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Challenges from North to South
Des défis du Nord au Sud

The hydrochemical behavior of the Aldermac abandoned mine site after its rehabilitation

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ABSTRACT

Before its reclamation Aldermac was considered as one of the most problematic abandoned mine site in Quebec due to the high production rate of acid mine drainage (AMD) by sulphidic mine tailings. This site was reclaimed between 2008 and 2009 to control tailings oxidation, and future production of AMD. For that purpose, the site was reclaimed using a monolayer cover combined with an elevated water table for the north zone and using low saturated hydraulic conductivity HDPE geomembrane cover for the south zone. The reclamation of the mine tailings impoundment should gradually improve the groundwater quality at the site. To evaluate this aspect, sampling campaigns from 2011 to 2013 were performed on site to assess the evolution of groundwater quality of the reclaimed Aldermac mine site. Hydrochemical results were interpreted with principal components analysis. Results show that the groundwater quality is improving and that the reclamation is helping to reduce groundwater contamination at the site.

RÉSUMÉ

Avant sa restauration, le site Aldermac a été considéré jusqu'à 2008 comme l'un des sites miniers abandonnés les plus problématiques au Québec. Ce site a été réhabilité entre 2008 et 2009 afin de contrôler l'oxydation des résidus miniers sulfureux et la production future du drainage minier acide (DMA). A cet effet, la zone Nord du site a été réhabilitée à l'aide d'une couverture de type monocouche combinée avec une nappe d'eau surélevée et la zone sud à l'aide d'une géomembrane de type PEHD. Cette réhabilitation devrait permettre une amélioration de la qualité chimique des eaux souterraines. Pour évaluer cet aspect, des campagnes d'échantillonnage des eaux souterraines ont été réalisées entre 2011 à 2013 dans le but d'évaluer leur qualité chimique. Les résultats des analyses ont été interprétés à l'aide des analyses en composantes principales et montrent une amélioration de la qualité chimiques des eaux souterraines et permettent de conclure que la réhabilitation permet de réduire la contamination des eaux souterraines du site Aldermac.

1 INTRODUCTION

The Aldermac abandoned mine site is located in the Abitibi region; in the province of Quebec about 15 km west of Rouyn–Noranda city (see Figure 1). This abandoned mine site has been exploited for its rich deposits of zinc and copper between 1931 and 1943. The mine produced nearly 1.5 million tons of acid-generating tailings, which covered an area of about 60.3 hectares, including both the tailings areas and affected spill zone in the valley of Stream 1 (see Figure 1). Therefore, the Aldermac mine site was considered until 2008 as one of the most problematic abandoned mine sites in Quebec.

After studying several reclamation scenarios, the Aldermac site was reclaimed between 2008 and 2009 (SNC-Lavalin 2010). The main objective of this reclamation was to prevent further reactive tailings oxidation and therefore inhibit the production of new acid mine drainage. The reclamation work at the Aldermac mine site was performed as follows (SNC- Lavalin 2010; Cyr et al. 2011):

1. Tailings of the South area were excavated and confined using a cover made of High-density polyethylene (HDPE) geomembrane.
2. Tailings and contaminated soils along the Stream 1 were excavated and deposited in the North area.
3. Tailings from the intermediate area were excavated and deposited in the North area.
4. In the northern sector, tailings were placed in two areas separated by a dike (Terrace 1 and 2, see Figure 2). These tailings were covered with a monolayer cover composed of a granular material (sand and gravel) and an elevated water table was created. The monolayer cover has a thickness of about 1 m.

Thus, two different techniques have been used for the reclamation of the abandoned Aldermac mine site: low saturated hydraulic conductivity cover made of an HDPE geomembrane and a monolayer cover combined with an elevated water table (EWT).

The concept behind a monolayer cover combined with an EWT is well described in the literature (see Dagenais 2005; Maqsoud et al. 2013; Ouangrawa et al. 2006, 2010). The performance of this EWT used at the Aldermac mine site was evaluated using piezometric measurements from 2011 to 2012 (see Maqsoud et al. 2013). This performance may allow for improved groundwater quality of the site.

Sampling campaigns were performed between 2011 and 2013 with the objective to assess the groundwater quality evolution at the Aldermac mine site.

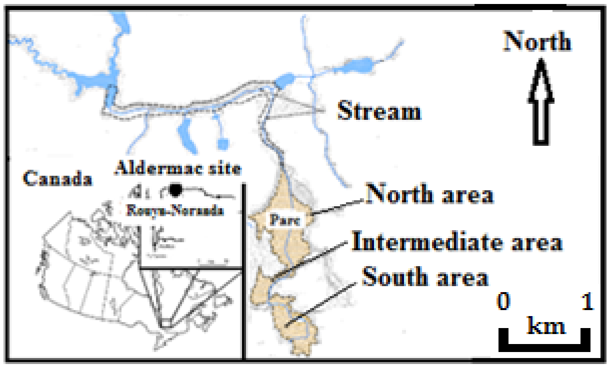

Figure 1. Localisation of the Aldermac mine site (modified from SNC–Lavalin 2010)

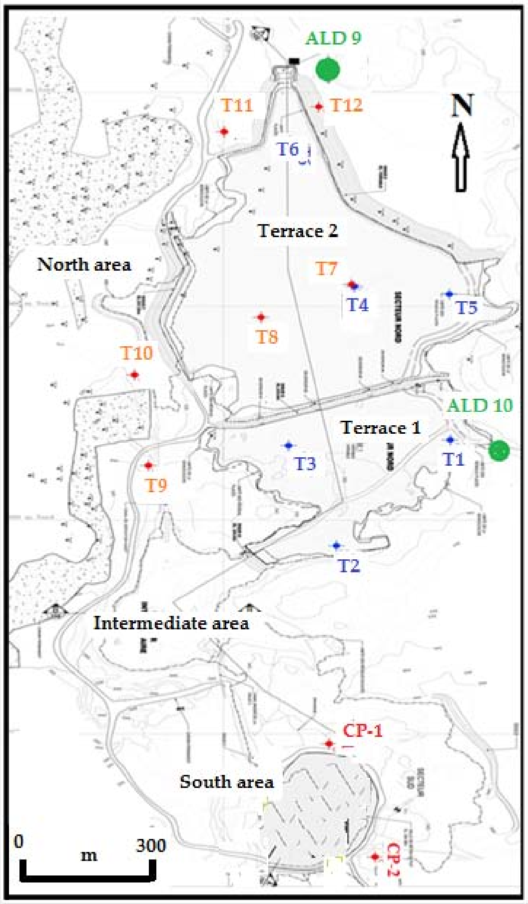

Figure 2. Localisation of different sectors of the Aldermac mine site

This paper presents a description of the localisation of the different piezometers used for groundwater samplings, followed by a brief description of groundwater sampling and principal components analysis (PCA) methods. Hydrochemical results are interpreted and analyzed with the PCA technique. Finally this paper ends with a discussion and conclusions about the impact of mine site reclamation on the groundwater quality.

2. FIELD INVESTIGATIONS AND ANALYSIS METHOD

2.1 Piezometer network

During the summer of 2011, 8 piezometers were installed on the abandoned Aldermac mine site (see Figure 2). A brief description of the boreholes is presented in Table 1 where the succession of the different layers encountered from top to bottom and their thickness are given. It is important to recall the presence of a clay layer between natural soil surface and glacial till formation in piezometer T7, T8, T11 and T12. The thickness of this layer ranges between 3.4 and 17.2 m.

Other piezometers were installed at the Aldermac mine site during the rehabilitation (T1 to T6 – see Figure 2). The depths of these piezometers are close to the interface between the granular cover and the underlying reactive tailings. These piezometers are mainly used for groundwater sampling.

All the piezometers installed were used for water sampling campaigns that were performed after the mine site reclamation. However, in this study we focus mainly on the groundwater of glacial till aquifer and not on the tailings pore water.

Table 1. Description and layer thickness (m) of the boreholes installed at the Aldermac mine site

	Sand gravel	Tailings	Soils	Clay	Glacial tills	Rock
T7	1.07	2.89	1.68	10.87	1.83	
T8	1.52	2.59	1.52	17.15	1.57	
T9					4.93	
T10			1.10		4.29	
T11			1.52	3.35	0.76	1.09
T12			1.10	3.76	2.05	
CP1					4.24	
CP2					4.12	1.24

2.2 Water sampling method

After the Aldermac mine site reclamation, three water sampling campaigns were performed each year: during spring, summer and fall seasons. The water samplings were performed using low-flow method (Puls and Cynthia 1995; Puls and Barcelona 1996). By using this method, the stress (drawdown) imposed to the system is minimized. Flow rates applied were in the order of 0.1 - 0.5 L/min. During pumping, different parameters were analyzed such as pH, electrical conductivity (EC) and temperature and were used to determine when water could be sampled (i.e. when parameter stabilization occurred).

All the samples were collected in clean polyethylene bottles and were transported to the laboratory in iceboxes. The samples were stored at 4°C before chemical analyses. All the chemical analyses were performed in a certified laboratory. The concentration of the following elements was determined: Aluminium (Al), Arsenic (As), Barium (Ba), Beryllium (Be), Bismuth (Bi), Calcium (Ca), Cadmium (Cd), Cobalt (Co), Chrome (Cr), Cupper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Lead (Pb), Sulfate (SO_4), Selenium (Se), Titanium (Ti) and Zinc (Zn).

2.3 Principal Components Analysis

The principal components analysis (PCA) is a statistical analysis technique, dealing with at least two variables, allowing a graphic representation of the correlation between variables (n) and positions of the individuals with regard to the vectors of these variables (Joliffe, 2005). Graphs are built from the matrix of the correlations, and the PCA describes, diagrammatically, the links between the various variables and the chosen factors. These graphs are represented in a circle of radius 1. The greater the correlation of the variable (-1 or +1) to a factor, the more the variable is correlated to this factor. The position of variables is thus determined by their correlation with the factors. The closer together two variables are, the greater their correlation.

This method was adopted in numerous hydrogeochemical studies (Bakalowicz 1979; Blavoux and Mudry 1985; Muet 1985; Lasne 1992; Maqsoud 1996; Helena et al. 2000; Maqsoud et al. 2004; Maqsoud 2007; Lghoul et al. 2013; Guan et al. 2013). Its efficiency is considered superior to other methods, such as Collins, Stiff, Schoeller and Piper diagrams (Güler et al. 2002) because this method can group samples based on water chemistry data.

3 MAIN RESULTS

This section presents the main results of two groundwater sampling campaigns: the first one performed just after the end of the reclamation work (November of 2011 campaign), and the second one performed 2 years later. These campaigns were performed during fall recharge and one can consider that these campaigns are performed under the similar hydrological conditions.

3.1 First campaign: November of 2011

Chemical analysis results showed that the concentration of As, Be, Bi and Se were very low and did not reach the ICP detection limit in all 8 samples. For this reason, these chemical elements will not be included in the analysis. For the other elements, statistical parameters such as minimum, maximum, median and mean value were evaluated. These parameters are presented in Table 2. This Table shows that the minimum and maximum values are included between 0.18 and 52.82 mg/l, 0.67 and 5466 mg/l, 0.01 and 49.89 mg/l, 18.00 and 343 mg/l, 19.00 and 9947 mg/l and 181.4 and 12270 µS/cm for Al, Fe, Zn, Ca, SO_4 and EC, respectively.

Also, the standard deviation of the Ca, SO_4, Zn and EC correspond to 123.89, 3339.63, 1892.93 and 3868.87, respectively (see Table 2). These values are high and indicate that the data for these parameters are spread out over a large range of values.

Principal components analysis (PCA) was performed on these elements using XLSTAT (Addinsoft 2014). The calculation was limited to three factors and the total percentage of the variance expressed by these three factors is 90.7 %.

Table 2. Statistical parameters of groundwater sampled on November 2011: EC is expressed in µS/cm and the other dissolved elements in mg/L

Variable	Minimum	Maximum	Standard deviation
EC	181.40	12270.00	3868.87
SO_4	19.00	9947.00	3339.63
Pb	0.00	0.05	0.02
Ni	0.01	0.22	0.08
Mn	0.06	17.16	5.71
Mg	0.95	187.00	58.90
Fe	0.67	5466.00	1892.93
Cu	0.01	1.13	0.45
Co	0.00	0.92	0.37
Cr	0.00	0.11	0.04
Ca	18.00	343.00	123.89
Cd	0.00	0.05	0.02
Ba	0.01	1.00	0.34
Al	0.18	52.82	17.76
Ti	0.04	0.76	0.28
Zn	0.01	49.89	17.05

Correlations between different variables are presented in Table 3, where one can observe that the EC is mainly correlated to most dissolved elements. Also SO_4 is correlated to all elements except for Pb, Cr, Ba and Ti. However, Pb is only correlated to Cr, Ba and Al.

The association between SO_4 and other elements indicates that the origin of this water can be related to AMD. However, the dissociation between Pb, Cr, Ba and Al and other element indicate that the first group had a different evolution and probably related to soil ions exchange.

The variance expressed by factors F1, F2 and F3 are 60.2, 23.9 and 6.6 %, respectively. The factor F1, which express 60.2 % of the variance, is correlated positively to EC, SO_4, Ni, Mn, Mg, Fe, Cu, Co, Ca, Cd, Ti, Al, and Zn. These ions are therefore characteristic of the acid mine drainage. The factor F2 which represent 23.9 % of the variance is correlated positively to Pb, Cr and Ba. The factor F3 which represent 6.6% of variance presents a very low correlation with all parameters and for this reason, factor F3 cannot be interpreted. The factor F1 and F2 did not present any opposition between their correlated elements (see Figure 3).

In the spatial representation (see Figure 4) and along factor F1 one can observe that groundwater samples which characterize the acid mine drainage (CP-1) are opposed to groundwater sample with low metallic concentrations (T8 and T11). So, this factor makes opposition between contaminated groundwater with high concentration of elements related to AMD and the groundwater without AMD contamination. This factor can be interpreted as natural attenuation of AMD by groundwater dilution.

Table 3. Correlation between different parameters from piezometer water analyses in the abandoned Aldermac mine site: November of 2011 campaign samplings

Parameters	EC	SO4	Pb	Ni	Mn	Mg	Fe	Cu	Co	Cr	Ca	Cd	Ba	Al	Ti	Zn
EC	1.00															
SO4	**0.97**	1.00														
Pb	0.01	0.11	1.00													
Ni	0.51	**0.56**	0.31	1.00												
Mn	0.81	**0.86**	0.01	**0.80**	1.00											
Mg	**0.83**	**0.90**	0.34	**0.71**	**0.91**	1.00										
Fe	**0.96**	**1.00**	0.13	0.51	**0.82**	**0.88**	1.00									
Cu	**0.60**	**0.68**	0.11	0.40	**0.60**	**0.61**	**0.67**	1.00								
Co	**0.82**	**0.82**	-0.07	**0.82**	**0.90**	**0.75**	**0.78**	0.45	1.00							
Cr	-0.26	-0.19	**0.84**	0.09	-0.15	0.17	-0.19	-0.20	-0.34	1.00						
Ca	**0.61**	**0.64**	0.37	0.54	**0.71**	**0.86**	**0.60**	0.24	0.51	0.46	1.00					
Cd	**0.91**	**0.96**	0.10	0.44	**0.77**	**0.82**	**0.97**	**0.83**	**0.69**	-0.23	0.49	1.00				
Ba	-0.32	-0.24	**0.93**	0.07	-0.31	0.02	-0.22	-0.23	-0.35	**0.91**	0.18	-0.26	1.00			
Al	**0.62**	**0.73**	**0.65**	**0.74**	**0.73**	**0.89**	**0.71**	0.69	**0.57**	0.39	**0.71**	**0.72**	0.34	1.00		
Ti	0.42	0.52	0.54	0.36	0.53	**0.78**	0.49	0.25	0.26	**0.64**	**0.92**	0.42	0.38	**0.72**	1.00	
Zn	**0.96**	**0.99**	0.08	0.54	**0.84**	**0.87**	**0.99**	**0.72**	**0.81**	-0.25	**0.56**	**0.98**	-0.27	**0.71**	0.44	1.00

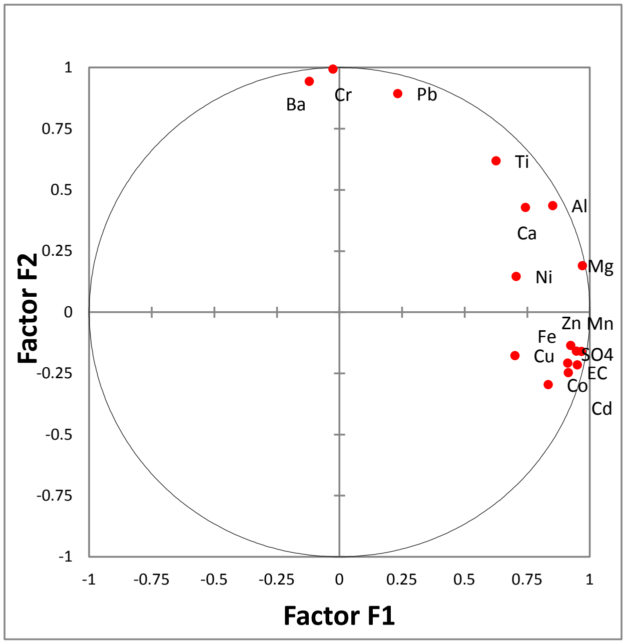

Figure 3. Principal component analysis (PCA) for the first groundwater sampling campaign: projection of variables on the F1–F2 plane

In the spatial representation and along factor F2, one can observe opposition between samples with relative high concentration in Cr, Ba and Pb (T7 and T12) to groundwater samples with low concentration in Cr, Ba and Pb (T9 and T10). It is important to recall that near T9 and T10, one can observe a contaminated water flow with AMD and there is no clay formation around these piezometers (see Table 1). Also, clay formation (sandwiched between soil surface and glacial till aquifer) was observed during T7 and T12 piezometer installation (see Table 1). The relative enrichment of groundwater in Pb, Cr and Ba is probably related to the clay leaching or to ions exchange with this media. Consequently the factor F2 can be identified as an exchange capacity of clay formations.

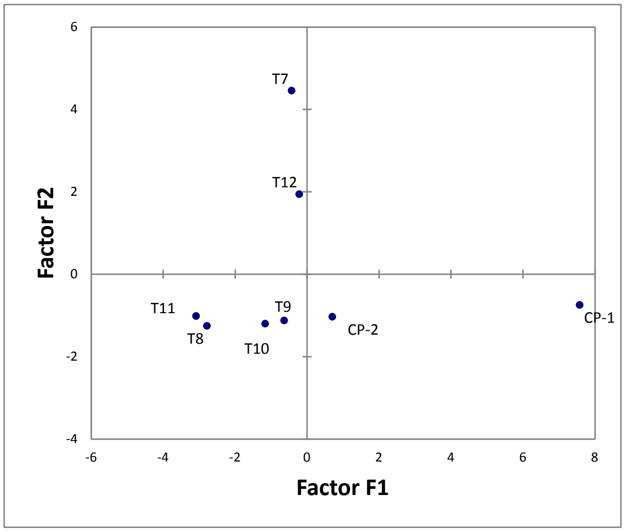

Figure 4. Principal component analysis (PCA) for the first groundwater sampling campaign: projection of individuals on the F1–F2 plane

3.2 Second sampling campaign: November of 2013

A second groundwater sampling campaign was performed two years after the first one. These two campaigns were performed during fall recharge and one can consider that these campaigns are performed under the same hydrogeological conditions; Comparisons can thus be done in order to evaluate if there is an evolution of groundwater quality at the Aldermac mine site since the reclamation work.

Statistical parameters are presented in Table 4 where one can observe that the minimum and maximum values are included between 0 and 37.19 mg/l, 0 and 1276 mg/l, 0.001 and 29.76 mg/l, 20 and 374 mg/l, 91.3 and 5661 mg/l and 401 and 7830 µS/cm for Al, Fe, Zn, Ca, SO_4 and EC, respectively. Based on the minimum and maximum value one can conclude that the measurement range of all the parameters (except for Mg) was reduced indicating an improvement in the hydrochemical composition of groundwater samples.

Table 4. Statistical parameters of groundwater sampled during November of 2013: EC is expressed in µS/cm and the other dissolved elements in mg/L;

	Minimum	Maximum	Standard deviation
EC	401.00	7830.00	2440.86
SO_4	91.30	5661.00	1396.90
Pb	0.00	0.01	0.001
Ni	0.00	0.20	0.076
Mn	0.00	12.97	5.12
Mg	0.07	159.00	73.31
Fe	0.00	1276.00	289.46
Cu	0.00	0.94	0.26
Co	0.00	0.76	0.23
Cr	0.00	0.01	0.002
Ca	20.00	374.00	144.31
Cd	0.00	0.03	0.006
Ba	0.01	0.07	0.03
Al	0.00	37.19	16.38
Ti	0.00	0.83	0.12
Zn	0.00	29.76	6.79

PCA was performed on these elements limiting the calculation to three factors and the total percentage of the variance expressed by these three factors is 94.9 %.

Correlations between different variables (not shown here) indicate that EC is mainly correlated to most dissolved elements except for Cr and Ba. Also SO_4 is correlated to all elements except for Cr and Ba. However, these last elements have a negative correlation. All these correlations indicate that mineral associations are different than the ones obtained for the first campaign.

The variance expressed by factors F1, F2 and F3 are 69.2, 14.5 and 11.2 %, respectively. The factor F1 is correlated positively to EC, SO_4, Pb, Ni, Mn, Mg, Fe, Cu, Co, Ca, Cd, Al, Ti and Zn (see Figure 5). The factor F2 is correlated positively to Cr and negatively to Ba. The factor F3 is correlated positively to Cu.

In the spatial representation (see Figure 6) and along factor F1, one can observe that groundwater samples which characterize AMD (CP-1) are opposed to groundwater samples with low metallic concentrations (T7, T8 and T12).

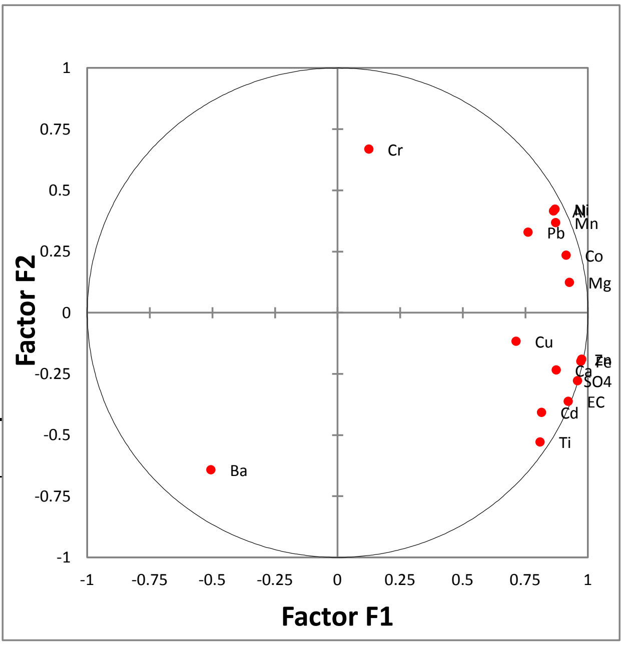

Figure 5. PCA for the last groundwater sampling campaign: projection of variables on the F1–F2 plane

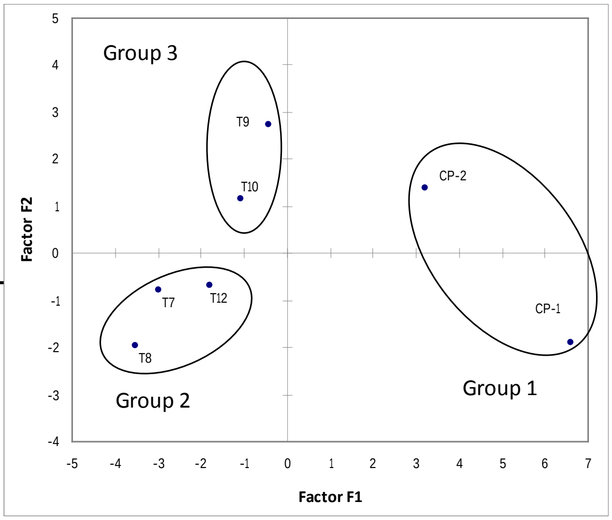

Figure 6. PCA for the last groundwater sampling campaign: projection of individuals on the F1–F2 plane

So, this factor shows the opposition between contaminated groundwater with high concentration of elements related to AMD and groundwater without AMD contamination. Along the factor F2, one can observe T9 and T10 are not opposed to samples; consequently this Factor cannot be interpreted.

However, three groups of groundwater can be identified:

- Group 1 characterized with high groundwater mineralisation and low pH;
- Group 2 characterized with low groundwater mineralisation and high pH;

- Group 3 characterized with low pH, moderate groundwater mineralisation and relatively high concentration in Cr.

4 DISCUSSION

The impact of the Aldermac mine site on the groundwater hydrochemistry was evaluated using two groundwater sampling campaigns; the last campaign was performed two years after the first one. Both campaigns were performed during fall recharge and one can consider that these campaigns are performed under the same hydrogeological conditions.

The PCA performed on the last campaign of groundwater sampling show some differences with to the first campaign (2 years before) which can be summarized as follow:

- Statistical analysis showed that measurement range of all the parameters was reduced by comparison to those of the first campaign;
- Matrix of correlations indicated that mineral associations were different than the other one obtained for the first campaign;
- Axes correlations with elements and with piezometers showed some evolution and particularly for piezometers T7 and T12 which changed from Factor 2 to Factor 1 and for piezometers T9 and T10 which changed from Factor 1 to Factor 2.

All these findings indicated a positive evolution in the hydrochemical composition of groundwater samples. To illustrate this aspect, piezometer CP-1 - considered as the most contaminated with acid mine drainage - was selected (see Figure 2 for location) and groundwater quality was analyzed from November 2011 (first campaign after reclamation) to November 2013 (last campaign). Statistical parameters are presented in Table 5 where one can observe that the minimum and maximum values ranged between 20.64 and 52.82 mg/l, 405 and 5466 mg/l, 22.05 and 49.89 mg/l, 343 and 447 mg/l, 5372 and 9947 mg/l and 6010 and 12270 µS/cm for Al, Fe, Zn, Ca, SO_4 and EC, respectively.

It is important to note that all the maximum values were measured during the first campaign after mine site reclamation (see Table 5).

PCA was performed using all hydrochemical data available for the piezometer CP-1. The total percentage of the variance expressed by three factors is about 90.4%. As presented in Table 6 and Figure 7, the factor F1 (54.7 %) is correlated positively to EC, SO_4, Mn, Mg, Fe, Cu, Co, Cd, Ba, Al, and Zn. The Factor 2 (24.9%) is correlated negatively to Pb and positively to Ni, Ca and Ti. The factor F3 (11.6 %) is only correlated positively to Cr.

It is important to indicate that matrix of correlation (not presented here) shows that SO_4 is not correlated to Ni, Cu, Co, Cr, Ba or Ti, indicating that these elements have probably evolved in the aquifer (due for example to precipitation). This hypothesis will be confirmed by calculation of saturation indexes.

Table 5. Statistical parameters of groundwater sampled from piezometer CP-1 from November 2011 to November 2013.

	Minimum	Maximum	Standard deviation
EC	6010.00	12270.00	2260.05
SO_4	5372.00	9947.00	1967.13
Pb	0.00	0.02	0.01
Ni	0.14	0.25	0.04
Mn	9.84	17.16	2.76
Mg	101.00	187.00	28.16
Fe	405.00	5466.00	1967.61
Cu	0.63	1.13	0.18
Co	0.59	1.10	0.20
Cr	0.00	0.65	0.26
Ca	343.00	447.00	39.62
Cd	0.02	0.05	0.01
Ba	0.02	0.03	0.01
Al	20.64	52.82	10.61
Ti	0.53	0.87	0.12
Zn	22.05	49.89	9.31

Table 6. Correlation between variables and Factors F1, F2 and F3 of groundwater sampled from piezometer CP-1 from November 2011 to November 2013.

Parameter	F1	F2	F3
EC	**0.762**	-0.402	-0.376
SO4	**0.737**	-0.587	0.215
Pb	0.377	**-0.779**	0.370
Ni	0.560	**0.752**	-0.249
Mn	**0.879**	-0.081	0.181
Mg	**0.850**	0.004	0.366
Fe	**0.728**	-0.592	-0.341
Cu	**0.916**	0.327	-0.054
Co	**0.757**	0.548	-0.083
Cr	-0.225	-0.118	**0.924**
Ca	-0.411	**0.811**	0.228
Cd	**0.976**	0.203	0.015
Ba	**0.768**	0.548	0.059
Al	**0.967**	0.118	0.148
Ti	0.308	**0.677**	0.299
Zn	**0.967**	-0.250	0.025

In the spatial representation (see Figure 8) and along factor F1, one can observe that the sample 2011-11-29 is opposed to sample 2013-08-22. The sample 2011-11-29 is characterized by high mineralisation (EC = 12270 µS/cm) in comparison to the sample 2013-08-22 (EC = 6840 µS/cm); the difference corresponds to 5430 µS/cm indicating a diminution of the EC. Also SO_4, Fe and Al concentrations were reduced from 9947 to 5372 mg/l, from 5466 to 544 mg/l and from 52.82 to 20.64 mg/l, respectively.

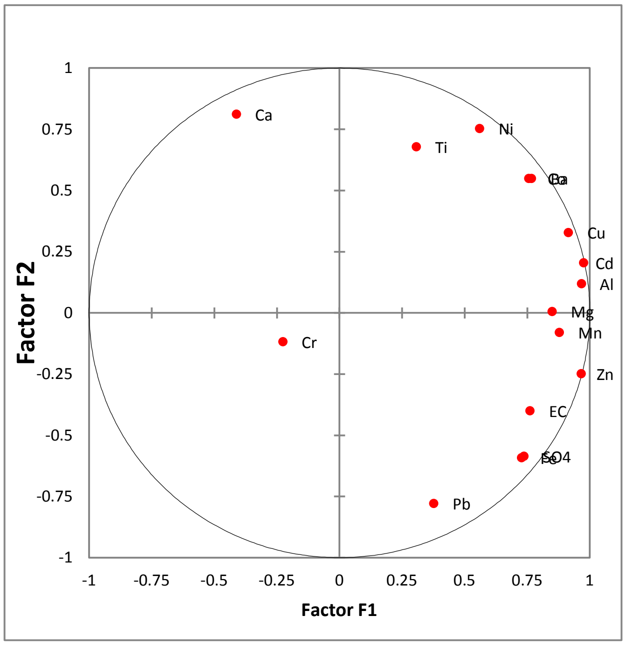

Figure 7. PCA for groundwater: projection of variables on the F1–F2 plane for groundwaters sampled from piezometer CP-1 between November 2011 and November 2013.

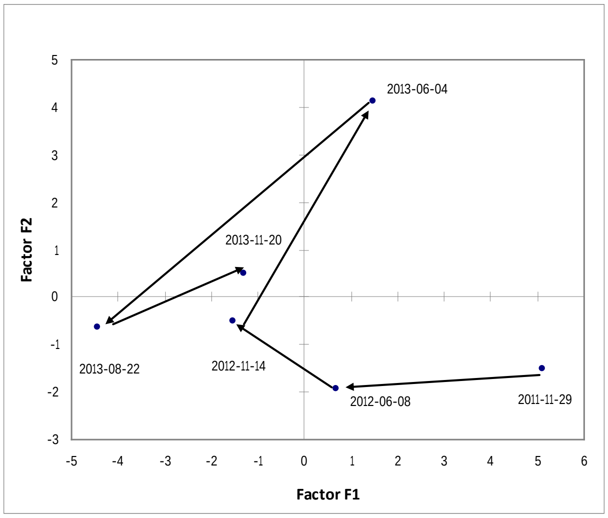

Figure 8. PCA for groundwater: projection of individuals on the F1–F2 plane for groundwaters sampled from piezometer CP-1 between November 2011 and November 2013.

Along the factor F2 (see Figure 8), one can observe that the sample 2012-06-08 is opposed to sample 2013-06-04. One can then observe opposition between a sample with relative high concentration in Pb and low concentrations in Ca, Ni and Ti and a sample with low concentration in Pb and high concentrations in Ca, Ni and Ti. It is important to note that Ca, Ni and Ti have a very low correlation (matrix of correlation not shown here). However, Ca and Pb have a high negative correlation (-0.69) indicating an opposite trend: the increase in Ca concentration accompanied by a decreases of Pb concentration. This evolution is probably due to the neutralisation phenomena in the vadose zone or to the infiltration of surface water with different water quality into the aquifer (water table is located near the surface soil).

As final remark, arrows were used in Figure 8 to show the chronological evolution of the chemical quality of groundwater sampled in piezometer CP-1. One can observe that after 2011, water quality has improved because the inflow from acid mine drainage was reduced due to the reclamation of the site.

5 CONCLUSIONS

This study was performed to evaluate the impact of the reclamation of the Aldermac mine site on groundwater quality. Hydrochemical analysis results, based on statistical analysis, indicated that:

- After two years, measurement results show that concentration of different dissolved element and EC were reduced by comparison to those of the first campaign;
- Matrix of correlations indicated that mineral associations of the 2013 campaign were different to those obtained for the first campaign;
- Axes correlations with analyzed elements and with piezometers showed some evolution and particularly for piezometer T7 and T12 that changed from Factor 2 to Factor 1 and for piezometer T9 and T10 that changed from Factor 1 to Factor 2.

All these results indicate a trend towards improvement of the hydrochemical quality of groundwater samples. This effect was confirmed by hydrochemical analysis of samples taken from the most contaminated piezometer where a concentration reduction in all dissolved element (from the beginning of hydrochemical monitoring until November 2013) was observed.

Consequently, these results showed that the groundwater quality indicate a trend towards improvement of the hydrochemical quality of groundwater samples due to the reclamation work performed at the Aldermac mine site. However it is recommended to continue the groundwater quality monitoring program. Also, modeling should be performed in order to estimate the time required for complete dissipation of AMD contamination at the Aldermac mine site.

6 ACKNOWLEDGEMENTS

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