THE EAST-SULLIVAN MINE SITE : MERGING PREVENTION AND TREATMENT OF ACID MINE DRAINAGE

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ABSTRACT
At East Sullivan, an innovative treatment of acid effluents is based on the sulphate reduction via the recirculation of water discharging around the impoundment through the organic cover. Data show that despite acid feeds down to pH 2.5, groundwater's pH near the dispersal zone is maintained above 6. Alkalinity decreases during the recirculation, but is back up to 800 mg/L and more the following spring, thanks to sulphate reduction. Fe^{2+} concentrations near the dispersal zone are maintained below 2 mg/L. Evolution of dissolved iron mass in the reservoirs surrounding the impoundment suggests that the contaminated groundwater flush is completed in the north and west sectors. The east and south ones are expected to be recovered within 3 years. As expected, the wood-waste cover, besides limiting sulphide oxidation, can fill the role of alkaline reducing barrier for the treatment of acidogenic waters, until a balance between acidity and alkalinity in the effluent is reached.

RÉSUMÉ
Au site East Sullivan, un traitement innovateur pour les effluents acides est basé sur la réduction des sulfates via la recirculation des effluents du parc à travers le couvert organique. Les données indiquent que, malgré des eaux d'alimentation ayant un pH aussi bas que 2.5, le pH des eaux souterraines à proximité se maintient supérieur à 6. L'alcalinité diminue lors de la recirculation, mais remonte à 800 mg/L et plus le printemps suivant, grâce à la réduction des sulfates. Les concentrations en Fe^{2+} près de la zone d'aspersion se maintiennent à moins de 2 mg/L. L'évolution de la masse de fer dissous dans les réservoirs, entourant le parc, indique que la purge des eaux de pores contaminées dans les secteurs nord et ouest est complétée; celle des secteurs est et sud le sera d'ici 3 ans. Comme attendu, le couvert organique, en plus de limiter l'oxydation des sulfures, joue le rôle d'une barrière réductrice et alcaline pour le traitement des eaux acides et ce jusqu'à ce qu'une balance entre l'acidité et l'alcalinité soit atteinte dans les effluents.

1. CONCEPT OF ACID-WATER TREATMENT

The East Sullivan mine site lies at 6 km East of Val d'Or, Québec, more precisely at 77°42'W; 48°05'N (Figure 1). Its characterization is presented in the companion paper by Tassé et al. (these proceedings). The climate normals in the region from 1971 to 2000 are precipitation of 0.91 m, and temperature daily maximum and minimum of 7.0 and -4.7°C. For more information on climate conditions for the station Val d'Or, see the website of Environment Canada (2004).

A forestry-waste cover can be exploited for the treatment of acid prone groundwaters flushed after cover placement. Its essential geochemical characteristics are similar as passive treatment systems such as constructed wetlands and reducing barriers, in which redox reactions improve the effluent quality (*e.g.* Wildeman et al. 1992; Benner et al. 2000). In those anoxic environments, sulphate-reducing bacteria, in the absence of molecular oxygen, secure their energy needs by oxidizing organic compounds, using the sulphur of sulphate as the terminal electron acceptor (Eq. 1). Metals are precipitated by reduced sulphur (Eq. 2).

$$SO_4^{2-} + 2CH_2O \longrightarrow H_2S + 2HCO_3^- \quad [1]$$
$$Me^{2+} + H_2S \longrightarrow MeS + 2H^+ \quad [2]$$

where Me represents Fe, Ni, Cu, Co, Zn, Cd, etc.

At East Sullivan, the characteristic H_2S smell of reduced sulphur was noted at some observation wells, which is clear evidence that sulphate reduction is going on. Alkalinity, below the wood-waste cover, reaches considerable values, up to 1000-1500 mg/L-$CaCO_3$ (Germain et al. 2003). Alkalinity values in this range correspond to dissolved inorganic carbon (DIC) between 120 and 270 mg/L-C, such values have been observed and indicate a carbonate alkalinity (Germain, 2000).

These alkaline and reducing properties observed below the wood waste cover at East Sullivan are essentially those of a constructed wetland. In the same way, reduction of sulphate to sulphide in these geochemical conditions can provide the counter-ions required for the precipitation of iron and other metal as sulphides. A treatment system was there waiting to operate. This was done by simply recirculating the acid effluents collected around the impoundment through the wood waste cover.

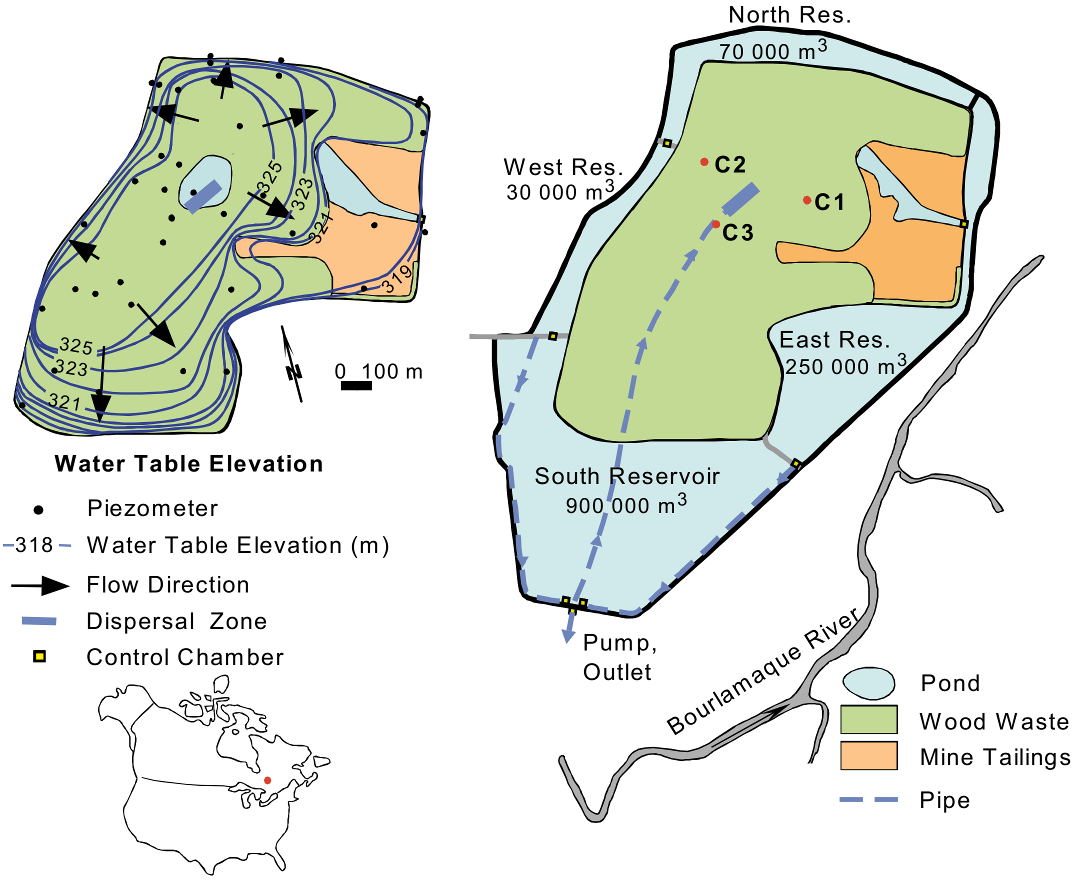

Figure 1. The East Sullivan tailings impoundment with the extent of the organic cover, the water table elevation when the recirculation is in operation, and locations of observation wells and dispersal zone.

2. COLLECTION AND RECIRCULATION SYSTEMS

The collection system of the effluents consist of four reservoirs: North (70 000 m^3), West (30 000 m^3), East (250 000 m^3), and South (900 000 m^3) (Figure 1). The recharge rates, in m^3/d, are, for North: 1 170; West: 430; East: 6 600 (South: currently not available). The high rate for the East reservoir reflects the fact that it drains most of the impoundment (see flow directions, Figure 1).

The water from the North reservoir flows into the West reservoir. Pipes are connected to the outlets of the West and East reservoirs and water is directed by gravity either to a pumping station or to the outlet at the southern end of the site. There, water from either West, East or South reservoirs can be pumped back over the organic cover, or is allowed to flow by gravity into the natural environment (Figure 1). The dispersal zone, 120 m long perforated pipe, is located over the oldest part of the cover (mid-eighties). The recirculation is in operation from the beginning of May to the end of October. Figure 2a shows the measured pumping rates from 2000 to 2003, and Table 1 indicates the mean pumping rate and the volume of water treated since 1998.

Table 1. Average pumping rate and total volume of water treated from 1998 to 2003.

Year	Mean pumping rate (m^3/d)	Volume (m^3)
1998	2 500	420 000
1999	3 750	630 000
2000	5 390	650 110
2001	5 928	741 530
2002	5 760	798 555
2003	5 060	724 783

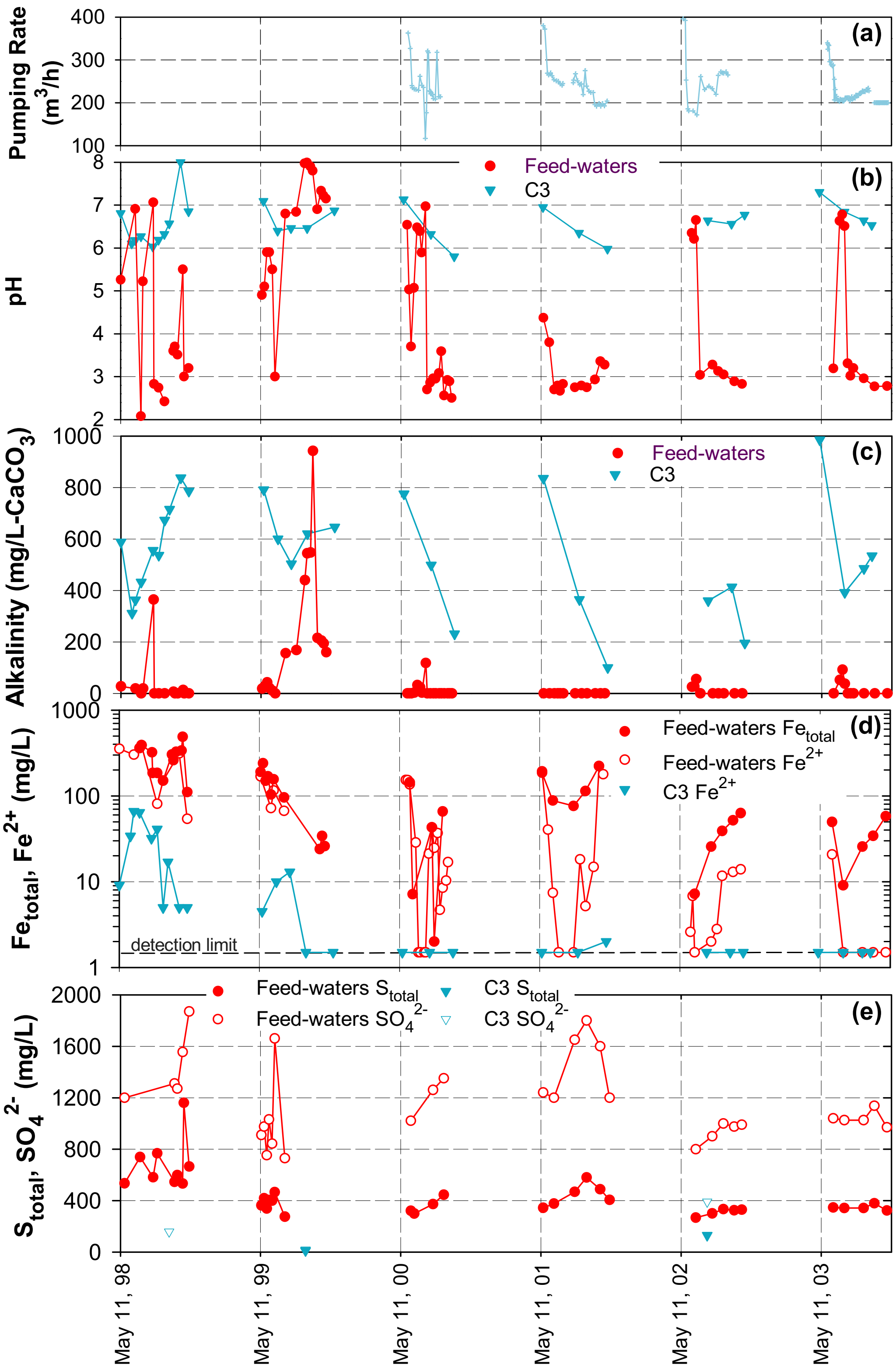

Figure 2. Pumping rate (a) from May 1998 to October 2003, and feed-waters and groundwater quality at station C3: (b) pH , (c) alkalinity, (d) Fe_{total} and Fe^{2+}, and (e) sulphates and S_{total}.

2.1 Water Quality at the Dispersal Zone

pH, alkalinity, Fe^{2+}, Fe_{total}, Sulphates and S_{total} concentrations in feed-waters are shown in Figure 2. Since 2000, the first reservoir being pumped at the beginning of the recirculation in May is the East reservoir until its quality meets the criteria shown in Table 2, then its water is released to the natural environment, and then the South reservoir is pumped until the end of October. Since the beginning of the water recirculation, the Fe_{total} varies between 500 and 2 mg/L. For the past four recirculation periods, pH was below 3.5 most of the time.

Table 2. Main water quality criteria

Inorganic parameters	Maximum concentration
Cu	0.3 mg/L
Ni	0.5 mg/L
Pb	0.2 mg/L
Zn	0.5 mg/L
Fe(total)	3.0 mg/L
pH	between 6.5 and 9.5
Organic parameters	
Chemical oxygen demand	100 mg/L
Biological oxygen demand	50 mg/L
Phenols	0.05 mg/L

2.2 Efficiency of the Water-Treatment System

The efficiency of the biofilter can be assessed by comparing feed-water descriptors to those of groundwater collected in a nearby observation well, C3-p4. It is located next to the dispersal zone at 3.1 m depth (Figure 1).

From 1998 to 2003, the pore waters quality at observation well C3-p4 also improved over time with respect to ferrous iron (Figure 2d). More specifically, the average Fe^{2+} concentration decreased from 28.2 mg/L in 1998 to less then 2 mg/L from 2000 to 2003. The fraction of ferrous iron removed increased progressively from 86% to 97% from 1998 to 2001 (Table 3). The increased efficiency of the biofilter over time is likely due to the establishment of bacteria colonies responsible for sulphate reduction.

pH was always near neutral in the six years surveyed, despite the more than often acid feed-waters (Figure 2b). This is because pH and alkalinity are two interrelated parameters: if an acid is added to an alkaline solution, pH is preserved while alkalinity is consumed. In 2001 and 2002, we calculated an average consummation of -4.25 mg/L-$CaCO_3$ per day at C3-p4 over the recirculation period (Germain et al., 2003). Despite these drops, alkalinity went back to 800 mg/L the following spring. Unfortunately, no data were gathered at this station in May 2002. In 2003, the organic cover was completed in the vicinity of the observation well C3-p4, which decreased significantly the vertical hydraulic gradient. Thus, the flow rate migrating through this well is smaller now, which explains the lower decrease in alkalinity (down to 400 mg/L-$CaCO_3$) despite acid feed-waters. The re-establishment of alkalinity during the non-recirculation period is mainly due to in situ alkalinity generated by on-going sulphate reduction (Eq. 1) and somewhat to alkalinity associated with the alteration of organic components.

Table 3. Average Fe^{2+} present in feed-waters and at observation well C3-p4, and its corresponding percentage removed from 1998 to 2003.

Year	Average Fe^{2+} (mg/L)		% removed
	Feed-waters	C3-p4	
1998	201.8	28.2	86
1999	93.3	5.9	94
2000	39.1	<1.5	>96
2001	47.3	1.6	>97
2002	3.6	<1.5	>58
2003	3.3	<1.5	>55

3. IMPACT ON GROUNDWATER QUALITY

pH, alkalinity and Fe^{2+} have been monitored since 1998 in the groundwater. Here, Fe^{2+} is the key parameter for water quality, since its oxidation and hydrolysis are responsible for the acid mine drainage. Despite the recirculation of acid and ferrous waters, none of these fronts was developed under the dispersal zone at any time. In fact, the pH of all groundwater samples underlying the zone varies between 5.0 and 8.0 for the entire 1998-2003 database, which suggests efficient H^+ neutralization by local alkalinity and/or adsorption by colloidal and particulate wood waste. There is more. Fe^{2+} is less than 2 mg/L since 2000 in all eight near-surface observation wells in the vicinity of the dispersal zone. Since feed-water with sometimes over 100 mg/L-Fe^{2+} was pumped directly over the area, it can be concluded that Fe^{2+} attenuation did occur and that the recirculation did not compromise the groundwater quality.

On the contrary, the recirculation has allowed a more rapid flushing of Fe^{2+} rich pore waters, as shown at observation wells C1 and C2 (Figure 3). These stations are in the vicinity of the dispersal zone, over the old cover (see Fig. 1). Two flushing effects are observed. The natural one by the increase recharge due to the coarse fragments of the cover and the imposed one by the recirculation. The natural flushing is observed at these wells, with a decrease of yearly average Fe^{2+} concentrations (Figure 3). That decline starts over the first years of the available database, in 1992. The effects of water treatment and flushing is noted mainly at C1. A steep decline in Fe^{2+} occurs from 2000 to 2001 and its consistent low concentration since is likely caused by the migration of "clean waters." The less pronounced decline at C2 is due to a deeper location (8.45 vs 4.87 m) and a lower hydraulic conductivity (2.0E-7 vs 7.5E-7 m/s).

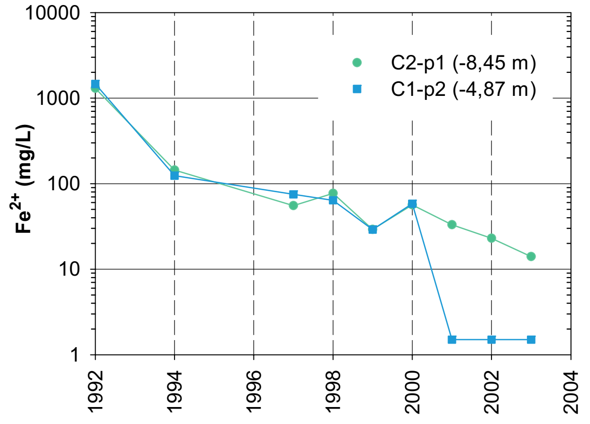

Figure 3. Evolution of Fe^{2+} at observation wells located in tailings at C1 and C2 from 1992 to 2003 (see Figure 1 for location).

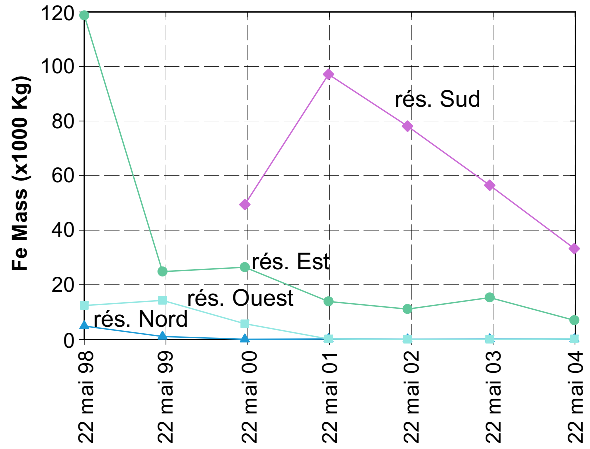

Figure 4. Evolution of the Fe mass in the reservoirs prior to the beginning of the recirculation, from 1998 to 2004.

4. IMPACT ON SURFACE WATER QUALITY

Data on water composition of each reservoir were gathered from May to November, every year since their completion (North: 1994; East: 1997; West: 1994; South: 1998). The North, the West, the East, and the South reservoirs show respectively the two good, the intermediate, and the worst with respect to their actual water quality.

4.1 Fe Mass in Each Reservoirs

Figure 4 shows the evolution of the Fe mass present in each reservoir in the spring prior to the beginning of the recirculation, from 1998 to 2004. The Fe mass in the North reservoir is the lowest since it is adjacent to the oldest section of the cover. Therefore, the natural flushing of the pore water had occurred. Since 6 years, its quality comply with the target values (Table 1) without any treatment.

The West reservoir drains a small section of the impoundment but made of highly permeable porous media, mainly dikes (Figure 1). These pore waters were characterised with high Fe_{total} concentrations: 540 mg/L in 1994. With the recirculation, the water table rises and increases the hydraulic gradient, which accelerate the flushing of these altered pore waters. Thus, despite a more recent cover in comparison to the north section, its waters also do not require any treatment since the past 4 years.

The impact of flushing altered pore waters due to the recirculation is also observed in the East Reservoir, in particular during the first year of the recirculation. Also, additional forest wastes were deposited along the dikes next to this reservoir allowing a greater natural infiltration. These combined flushing mechanisms have allowed the steepest Fe mass drop observed within a year (79%).

The impacts of the recirculation and the increase natural infiltration are also well illustrated by the evolution of the Fe mass in the South reservoir, where it has decreased by more then 65%, at a constant rate of -21 300 Kg/a from 2001 to 2004. If this trend is maintained, its water quality will significantly be improved within the next 2 years. This reservoir drains a small section of the impoundment. However, the surface waters are among the highest Fe concentrations observed around the impoundment. The tailings adjacent to the South reservoir are fine-grained on the east side but coarse-grained on the west side. Iron concentrations in pore waters are low on the east side, except along dikes. However, coarse material on the west side did favour sulphide oxidation and high Fe^{2+} in the pore waters, by maintaining an important vadose zone, not only in the dikes' vicinity but also deep into the impoundment. Moreover, the Fe^{2+} rich plume is migrating southward and is discharging in the South reservoir (see Figure 2, Germain et al., 2003).

4.2 Detailed Pore Water Quality : East Reservoir

The East reservoir drains most of the treated water (see flow direction, Figure 1). For this reason, after pumping its water for 3 to 4 weeks in the spring, its quality is significantly improved and meets the target values. Since most of the water released to the natural environment is discharged via the East reservoir, its surface quality is presented in detail.

4.2.1 Fe_{total}, alkalinity, pH, and metals

The presence of a pond in the north-east section of the impoundment since its closure testifies of the fine-grained nature of the tailings (Figure 1). Similar muddy sediments were accumulated next to the eastern dike, to the south. These relatively high levels of water saturation contributed to limit sulphide oxidation in those areas, prior to cover placement. Significant alteration was limited to coarser-grained dikes and former dikes. It follows that, notwithstanding these dikes, pore waters showed initially relatively low dissolved iron. Cover placement stopped oxidation and also increased infiltration, flushing these relatively poor Fe_{total} pore waters into the reservoir.

Figure 5 shows the evolution of Fe, alkalinity and pH of the East reservoir. The maximum Fe_{total} concentration in the spring, drops gradually from 108 mg/L in 2000 to 35 mg/L in 2004, representing a drop rate of -18 mg/L per year (Fig. 5, slope of pink line). Thus, if this trend is maintained, in 2 years this reservoir will not require any treatment with respect to iron. In 1999, alkalinity increased from 50 mg/L (mid-June) to 888 mg/L (September), then dropped to 116 mg/L (October). Between 2000 and 2003, alkalinity increased from nil values in the spring to values varying between 100 and 250 mg/L. pH varied between 5.0 and 8.5, except in the spring of 2001 and 2003, when it dropped below 4. With regard to metals (cadmium, chrome, cupper, and lead), their concentrations have always been below 0.2 mg/L since 1999. While for zinc, its concentration is less then 2.2 mg/L in the spring and less then 0.5 in the summer and fall, since 1999.

4.2.2 Organic parameters: DCO, DBO_5, and phenols

Figure 6 shows the evolution of the chemical and biological oxygen demands, and phenols, from 1999 to 2003. Both demands significantly decrease within the first two years; then they meet the target values for the remaining period. A similar behaviour is also observed for phenols.

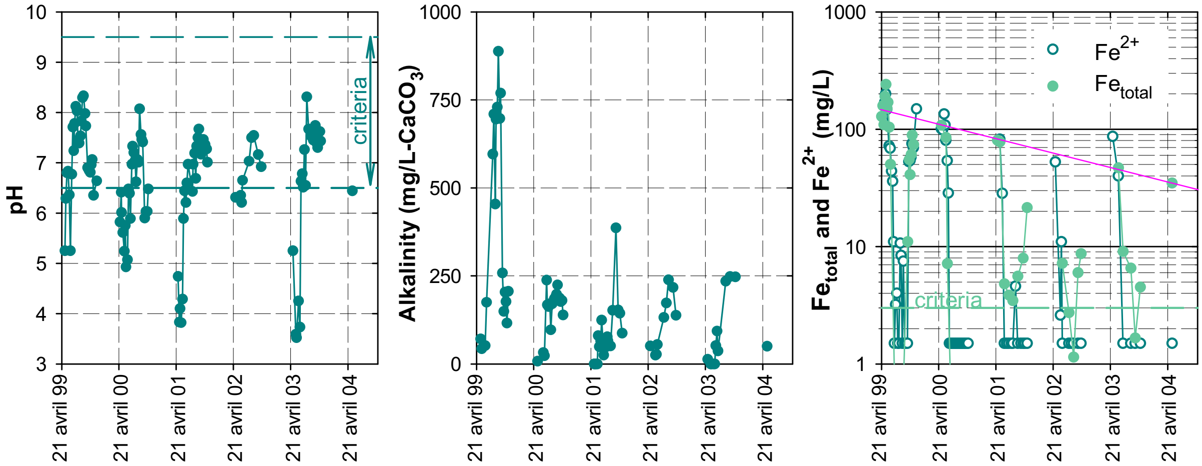

Figure 5. Evolution of pH, alkalinity, Fe_{total} and Fe^{2+} in the East reservoir, from 1999 to 2004; the pink line represents the Fe-drop trend in the spring.

5. CONCLUSIONS

A cover of coarse forestry wastes, besides stopping the atmospheric oxygen migration, favour higher infiltration and a water table rise, which plays the role of a "wet cover". This also allows a more rapid flushing of acidogenic groundwater. Furthermore, a wood-waste cover can fill the role of an alkaline reducing barrier for the treatment of these acidogenic waters, until a balance between acidity and alkalinity in the discharged water is reached. Such a system holds several advantages over conventional constructed wetlands, which are driven by the same geochemical processes: it is a priori less sensitive to hydrogeologic and vegetative cycles that affect wetlands, because anaerobic conditions can persist despite large fluctuations in influent and climatic conditions; contact time can be long relative to a constructed wetland, and levels of over-saturation solution are likely to be attained and maintained.

Evolution of surface water quality suggests that the contaminated groundwater flush is completed in the north and north-west area of the impoundment. The east and South sectors are under recovery, as shown by the decline of the Fe mass in the East and South reservoirs. In the South reservoir, its mass dropped by 66% during the last 4 years. Its drop rate of -21 300 Kg/a is constant since 2000,

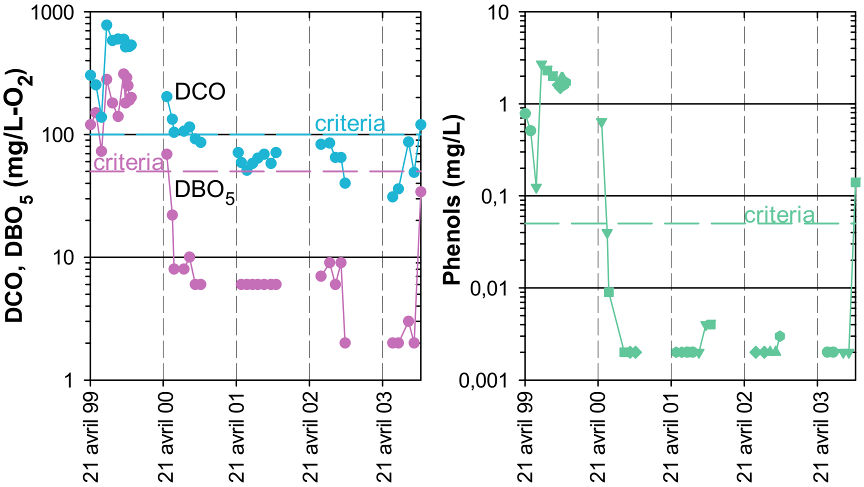

Figure 6. Evolution of chemical and biological oxygen demands, and phenols in the East reservoir, from 1999 to 2003.

indicating that within the next 2 years its water quality with respect to iron will significantly be improved.

The maximum Fe_{total} concentration of the East reservoir in the spring, drops gradually at a rate of -18 mg/L per year since 2000. In May 2004, its concentration was down to 35 mg/L. If this trend is maintained, in 2 years this reservoir will not require any treatment with respect to iron. With regard to the organic parameters, since the summer 2000 they meet the target values.

It is clear that an organic cover not only can act as an oxygen barrier, but can also be integrated in a strategy for a highly efficient treatment system of transient acidogenic waters rich in metals.

6. ACKNOWLEDGMENTS

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