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TECHNICAL ARTICLE

Assessment of Soil and Water Contamination at the Tab-Simco Coal Mine: A Case Study

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Abstract In 1996, the Tab-Simco site, an abandoned coal mine 10 km southeast of Carbondale, Illinois, was listed as one of the most highly contaminated AMD sites in the mid-continent region. A suite of impacted soil and water samples were collected from various locations to characterize the current extent of AMD pollution, following standard U.S. EPA protocols. The mean pH of soil and water samples were found to be 2.69 and 2.07, respectively. The mean sulfur content of the soil samples was 0.5 %. The AMD-impacted soils contained high concentrations of Fe, Zn, Ni, Cr, Cu, Pb, and As. The AMD also contained high concentrations of Fe, As, Zn, Pb, Cr, Al, Cd, Cu, and Ni, as well as SO_4^{2-}, all of which were significantly above their U.S. EPA permissible limits for surface water.

Keywords Acid base accounting · RCRA 8 metals · Reclamation · Sulfate reducing bioreactor · Surface mining

Introduction

Surface mining is an important industry throughout the world. A major environmental concern associated with this industry is the generation of acid mine drainage (AMD) and acid sulfate soil, which are responsible for habitat deterioration of the surrounding ecosystem (Ferguson and Erickson 1988; U.S. EPA 1994a). AMD can degrade adjacent surface water quality, which becomes unsuitable for sustaining biodiversity. In addition, the acid sulfate soils are structurally unstable and highly prone to erosion. Former mine sites require proper management practices, sometimes for decades, to minimize the overall environmental impact; otherwise, the environmental damage could persist forever (U.S. Forest Service 2005; RoyChowdhury et al. 2015). In the eastern USA, more than 7000 km of streams are currently impacted by AMD, and in the western USA, the number is between 8000 and 16,000 km (Benner et al. 1997; Jennings et al. 2008; Kim et al. 1982; U.S. EPA 1994a, 2011; U.S. Forest Service 1993). The severe impact of AMD on aquatic biodiversity has been reported by many researchers (Gerhardt et al. 2004; Martin and Goldblatt 2007; Hansen et al. 2002; Jennings et al. 2008; Schmidt et al. 2002; Soucek et al. 2000; Trout Unlimited 2011).

Tab-Simco is an abandoned coal mine located 9.7 km southeast of Carbondale, IL (Fig. 1). The area is “horseshoe” shaped, and is approximately 37 m higher than the surrounding lowland (Behum et al. 2011; Smith 2002). The shallow bedrock of Tab-Simco consists of shale, sandstone, siltstone, and limestone. The Murphysboro and Mount Rorah coal seams were located within the Spoon formation; the coal seams were separated by a 3–8 m thick layer of shale and capped by a 10 m thick layer of pyritic sandstone (Behum et al. 2011, 2012, 2013; Segid 2010; Smith 2002). Between 1890 and 1955, underground mining in this region targeted the lower approximately 2.5 m thick continuous Murphysboro seam, and the upper 0–1.5 m thick discontinuous patchy Mount Rorah seam (Behum et al. 2012, 2013; Smith 2002).

As underground mines closed, water flowed into the mined areas, generating AMD. The resultant mine pool contains an estimated 40,000–77,000 m^3 of severely

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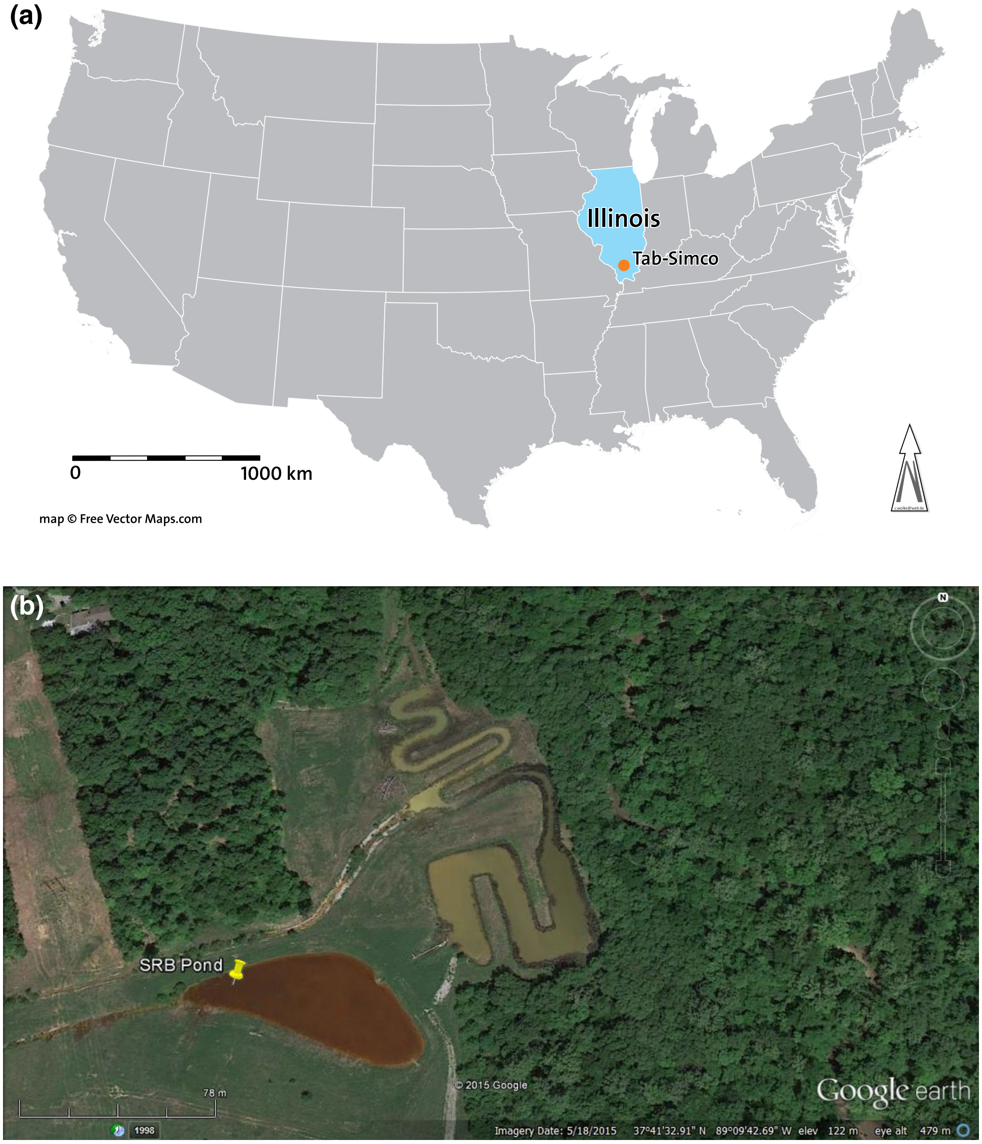

Fig. 1 **a** Location of the Tab-Simco site. **b** Google Earth image of the Tab-Simco site (© Google Earth)

contaminated water (Behum et al. 2012, 2013; Smith 2002). Surface mining in the 1960s and 1970s was responsible for several break-ins to the previously sealed underground structure. An average of 150 m^3 a day of AMD emerges through the fractured zones and contaminates the surrounding ecosystem (Smith 2002). In 1996, the Tab-Simco site was reported as one of the most highly contaminated AMD sites in the mid-continent region (Segid 2010; Smith 2002). AMD has created a 36,421 m^2 "kill zone" in the floodplain on its way to Sycamore Creek (Fig. 2) and more than 3 km of Sycamore Creek has been heavily contaminated (Behum et al. 2011, 2012, 2013; Segid 2010; Smith 2002).

In 2007, a 3000 m^2 sulfate-reducing bioreactor (SRB) was constructed in the Tab-Simco site to assist in managing

Fig. 2 The AMD-impacted Sycamore Creek at Tab-Simco

Fig. 3 The non-functional SRB filled with AMD at Tab-Simco

the AMD. The SRB, from bottom to top, comprised a 0.3 m thick limestone layer, 2 m thick organic layer, and 0.3 m water impoundment. The organic layer was composed of woodchips, ground limestone, straw mulch, and compost (Behum et al. 2010, 2011, 2012, 2013; Burns et al. 2012; Segid 2010). The SRB started operating early 2008 (Lewis 2008; Segid 2010), but failed in 2011 (Behum et al. 2013), presumably because the planned resupply of the nutrients never took place. The bioreactor is currently filled with AMD (Fig. 3).

The main objective of this study was to characterize AMD-impacted soil and water from the Tab-Simco site to better understand the current extent of the problem. No data was available for the site since the SRB failed; this study was intended to fill that gap.

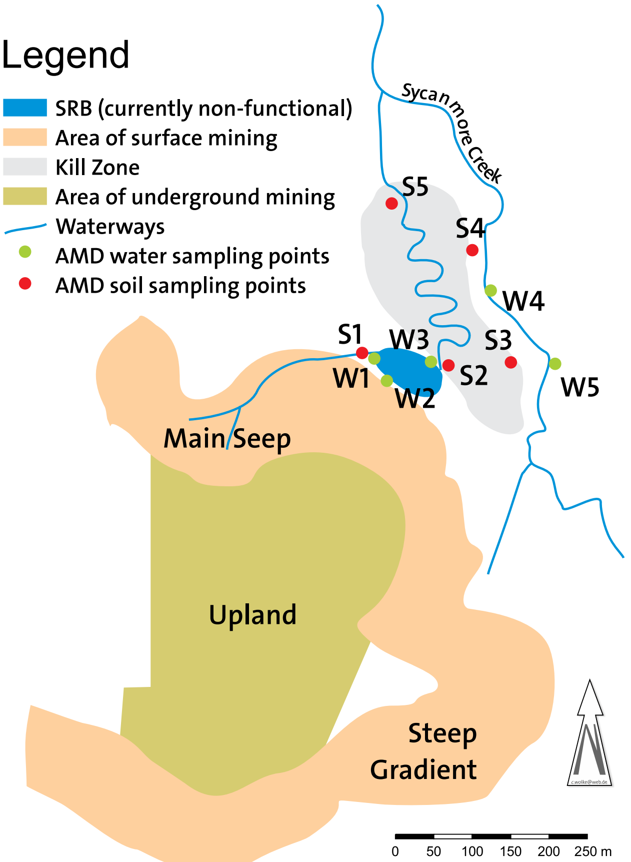

Fig. 4 Map of the Tab-Simco showing sampling points; original map was taken from Behum et al. (2011, 2012, 2013) and Segid (2010), and modified to show sampling points

Materials and Methods

Sample Collection

Composite soil samples were collected from the impacted areas around the SRB (S1 and S2), and from three different locations (S3, S4, and S5) within the "kill zone" (Fig. 4). At each sampling location, soil from four different points were collected and mixed, following the 1981 EPA/CE-81-1 protocol (Plumb 1981). Water samples were collected from three different locations (W1, W2, and W3) of the currently non-functional SRB pond, plus two other locations (W4 and W5) from the AMD-impacted portion of Sycamore Creek (Fig. 4). Sampling was conducted in October, 2014. All samples were transported back to Montclair State University, NJ for characterization.

Soil Sample Characterization

Collected soil samples were dried, ground, and sieved through a 1–2 mm mesh. Fractions <2 mm were used for the following soil characterization protocols. Paste pH and electrical conductivity (EC) measurements were conducted following standard protocols using an Oakton ion 510 series pH meter and an Orion conductivity meter (Mills 2014; Page et al. 1982; Rhoades 1996; Sobek et al. 1978). Soil texture (% clay, silt and sand) was determined using a Malvern Mastersizer 2000 laser particle size analyzer. All analyses were done in triplicate.

Total C, H, N, and S concentrations in soil samples were analyzed by an Elementer Vario EL-III CHNS analyzer. Dried soil samples were sieved through a 0.5 mm sieve and only the particles that passed through the sieve were used for this analysis. All analyses were done in triplicate.

Concentrations of different metals in the soil samples were determined using the U.S. EPA (1996) 3050B soil digestion method, using a Linx wireless digestion system. Digested samples were filtered using a 0.45 µm nylon syringe filter, and analyzed for total RCRA 8 metals (Ag, As, Ba, Cd, Cr, Hg, Pb, Se) plus Fe, Al, Ni, Cu, and Mn concentrations using an inductively coupled plasma mass spectrometer (ICP-MS, X-series, Thermo Scientific).

Water Sample Characterization

The pH and EC of the water samples were measured using an Oakton ion 510 series pH meter and an Orion conductivity meter. Measurements were made on-site and then validated in the laboratory. All measurements were made in triplicate.

Water samples filtered using a 0.45 µm syringe filter were diluted 100 fold and analyzed for total-recoverable RCRA 8 metals plus total Fe, Al, Ni, Cu, and Mn by ICP-MS. Water samples filtered using a 25 µm syringe filter were diluted 50-fold and analyzed for total sulfate (SO_4^{2-}) concentration using a Dionex ion chromatograph.

Mineral and total acidity of the water samples were measured using the U.S. EPA 305.1 titration method and a 1 N NaOH solution (U.S. EPA 1994b). Mineral acidity (methyl orange acidity) was measured by titration to a pH of 3.7, the methyl orange end point. Titration to the phenolphthalein end point (pH 8.3) measures both mineral acidity plus acidity due to weak acids, as weak acids are neutralized by titration to pH 8.3. This total acidity is also called phenolphthalein acidity. A 50 mL water sample was used for the titration. Analysis was done in triplicate.

The following equations were used to calculate the mineral and total acidity:

$$\text{Mineral acidity}\left(\frac{\text{mg}}{\text{L}}CaCO_3\right) = \frac{Volume\ of\ NaOH\ to\ raise\ pH\ to\ 3.7 \times Normality\ of\ NaOH \times 50 \times 1000}{Volume\ of\ sample\ taken} \tag{1}$$

$$\text{Total acidity}\left(\frac{\text{mg}}{\text{L}}CaCO_3\right) = \frac{Volume\ of\ NaOH\ to\ raise\ pH\ to\ 8.3 \times Normality\ of\ NaOH \times 50 \times 1000}{Volume\ of\ sample\ taken} \tag{2}$$

All measurements were carried out in triplicate, following the established QA/QC protocols of the Environmental Geochemistry Laboratory of Montclair State University, and using external standards. Spike recoveries of ±10 % were considered acceptable for ICP-MS analyses. Continuing calibration verifications were performed at ten sample intervals.

Results and Discussion

Soil Characterization

Table 1 presents selected physico-chemical properties of the Tab-Simco soils. All of the soils from the sampling area were highly acidic, with a mean pH of 2.69 ± 0.05. Mean EC was 2.35 ± 0.14 mS/cm. The soil was comprised mostly of silt (53.5 %) and sand (36.8 %), followed by clay (9.7 %). The total S content of the soil was 0.54 %. The soil contained an average of 7.8 % total nitrogen, and 0.08 % total carbon.

Physico-chemical characterization of the Tab-Simco soil revealed its acidic nature. Due to this high acidity, the metals are likely to become soluble and bioavailable. Only those metals that were found in high concentrations in Tab-Simco soil after acid digestion are listed in Table 2. High concentrations of Fe (41,012 ± 10 mg/kg) were reported in all of the soil samples. High concentrations of Zn (419 ± 63 mg/kg), Ni (175 ± 5.9 mg/kg), Cr (152 ± 15 mg/kg), Cu (148 ± 2.1 mg/kg), Pb (145 ± 25 mg/kg), As (127 ± 16 mg/kg), Cd (4 ± 0.5 mg/kg), and Hg (3.7 ± 0.2 mg/kg) were also reported in the soil samples.

From the soil characterization results, it was clear that the Tab-Simco soils were heavily impacted by the AMD from the underground mine pool. A number of metals were found in high concentrations in the soil. Moreover, the high acidity increases the toxicity of the metals to biological organisms as the metals become more bioavailable.

Water Characterization

The impact of AMD on the Tab-Simco water samples is apparent (Table 3). Samples W1, W2, and W3 verified that the SRB was not functional (Behum et al. 2013), and reflected the characteristic properties of AMD, as did the samples collected from Sycamore Creek (W4 and W5). The water samples had a mean pH of 2.07 ± 0.02. The mean EC was 3.94 ± 0.03 mS/cm. The mineral and total acidity of the water were 467 ± 50 mg/L $CaCO_3$ and 1089 ± 60 mg/L $CaCO_3$, respectively, indicating that the Tab-Simco mine is negatively impacting the surrounding water bodies, making them potentially unsustainable in terms of aquatic population and biodiversity.

The Tab-Simco water samples contained 137 (±5) ppm of Fe, which was more than 100 times higher than the U.S. EPA permissible limit of Fe (1 ppm) in surface water (NCAC 2003; U.S. EPA 1994c). Also, the concentrations of As (4 ± 0.01 ppm), Zn (11 ± 0.9 ppm), Pb (7 ± 1.2 ppm), and Cr (1 ± 0.04 ppm) were well above the U.S. EPA permissible limits (0.05, 0.5, 0.25, 0.5 ppm, respectively) (NCAC 2003; U.S. EPA 1994c). Other metals, such as Al (80 ± 15 ppm), Cu (4 ± 0.05 ppm), Cd

Table 1 Physico-chemical properties of the Tab-Simco soil samples, indicating soil properties for individual sampling sites (n = 3) along with the mean (n = 5) value for the entire area

Sample	pH	EC (µs/cm)	Total C (%)	Total H (%)	Total N (%)	Total S (%)	Soil texture		
							Clay (%)	Silt (%)	Sand (%)
S1	2.69	2.25	0.08	1.62	7.9	0.54	9.7	53.8	36.5
S2	2.76	2.47	0.09	1.59	7.8	0.59	9.7	53.5	36.8
S3	2.74	2.52	0.07	1.69	7.8	0.53	9.8	53.3	36.9
S4	2.65	2.35	0.07	1.65	7.8	0.5	9.7	53.5	36.8
S5	2.64	2.15	0.08	1.55	7.9	0.56	9.7	53.4	36.9
Mean	2.69 ± .05	2.35 ± .14	0.08 ± .01	1.64 ± 0.05	7.8 ± .06	0.54 ± .03	9.7 ± .3	53.5 ± .2	36.8 ± .1

Table 2 Metal concentrations (mg/kg) in the Tab-Simco soil samples

Sample	As	Cd	Cr	Cu	Fe	Hg	Ni	Pb	Zn
S1	125	4	160.7	148	41,005	3.8	174	146	526
S2	116	3.3	125.9	145	41,002	3.3	165	103	409
S3	109	4.5	152.9	151	41,029	3.5	176	148	410
S4	149	3.7	161.7	148	41,015	3.9	181	157	362
S5	137	4.5	162.1	148	41,012	3.8	177	169	386
Mean	127 ± 16	4 ± 0.5	152 ± 15	148 ± 2.1	41,012 ± 10	3.7 ± 0.2	175 ± 5.9	145 ± 25	419 ± 63

Data show metal concentrations at individual sampling sites (n = 3) along with the mean (n = 5) value for the entire area

Table 3 Characterization of the Tab-Simco water samples for individual sampling sites (n = 3) along with the mean (n = 5) value for the entire area

Sample	pH	EC (ms/cm)	Mineral acidity (mg/L $CaCO_3$)	Total acidity (mg/L $CaCO_3$)
W1	2.06	3.94	480	1100
W2	2.07	3.92	520	1170
W3	2.06	3.92	400	1000
W4	2.11	3.99	430	1089
W5	2.09	3.95	500	1090
Mean	2.07 ± 0.02	3.94 ± 0.03	467 ± 50	1089 ± 60

Table 4 Concentrations (mg/L) of different contaminants in the Tab-Simco water samples at individual sampling sites (n = 3) along with the mean (n = 5) value for the entire area

Sample	Al	As	Cd	Cr	Cu	Fe	Ni	Pb	Zn	SO_4^{2-}
W1	90	4	1.06	1.09	4	135	3.5	8.7	11.8	2515
W2	95	4	1.05	1.01	4	136	3.4	8.1	11.5	2516
W3	87	4	1.04	1	4	135	3.1	8.3	11.1	2525
W4	61	3.96	1.01	1	3.88	132	2.9	6.05	9.6	2420
W5	69	3.99	1.05	1	3.97	145	3	6.34	11.7	2433
Mean	80 ± 15	4 ± .01	1 ± .01	1 ± .04	4 ± .05	137 ± 5	3 ± .25	7 ± 1.2	11 ± 0.9	2481 ± 50

(1 ± 0.01 ppm), and Ni (3 ± 0.25 ppm) were also present, along with high SO_4^{2-} concentrations (2481 ± 50 ppm). These results (Table 4) clearly demonstrate the impact of the AMD. The presence of metals such as Fe, Al, and Mn in AMD-contaminated sites have been reported in Alabama, Indiana, Kentucky, Maryland, Ohio, Tennessee, and West Virginia (Skousen and Ziemkiewicz 2005). What makes the Tab-Simco mine site unusual for a coal mining site is significantly higher amounts of some contaminants normally only associated with hard rock mines. Although

exploring the specific sources of these metals was beyond the scope of this study, the very low pH makes these metals soluble, and hence mobile, thus exposing the surrounding ecosystem to high concentrations of bioavailable metals.

Conclusion

The objective of this study was to evaluate the current extent of AMD pollution at the Tab-Simco mine site after failure of the SRB in 2011. The results clearly showed that both soil and water in the area have been heavily impacted by AMD. High concentrations of Fe, Zn, Ni, Cr, Cu, Pb, and As were found in the soil samples, which are very likely mobile in the highly acidic environment. The water samples were also characterized by their very low pH, and high mineral and total acidity. The water samples contained high concentrations of Fe, As, Zn, Pb, Cr, Al, Cd, Cu, and Ni, and very high SO_4^{2-} concentration. Samples collected from Sycamore Creek indicated severe AMD impact. Given that mining at the Tab-Simco site ceased in the 1970s, this study reveals the extent of AMD pollution that can persist at an abandoned mine site decades after mining, and the necessity of developing proper remedial and/or management plans to protect the surrounding ecosystem from AMD pollution.

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