at a height of 2.5 m. Results (not presented) show that the two anemometers indicated the same wind direction, but the wind speeds obtained with the microanmometer were lower than those obtained at the WUY station, partly due to the difference in height. The simplest elevation correction of the wind speed U_z, measured at an elevation z (m) (here z = 2.5 m), was applied to obtain the corresponding measured wind speed U_{10} at the standard 10 m reference level, using the following equation (CERC 2002; Johnson 1999):

$$U_{10} = U_z(10/z)^{1/7} \quad (1)$$

Figure 3 compares the measured and corrected wind speed U_{10} from the two anemometers. The correspondence was acceptable but not perfect for several reasons. The application of a wind speed correction factor is actually more complex than the procedure used here because this factor depends not only on the height difference, but also on thermal stability effects due to the temperature difference between air and soil, the friction velocity, the surface roughness, etc. (e.g. CERC 1984, 2002; Johnson 1999). Based on the observed results, it was concluded that the microanemometer is a reliable tool for measuring wind speed. After this reliability verification, the microanemometer was installed on the roof of a cabin located on the northwest side of the Don Rouyn shallow water cover at a height of about 10 m above the cover.

The results obtained in 2008 (not presented) indicated that winds blew at all wind speed intensities (including zero) in all directions, except for directions 40°–150°N, where the wind speed was always greater than zero. Wind

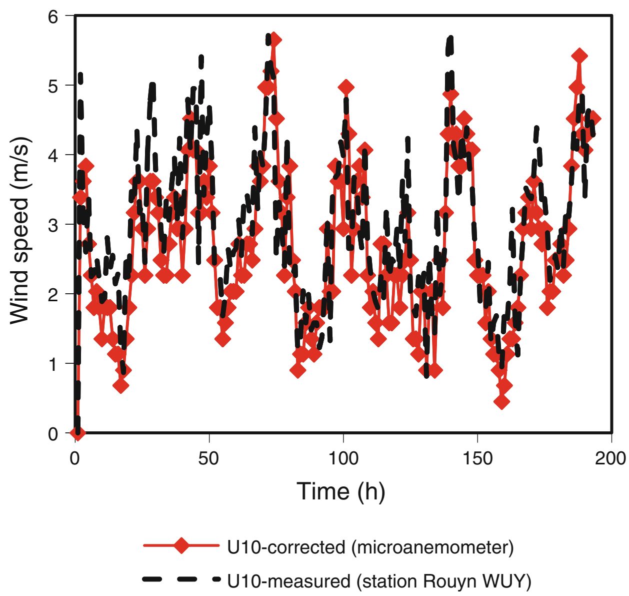

Fig. 3 Comparison of wind speeds measured at 10 m from the ground surface at the WUY station at Rouyn and height-corrected wind speeds obtained by the microanemometer at 2.5 m from the ground

directions between 200°N (southwest) and 355°N (northwest) were more frequent. These wind directions fall into the same range of the prevailing wind directions determined by Beaud (2005) using WUY data. Knowing the direction of the prevailing winds, the fetch of the shallow water cover at the Don Rouyn site was estimated at about 392 m in the northwest. This fetch is used below to calculate the total bottom shear stress to determine whether resuspension of tailings has occurred at the Don Rouyn site.

Measurement of Suspended Solid Sediment Concentration (SSC)

SSC by Filtration

Suspended solid sediment concentration (SSC, mg/L) was determined in different water samples collected from the shallow water cover near the water–tailings interface following ASTM D3977-97(2007), or CEAEQ (2004). A known volume (about 1 L) of a previously stirred water sample was vacuum filtered through 0.45 µm filter paper. The filter paper containing the solids was rinsed with 150–250 mL of deionised water after filtration to remove any salts. The mass of dry solid grains contained in the volume was obtained from the difference between the mass of the dry filter pad before and after filtration.

Continuous SSC Measurement

SSC was also continuously measured using a SuSix® probe (MJK Automation A/S). This optical sensor can measure both turbidity and SSC. The SuSix® probe measures SSCs between 1 and 400,000 mg/L at a temperature of 0–60 °C at 5 % accuracy with a 1 s response time. The description of this probe can be seen in the manufacturer's specification (MJK Automation A/S). The SuSix® probe was calibrated in the laboratory using the tailings from the Don Rouyn site before it was used for field measurements.

The SuSix® probe was installed at a station located near the north border of the east–west shallow water cover at Don Rouyn (with coordinates 5,346,080 m North and 337,000 m East; see Fig. 2). This location was selected to prevent possible disturbance from the aggregates operation on the west side of the site and allow the converter and power supply to be set up on the bank (Fig. 4). At this station, "Su", the water depth was approximately 1 m, which facilitated installing the probe from a boat. The probe was attached to a support anchored in the tailings and deployed perpendicular to the tailings surface so that the optical windows were about 10 cm from the tailings–water interface. SSC were measured and recorded at 5 min intervals. Data were retrieved monthly, and the probe was cleaned regularly to prevent dirt from obscuring the optical window.

Results and Interpretation

Tailings Characterization

The particle size characteristics and density of solid grains of the two samples analyzed are presented in Table 1. D_x is the diameter corresponding to x percent finer on the grain-size distribution. A significant similarity was observed between the two tailings samples, with very similar sized diameters D_{10}, D_{50}, D_{60}, and D_{90}.

The coefficients of uniformity C_U ($C_U = D_{60}/D_{10}$) for the two samples range from 9 to 10. The coefficients of curvature C_C [$C_C = (D_{30})^2 (D_{60} D_{10})^{-1}$] approach 1. These characteristics are similar to those for other tailings from hard rock mines (Bussière 2007). The relative densities of solid grains are almost identical for the two tested samples (4.57 and 4.59). These results are close to the relative density of solid grains of pure pyrite, which is 5.01 (Landry et al. 1995), indicating a high pyrite content in the tailings.

The main mineralogical components obtained by XRD show pyrite content C_P varied from 82 to 84 % for both samples. This high pyrite content was also observed visually in the dry tailings samples. These results confirmed those obtained by Beaud (2005) (see also Mbonimpa et al. 2008), who measured a C_P value of 92 %. The high pyrite content is in good agreement with the above-presented high relative density of solid grains. Other minerals present in significant proportions were quartz (6.4 %), chlorite (8.9 %), and muscovite (1.9 %). None of these minerals are

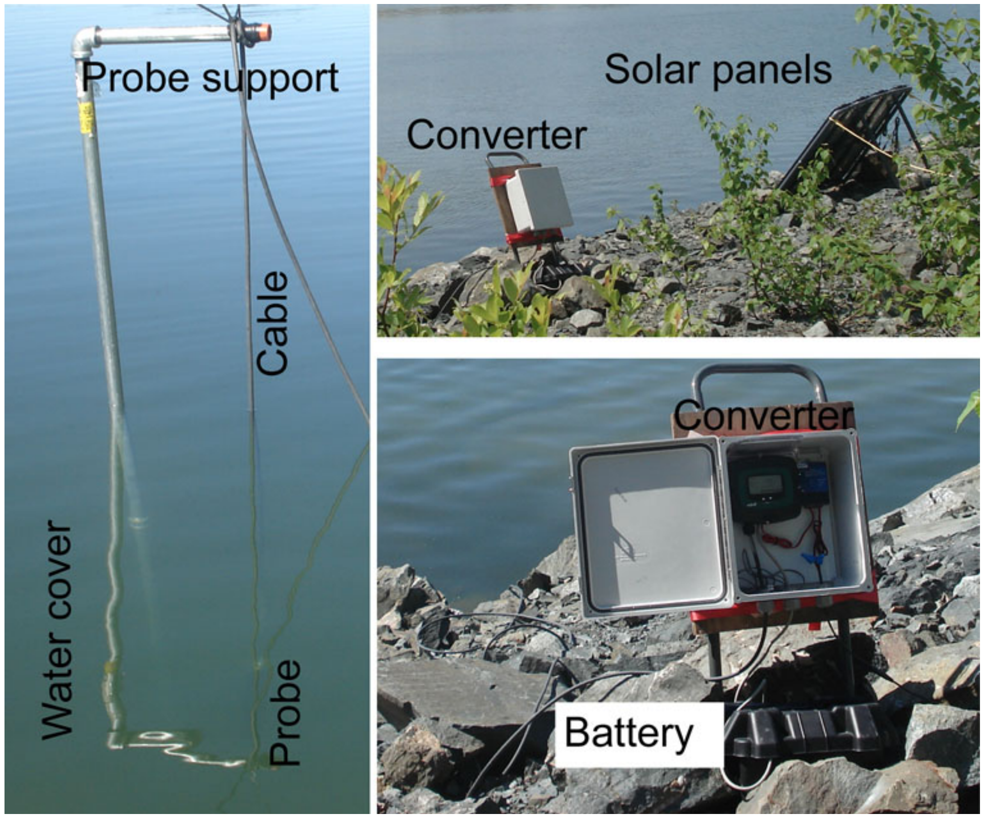

Fig. 4 SuSix® probe installation at the Don Rouyn site

Table 1 Grain-size characteristics and relative density of solid grains

Sample	1	2	Average
Finer than 80 μm (%)	82	87	85
Finer than 2 μm (%)	5	5	5
D_{10} (μm)	4.98	4.90	4.94
D_{50} (μm)	38.68	34.22	36.45
D_{60} (μm)	50.53	44.10	47.32
D_{90} (μm)	118.44	100.19	109.32
C_u	10.16	8.99	9.57
C_c	1.40	1.53	1.47
D_r	4.57	4.59	4.58

known for their neutralizing capacity (Lawrence and Wang 1997), which means that these tailings are highly acid generating. The results of the ICP-AES analysis of the two tailings samples for four major elements (Fe, S, Al, and Zn) clearly indicated a predominance of Fe and S, with average contents of 48.9 and 38.7 %, respectively. The analysis also showed the presence of Al (0.91 %), Zn (0.38 %), and trace amounts of Pb (0.068 %), Cu (0.049 %) and Ni (0.001 %). Unlike the XRD analysis, the ICP-AES analysis showed the presence of Zn. SEM analysis confirmed the presence of Zn as sphalerite (ZnS) that was free, attached to pyrite, and included within pyrite (Awoh 2012).

Quality of the Final Effluent and Cover Waters

Temperature (T) and Dissolved Oxygen (DO) Profiles in the Shallow Water Cover

For each station P1–P4, DO and T profiles were monitored monthly in the shallow water cover at 20 cm intervals from July to Oct. 2008. No significant variation in T or DO with depth was observed at any station at a given measurement date, corroborating the findings of Beaud (2005) (see also Mbonimpa et al. 2008). This observation has also been made at other shallow water cover sites (e.g. Holmström and Öhlander 1999; Rescan 1996; Vigneault et al. 2001). Given the relatively uniform values of T and DO for all stations at a given monitoring time, mean values are presented in Table 2. Results showed that, from July to Oct. 2008, average DO concentrations increased with decreasing temperature (Table 2). This was because oxygen's solubility in water increases with decreasing temperature (Benson and Krause 1984; Hillel 1998). Temperature and DO monitoring was limited to 2008 due to the relative similarity of the results on the four stations in 2008. Table 2 also shows the DO concentrations at saturation (DO_{sat}), calculated using Benson and Krause's (1984) equation, for each average water temperature at each measurement date. The measured DO were generally

Table 2 Average concentrations of DO (mg/L) and T (°C) from July to October 2008

Date	Station P1			Station P2			Station P3			Station P4		
	T	DO	DO_{sat}	T	DO	DO_{sat}	T	DO	DO_{sat}.	T	DO	DO_{at}.
10 July	16.6	7.9	9.8	17.6	8.1	9.6	18.4	7.9	9.4	19.7	7.9	9.1
19 Aug.	18.8	9.6	9.3	18.7	9.2	9.3	18.7	8.9	9.2	18.4	8.7	9.4
11 Sept.	14.0	10.2	10.3	14.0	10.2	10.3	14.0	10.3	10.3	13.8	10.4	10.3
28 Oct.	5.1	12.5	12.7	5.0	12.5	12.8	4.9	12.8	12.8	4.7	12.9	12.9

closed to saturation DO_{sat}. In other words, the shallow water cover at the Don Rouyn site was well mixed.

Physicochemical and Chemical Results

No significant variation in the physicochemical parameters was observed in the water cover near the air–water (a–w) interface or the water–tailings (w–t) interface for the P1–P4 stations, so the mean parameters for the four stations are presented for each monitoring date.

Measurements of pH at the final effluent ranged from 7.4 to 8 and from 6.7 to 8.4 in the shallow water cover (Fig. 5). All pH values were within the same range, and very close to neutral conditions. In addition, they were within the pH limits defined by Canada's Metal Mining Effluent Regulations, which require a pH between 6 and 9.5 (Department of Justice Canada 2011).

The Eh ranged from 189 to 370 mV for the final effluent and from 140 to 400 mV for the shallow water cover (Fig. 6). These values were positive, indicating an oxidizing environment. The measured Eh were generally below the Eh threshold (400 mV) above which kinetic testing would show AMD generation (MEND 1991), and they were below the Eh observed in AMD water (Aubertin et al. 2002).

On the other hand, electrical conductivity (EC) generally varied from 300 to 500 µS/cm in the final effluent and in the cover (Fig. 7). This is relatively low compared with the EC found at other shallow water cover sites (e.g. mean EC of 3,350 µS/cm at the Equity Silver site, Rescan 1996; mean EC of 106.5 µS/cm at Stekenjokk site, northen Sweden, Holmström and Öhlander 1999). The ICP-AES results for the eight final effluent and 32 cover water samples are presented in Table 3 in terms of minimum and maximum for seven major components: As, Cu, Fe, Ni, Pb, Zn, and SO_4^{2-}. Sulfate concentrations were generally uniform, at values between 91 and 121 mg/L for the final effluent and between 91 and 128 mg/L for the cover water.

Concentrations of As, Cu, Ni, and Pb in the final effluent and concentrations of As, Pb, and Ni in the shallow water cover were generally below the detection limit (Table 3). Concentrations of Fe and Zn in the final effluent were respectively from 0.006 to 0.027 mg/L and from 0.029 to 0.117 mg/L. In the shallow water cover, Zn concentrations (0.031–0.12 mg/L) were comparable to those of the effluent, whereas Cu (0.003–0.011 mg/L) and Fe (0.006–0.057 mg/L) concentrations were higher than in the effluent. In all cases, the maximum Zn concentration (0.120 mg/L) observed in 2008 was 11 times higher than the maximum concentration

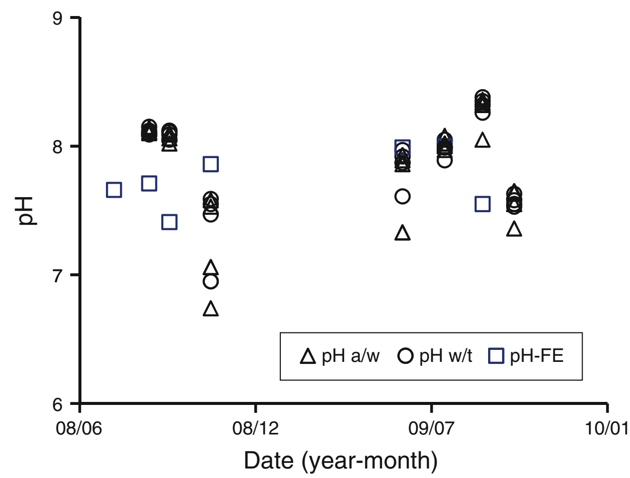

Fig. 5 Evolution of pH in the effluent and the shallow water cover (*a/w* near the air–water interface, *w/t* near the water-tailings interface, *FE* final effluent)

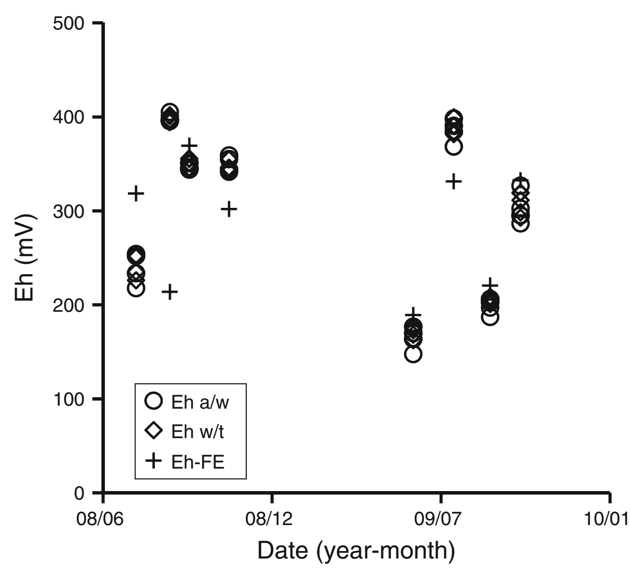

Fig. 6 Evolution of Eh in the effluent and the shallow water cover (*a/w* near the air–water interface, *w/t* near the water-tailings interface, *FE* final effluent)

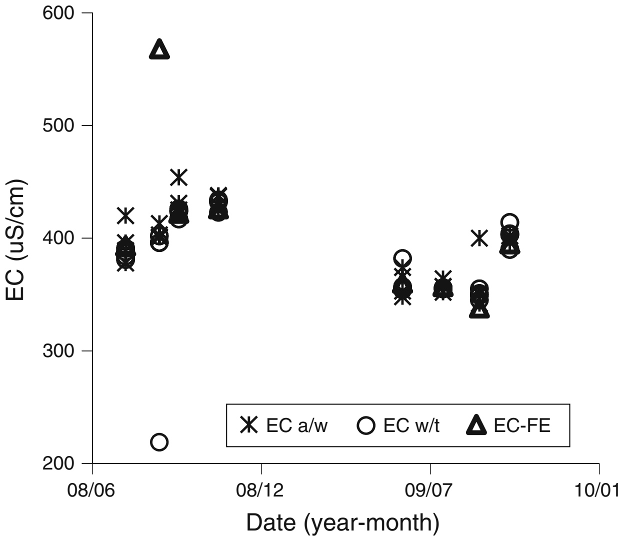

Fig. 7 Evolution of EC in the effluent and the shallow water cover (*a/w* near the air–water interface, *w/t* near the water-tailings interface, *FE* final effluent)

of Cu (0.011 mg/L). This was in accordance with the ICP-AES results on the tailings.

The metal concentrations measured at the Don Rouyn site were below the local environmental criteria (3 mg/L for Fe, 0.3 mg/L for Cu and 0.5 mg/L for Zn; MDDEP 2005). The Zn concentration was also below the criteria stipulated in Canada's Metal Mining Effluent Regulations (Department of Justice Canada 2011). The Fe and Zn concentrations also met Canada's recommended levels for the quality of drinking water from raw water (surface and ground water), which specifies maximum concentrations of 0.3 mg/L for Fe and 5 mg/L for Zn (Health Canada 2008).

Characteristics of the Groundwater Around the Don Rouyn Site

Well Water Levels

The water levels measured at different dates in each of the piezometers are given in Fig. 8. Elevations ranged from 308.6 to 320.7 m. Considering that the maximum water level of the shallow water cover is imposed by a weir at 308.5 m, the results indicated that the water level in the shallow water cover was lower than the water levels in each of the piezometers. This suggests that the hydraulic gradient drove the water flow from the groundwater to the Don Rouyn pit, which captured it. A generally high difference in level was found between the weir crest and wells F2, F3, and F5 (>3.5 m). A water level increase of this amount is unlikely in the pit. The water levels in piezometers F1 and F6 were close to the weir crest level. As these two wells are located near the discharge area for water from the Don Rouyn site, and because this water was not contaminated, water flow from the pit to the groundwater would be unlikely.

Physicochemical and Geochemical Properties

2008–2009 measurements of pH in the groundwater were between 6 and 8. These pH values were in the same range as those measured in these piezometers by GEOCON in 1997a ($7.2 \leq pH \leq 8$) and the Xstrata Copper Horne Smelter in June 2008 ($6.4 \leq pH \leq 7.7$). These pH values approached neutral pH, and were similar to the pH measured in the shallow water cover and the final effluent. Eh in the piezometers ranged from 80 to 384 mV, and were generally lower than in the shallow water cover. EC measured in the groundwater ranged from 264 to 785 µS/cm for all piezometers, except for F3, ranging from 1,364 to 2,780 µS/cm. GEOCON (1997a, b); Beaud (2005) also found particularly high EC in this borehole. This high conductivity was confirmed by high concentrations of Ca, Mg, Si, and SO_4^{-2} in the water samples collected from this well (see details below).

With the exception of F3, sulfates were between 7 and 190 mg/L, and below the recommended standards for groundwater used for drinking water, for which the prescribed threshold is 250 mg/L (Appelo and Postma 1994). Most metal concentrations were below the ICP-AES detection limits. Two metals (Ba and Zn) were present in

Table 3 Minimal and maximal geochemical parameters in the shallow water cover and final effluent and maximum concentrations specified in Quebec's Directive 019 and Canada's Metal Mining Effluent Regulations

Parameter	Detection limit	Final effluent (mg/L)	Shallow water cover (mg/L)	Quebec's directive 019 (mg/L)	Federal metal mining effluent regulations (mg/L)
As	0.01	<DL	<DL	0.2	1
Cu	0.003	<DL	0.003–0.011	0.3	0.6
Fe	0.006	0.006–0.027	0.006–0.057	3	–
Ni	0.004	<DL	<DL	0.5	1
Pb	0.02	<DL	<DL	0.2	0.4
Zn	0.005	0.029–0.117	0.031–0.120	0.5	1
SO_4^{2-}	–	91–121	91–128	–	–

– not defined

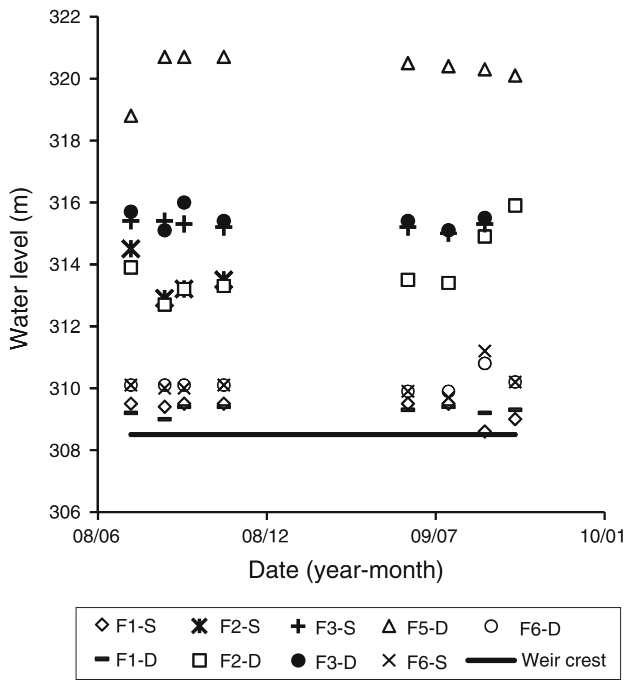

Fig. 8 Variation in water level in the piezometers around the Don Rouyn site during summer and fall 2008 and 2009

measurable quantity in the groundwater samples. The concentrations obtained were below the criteria for groundwater quality (Health Canada 2008; MDDEP 2008). As mentioned above, piezometers F3-S and F3-P showed particular characteristics, with highly mineralized groundwater. Sulfate concentrations ranged from 309 to 663 mg/L. Concentrations of Ca, Mg, Si, and Mn ranged from 199 to 320 mg/L, 29 to 50 mg/L, 4 to 10 mg/L, and 27 to 48 mg/L, respectively. These were high concentrations compared to the other piezometers (which were below detection limits). It can be assumed that the high amount of sulphate ions, Ca, Mg, Si, and Mn in the groundwater from well F3 was due to the presence of carbonate (calcite, dolomite), clay (montmorillonite), and sulfide minerals in the fill through which F3 was drilled. Because these ions can be easily dissolved, rainwater infiltrating through the fill could have resulted in their release into the groundwater (Banton and Bangoy 1999).

Water Geochemical Facies

Geochemical hydrofacies at Don Rouyn were determined using a Piper diagram. Piper diagrams consist of two triangles representing the cationic and anionic facies and a diamond synthesizing the global facies (Banton and Bangoy 1999). The geochemical facies of the Don Rouyn water (effluent EF and wells) are presented in Fig. 9. The bicarbonate facies was found in most groundwater. It distinguished sulfate calcium bicarbonate water, calcium bicarbonate water, and calcium and magnesium bicarbonate water, with the exception of groundwater in borehole F3, which contained more calcium, magnesium, and sulfate. This could be explained by the abnormally high concentrations of sulfate and other components in these wells, as discussed above. In contrast, the final effluent of the shallow water cover showed calcium sulfate water. These results indicated that the groundwater's composition differs from that of the cover water. This helps confirm that the groundwater was not influenced by the cover water, corroborating the observation above that was based on a water level comparison, which suggested that the cover water did not leak into the groundwater.

Suspended Sediment Concentration (SSC)

SSC Measurement by Filtration

SSCs were determined by filtration, as described earlier, for all water samples collected near the tailings–water interface at stations P1–P4 (where water cover depths varied between 1.1 and 1.7 m). The SSC varied from 1.1 to 15 mg/L for the four stations. The wind speed U_{10} measured at the time of water sampling at the Don Rouyn site varied from 1 to 6 m/s. SSCs were correlated with U_{10}; there was no evidence of a link between U_{10} and SSC.

It should be noted that the final effluent flows through a narrow channel excavated in the rock. This channel is only slightly influenced by the wind. SSCs of the final effluent were lower than those obtained for the shallow water cover (about 5 mg/L in 2008). Even in the shallow water cover, SSCs were less than the maximum allowable concentration in an instantaneous sample (30 mg/L), as recommended by the Canadian Metal Mining Effluent Regulations (Department of Justice Canada 2011). These SSCs measured in the shallow water cover were also below the maximum acceptable SSC (30 mg/L) recommended by Quebec's Directive 019 on the mining industry (MDDEP 2005).

SSC Measurements by Probe

SSCs were continuously measured from June to Sept. 2010 using the SuSix® optical probe installed 10 cm above the water–tailings interface, as described earlier. SSCs were measured continuously at 5 min intervals to calculate the hourly arithmetic mean. Figure 10 presents the temporal evolution of continuously measured SSCs. For the measurement period, the average hourly SSCs ranged from 0.91 to 18.5 mg/L, comparable to those measured by filtration. The absence of SSCs from July 11 to Aug. 5, 2010 was due to a clogged SSC probe, which consequently recorded abnormally high SSCs. The probe was cleaned for further measurements. SSC peaks were also observed at certain times.

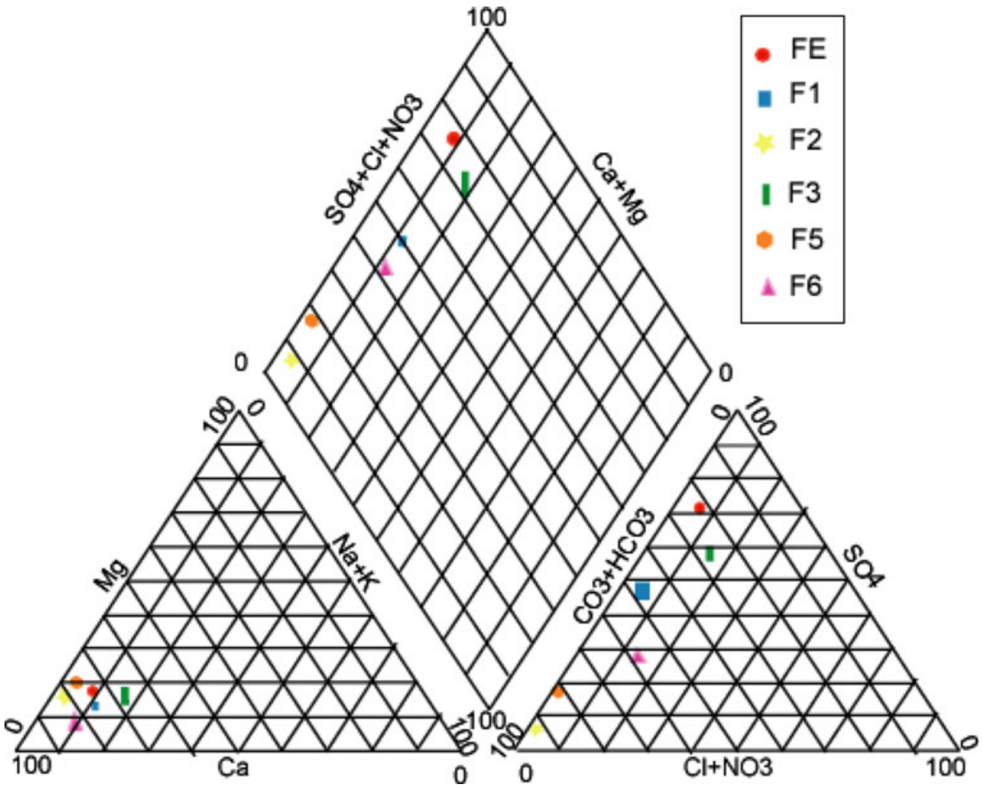

Fig. 9 Water geochemical hydrofacies using the Piper diagram for wells *F1–F6* (without destroyed well 4) and for the final effluent (FE)

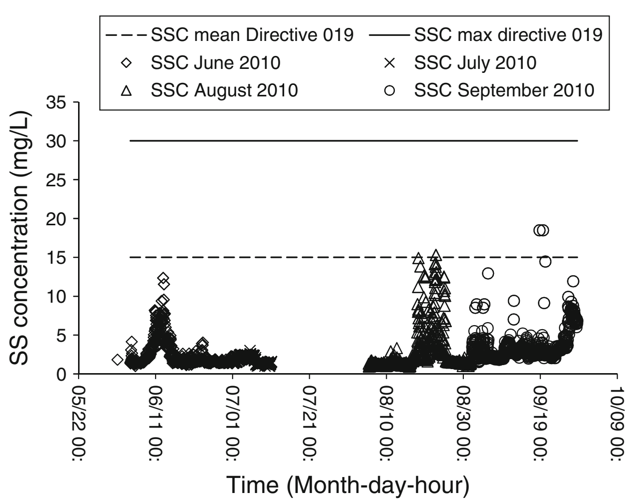

Fig. 10 SSC evolution during summer 2010

Attempts were made to correlate hourly SSC concentrations with measured hourly wind speed U_{10} and wind direction from the National Climate Archives of Environment Canada for the WUY station at Rouyn (Environment Canada 2010). High SSCs were observed at low wind speeds and SSC tended to decrease with increasing wind speed. Also, both low and high SSCs were present for all wind directions. The expected correlation between wind speed, wind direction, and SSC was not observed. This is consistent with the SSC results measured by filtration. An analysis of these results suggests that the resuspension of tailings particles at the Don Rouyn site was probably controlled by factors other than hourly direction and wind speed. This aspect will be addressed further below.

Discussion

Several results were presented above to assess the performance of the shallow water cover at the Don Rouyn site. SSCs were measured, even at low wind speed. It is hence useful to examine the yield wind speed above which tailings resuspension was induced.

Hydrodynamic Conditions for Tailings Resuspension

Tailings are resuspended in a shallow water cover when the total shear stress (τ_{tot}) exerted on the tailings exceeds the critical shear stress (τ_{cr}). The total shear stress (τ_{tot}) includes the stress induced by waves (τ_w) and the stress caused by the return current near the bed (τ_{ret}) (Adu-Wusu et al. 2001; Samad and Yanful 2005; Yanful and Mian 2003).

$$\tau_{\mathrm{tot}} = \tau_{\mathrm{w}} + \tau_{\mathrm{ret}} \quad (2)$$

The bottom shear stress τ_w (Pa) can be estimated as follows (Adu-Wusu et al. 2001; Samad and Yanful 2005; Yanful and Catalan 2002; Yanful and Mian 2003):

$$\tau_w = \frac{1}{2}\rho_w f_w U_w^2 \tag{3}$$

where ρ_w is the density of water (1,000 kg/m^3) and f_w is the wave friction factor, which is a function of the Reynolds number and the relative roughness of the boundary (Adu-Wusu et al. 2001). U_w is the bottom velocity for the wind-induced waves (m/s) (Adu-Wusu et al. 2001). U_w is a function of the wave characteristics T (s), L (m), and H (m), which are the significant wave period, length, and amplitude, respectively. The wave characteristics T, L, and H can be estimated for deep-water waves (h/L >0.5) or shallow-water waves (h/L <0.5) depending on the wind speed U_{10} (measured at 10 m above the surface of the water recovery) and the fetch F.

The shear stress due to return currents τ_{ret} (Pa) at the water–tailings interface is given by Eq. 4 (Adu-Wusu et al. 2001):

$$\tau_{ret} = 10^4\left(0.75 + 0.067U_a\right)\rho_a U_a^2) \tag{4}$$

where ρ_a is the density of air (1.24 kg/m^3 at 10 °C) and U_a is the wind stress factor with $U_a = 0.71\, U_{10}{}^{1.23}$.

The critical shear stress (τ_{cr}) can be estimated as follows (Adu-Wusu et al. 2001; Chien and Wan 1998):

$$\tau_{cr} = 1/77.5\left[3.2(\gamma_s - \gamma_w)D_{50} + (\gamma_b/\gamma_{bo})^{10}(0.00029/D_{50})\right] \tag{5}$$

where γ_s and γ_w are respectively the weight and volume of specific residues (N/m^3) and water (1,000 N/m^3). γ_b and γ_{bo} are the unit weights of the tailings at the interface (N/m^3) and the consolidated tailings (N/m^3), respectively. These two unit weights are usually assumed to be equal when the tailings are stored under water for a long time, as is the case here. D_{50} is the mean diameter of the tailings.

Taking all parameters into account, the critical shear stress τ_{cr} for the tailings submerged at Don Rouyn was estimated at 0.16 N/m^2. Other equations presented in the literature (e.g. Millet et al. 2010) generate a very similar critical shear stress.

The total shear stress was calculated for the Don Rouyn site with a fetch of 392 m for shallow water cover depths h of 0.81, 1, and 1.16 m and wind speeds U_{10} from 1 to 20 m/s (Fig. 11). The depths h of 0.81 and 1.16 m correspond to the minimum and median depths of the shallow water cover at Don Rouyn. The depth $h = 1$ m was the targeted design depth of the Don Rouyn shallow water cover (GEOCON 1997a). The calculations were first performed for the deep-water wave conditions (h/L >0.5) prevailing when U_{10} <11 m/s for $h = 0.81$ m, U_{10} <14 m/s for $h = 1.0$ m, and U_{10} <17 m/s for $h = 1.16$ m. Figure 11 also shows the critical shear stress calculated using Eq. 5. Shear stress calculations were not performed for shallow-water waves (h/L <0.5) because the total shear stress became greater than the critical shear stress for the deep-water wave conditions. For the Don Rouyn shallow water cover, the results presented in Fig. 11 indicate that tailings resuspension ($\tau_{tot} \geq \tau_{cr}$) starts when $U_{10} \geq$10 m/s for $h = 0.81$ m, when $U_{10} \geq 11$ m/s for $h = 1$ m, and when $U_{10} \geq$12 m/s for $h = 1.16$ m. The highest wind speeds observed at the WUY station for each of the last 10 years varied from 10.83 to 14.44 m/s. Although resuspension would occur under such conditions, these conditions were rare.

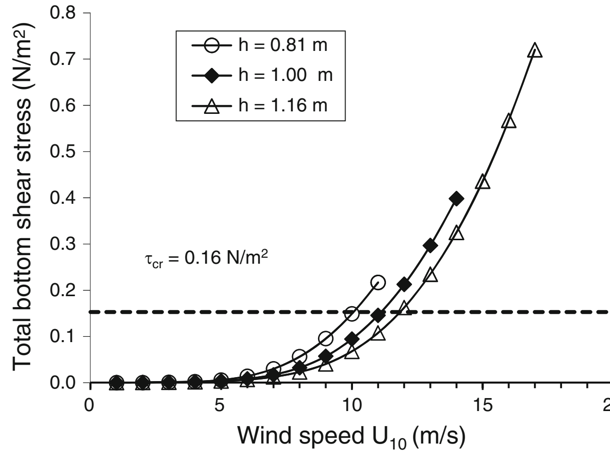

Fig. 11 Variation in total bottom shear stress with respect to wind speed

However, the field measurements indicate that tailings resuspension occurred at wind speeds lower than 10 m/s. There was no causal relationship between the evolution of SSC and gust speeds observed at the site. This means that the equations used to calculate shear stress may not be representative of the hydrodynamic conditions at the Don Rouyn site. It can be assumed that the SS observed came from a thin layer of very fine particles deposited at the tailings surface that likely had the potential to remain in suspension for some time.

Finally, the measured SSCs represent a combined resuspension-transport-deposition process, which makes it difficult to isolate the influence of wind speed. Numerical models should be used to solve the differential equations of the balance between the upward and downward transport of particles (e.g. Millet et al. 2010; Vlag 1992).

Comparison of Don Rouyn SSC with Other Sites

Compared to other shallow water cover sites, SSCs in the Don Rouyn site are low. For example, in Cell 14 of the Quirke shallow water cover site near Elliot Lake (Ontario, Canada) with a fetch of 1.5 km, SSCs varied from 100 to 1,000 mg/L for wind speeds ranging from 0 to 15 m/s (Adu-Wusu et al. 2001). From Oct. 1992 to Oct. 1999, Peacey et al. (2002) measured SSC between 98 and 101 mg/L in the same Cell 14 of the Quirke site. At the Heath Steele site, Peacey and Yanful (2003) measured a SSC of 37.5 mg/L in Oct. 1998 and 152 mg/L in May 1999.

Kachhwal and Yanful (2010) continuously measured SSC for only 18 h using two optical backscatter (OBS) sensors at the Shebandowan site located 100 km northwest of Thunder Bay, Ontario, Canada, and obtained SSCs ranging from 5 to 25 mg/L with the first OBS sensor located 10 cm above the tailings and from 2 to 8 mg/L with a second probe located 25 cm above the tailings. The wind speed ranged from 4 to 9 m/s during the 18 h study (compared to from 1 to 5 m/s over the 4 months at the Don Rouyn site). The Shebandowan site is larger (total area 115 ha) than the Don Rouyn (only 7 ha), which can produce a much higher fetch, depending on the wind direction. The configuration of the Shebandowan site, which is surrounded by engineered dykes, differs from that of the Don Rouyn pit, which is partially surrounded by some very high rock walls. The depth of the shallow water cover varied from 0.6 to 3 m at the Shebandowan site, and from 0.81 m to 2.8 m at the Don Rouyn site. The average tailings diameter (D_{50}) ranged from 6.5 to 9 µm at the Shebandowan site, and was around 36 µm at the Don Rouyn site. When all these characteristics are compared, it may be concluded that the Shebandowan tailings may be more prone to resuspension than the Don Rouyn tailings for the same wind speed.

Suspended sediment concentrations were obtained by filtration and using a SuSix® optical probe. It was found that resuspension was not significant (usually less than 20 mg/L) and not correlated to wind speed for all hourly wind speeds and directions, which is contrary to what was predicted by theoretical calculations, which suggested resuspension of tailings for wind speeds exceeding 10–12 m/s. The theoretical calculation concepts appeared to not adequately represent the particular hydrodynamic conditions at the Don Rouyn site. The measured SSCs remained below regulatory limits, and did not affect the quality of the cover water (pH and metal concentrations were within regulatory limits).

Conclusion

This study assessed the efficiency of the shallow water cover at the Don Rouyn site by evaluating the chemical and physical stability of the submerged tailings. Field monitoring and laboratory tests were performed. Results of water quality analyses suggest that, at the time of the study, there was no contamination in either the final effluent or the water cover. All parameters met the requirements of Canada's Metal Mining Effluent Regulations and Quebec's Directive 019 for the mining industry; Zn concentration was higher than other metals.

The groundwater met the criteria for groundwater contamination and the Canadian guidelines for water quality. Water levels in the piezometers placed around the water cover site were higher than the level of the weir crest that controls the water level in the pond. Furthermore, the dominant hydrochemical facies of the groundwater and cover water differed. Therefore, under the current site conditions, the water cover should not affect the surrounding groundwater.

This study shows that water covers can be used to successfully control the generation of AMD, even for tailings containing a high concentration of sulphide minerals, such as those from the Don Rouyn site. However, the applicability or transferability of the results to other sites must consider that the efficiency of each water cover depends on different parameters such as the chemical, mineralogical, and physical properties of the tailings and on the hydrodynamic conditions of the site. Therefore, these parameters should be studied specifically for each site. For example, for the same tailings, water cover simulations using laboratory columns showed a significant impact of various hydrodynamic conditions on water quality (Awoh 2012).

Results from this study showed that efforts are still required to further study the correlation between SSC and wind speed at the Don Rouyn site. Installation of multiple probes for continuous measurement of SSC at different locations and different depths above the tailings-water interface would help in that perspective. The installation of an anemometer directly above the water cover surface would provide the actual values of wind speed and thus refine any possible relationship between SSC and wind speed.

Furthermore, geochemical modeling is required to further study the long term performance of the water cover, taking into account DO migration, sulphide mineral oxidation, and mass transport. Additional tailings characteristics must be determined for that purpose, including the reaction rate coefficient of tailings with DO; this aspect was addressed by Awoh (2012). An analysis of the tailings-water interface could also be performed to examine the probable presence of a biofilm, and thus, to assess its role on the long-term efficiency of the water cover at the Don Rouyn site. The beneficial impact of such a biofilm was studied at the Louvicourt site by Vigneault et al. (2007). Finally, tracer tests could be considered to confirm the hydraulic interaction between groundwater and water cover.

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