Aeration via Renewable Energies Improves Passive Treatment System Performance

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Abstract

Successful passive treatment requires effective aeration of mine waters to address both ecotoxic metals concentrations (e.g., removal via oxidation, hydrolysis, and precipitation) and nuisance constituents (e.g., sulfide and oxygen demanding substances produced by sulfate-reducing bioreactors). In the flat landscape of the Tri-State Lead-Zinc Mining District of the central United States, renewable energy-driven aeration technologies were implemented at two full-scale passive treatment systems with limited total relief. Solar-powered units, with the ability to store energy, provided consistent and effective aeration compared to wind-powered technologies. Off-the-grid aeration devices can enhance water quality improvement and may be especially attractive for use remote locations.

Keywords: Aeration, oxygenation, sulfide, iron, Tar Creek

Introduction

In passive treatment systems, effective aeration of mine waters is often needed to address elevated concentrations of ecotoxic metals and/or nuisance constituents produced by sulfate-reducing bioreactors. In many mining regions, substantial topographic variability provides site-specific opportunities for cascade aeration (Chen and Jiang 2012, Oh et al. 2016) and other related technologies relying on hydraulic head differences. At mine water sites in flat landscapes, differences in hydraulic head may be insufficient to provide effective aeration via these approaches. At derelict and abandoned mine water sites in these landscapes, where passive treatment may be an especially attractive option given its lesser long-term operation and maintenance commitments, aeration via traditional energy-intensive engineering technologies (e.g., fossil-fuel driven mechanical, bubble or pressure aerators) may not be a feasible economic or technical option. Utilization of renewable energy-driven aeration (e.g., solar- and wind-powered technologies) may offer a cost-effective and efficient option at these locations.

Solar- and wind-powered aeration technologies have been used in aquaculture, lake and reservoir management, and wastewater lagoon operations to promote mixing and increase dissolved oxygen (DO) concentrations (e.g., Westerman and Zhang 1997, Boyd 1998, DeMoyer et al. 2003). These systems are typically submerged and consist of a renewable power source that builds pressure in an air compressor or blower. The pressure is typically released through a valve and line to submerged diffusers at the bottom of the pond which produce "bubble plumes" that rise to the surface. The bubbles cause vertical and lateral circulation by entraining water as they rise, and the bubble interfaces help to transfer oxygen to the water. Further oxygen mass transfer may occur at the pond surface due to turbulence at the air-water interface created by the bubble plume.

In mine water passive treatment systems, effective aeration (and re-aeration) may drive several demonstrable water quality improvement processes. In ponds and wetlands, rates of iron oxidation are enhanced by the entrainment or addition of oxygen beyond passive diffusion or photosynthetic activity (Jageman et al. 1988, Hedin et al 1994, Kirby et al. 2009). In net alkaline mine drainage, degassing of elevated concentrations of carbon dioxide (CO_2) drives pH values upward, further enhancing iron oxidation rates (Kirby et al. 2009, Nairn 2013). Vertical flow bioreactors (VFBRs), designed to promote bacterial sulfate reduction and subsequent metal sulfide retention, often produce water with low oxidation-reduction potential (ORP) and DO concentrations, and elevated sulfide concentrations and biochemical oxygen demand (e.g., Yepez and Nairn 2012). Effective aeration helps to strip oxygen demand and sulfide and increase DO and ORP. In this preliminary study, the initial efficacy of renewable energy-driven aeration devices was evaluated for increasing DO and ORP, enhancing iron oxidation, and stripping sulfide and oxygen demand.

Methods

In the relatively flat landscape of the abandoned Tri-State Lead-Zinc Mining District of the central United States, off-the-grid aeration technologies were implemented at two full-scale passive treatment systems. Process unit designations, design functions and aeration status are summarized in Table 1. The Mayer Ranch system (Figure 1) has been in operation since late 2008 and the Southeast Commerce system (Figure 2) has been operational since early 2017. Each site has less than 1.8 m of total relief to facilitate gravity-driven treatment though multiple process units. Principal contaminants of interest are elevated concentrations of iron (138-192 mg/L), zinc (6-11 mg/L), lead (60-81 µg/L), cadmium (17-20 µg/L) and arsenic (40-64 µg/L) in net alkaline mine waters. Design volumetric flow rates are 1400 and 550 m^3/minute for Mayer Ranch and Southeast Commerce, respectively.

Aeration at Mayer Ranch includes two windmills powering vertical displacement air pumps and two solar units. In C1, a 6-m was installed including 12 1.85-m steel blades mounted on a self-governing upwind turbine with head-mounted vertical displacement compressor capable of producing 5 m^3/hour at 9000 Pa depending on wind speed, and dual rubber diaphragm bubble diffusers. In C4N, an additional 6-m windmill was installed including 12 1.78-m steel blades mounted on a self-governing upwind turbine with a Jet Stream direct drive compressor capable of producing 2.5 m^3/hour at 9000 Pa at wind speeds of 14-64 km/hour, and dual rubber diaphragm bubble diffusers. In C4S, a commercial solar lake bed aeration system was installed including a 120-W solar panel, high-volume compressor with air output of 8.5 m^3/hour, 30-amp charge control center, 210 amp-hour deep cycle solar battery, 12/24-volt smart box converter and dual rub-

__Table 1.__ Process unit designations, design functions and aeration type and capacity of the Mayer Ranch and Southeast Commerce passive treatment systems in the Tri-State Lead-Zinc Mining District, Oklahoma, USA.

	Design function	Aeration Type/Capacity (m3/ hour)
Mayer ranch passive treatment system		Wind/5
Initial oxidation pond (C1)	Oxidative Fe retention	---
Surface-flow wetlands/pond (C2N/C2S)	Trace metal sorption	---
Vertical flow bioreactors (C3N/C3S)	Additional Fe/ trace metals retention	C4N-Wind/2.5
	Trace metal sulfide retention	C4S-Solar/8.5
Re-aeration ponds (C4N/C4S)	Re-aeration and stripping of sulfide and	---
Horizontal flow limestone beds (C5N/C5S)	oxygen demand	Solar/0.5
Polishing pond/wetland (C6)	Polishing of Zn and addition of hardness	Solar/50
	Ecological buffering	---
Southeast Commerce passive treatment		Solar (OCS)/50
system		Solar/50
Initial oxidation pond (OX)	Oxidative Fe retention	
	Trace metal sorption	
Surface flow wetland/pond (WL)	Additional Fe/ trace metals retention	
Vertical flow bioreactors (VF)	Trace metal sulfide retention	
Final polishing unit (FP)	Re-aeration and stripping of sulfide and	
	oxygen demand	

ber diaphragm bubble diffusers. In C6, another commercial solar aerator system was installed including three 15-W solar panels, solar charge controller, 12-V deep cycle marine battery, 0.6 amp-hour pump house containing four compressors with air output of 0.5 m^3/hour, and a single rubber diaphragm bubble diffuser.

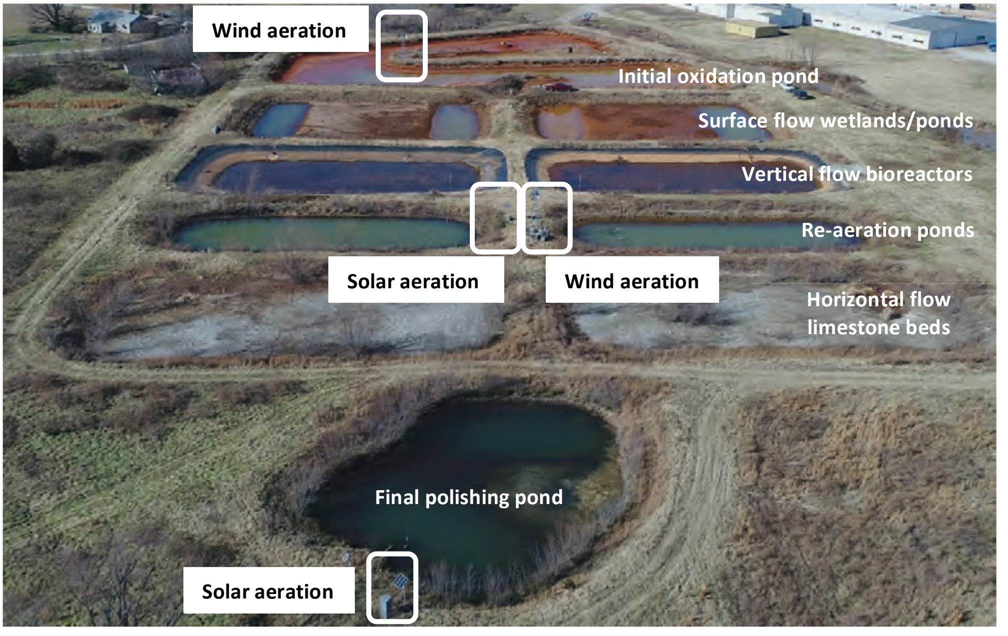

Figure 1 Oblique aerial photograph of Mayer Ranch passive treatment system in December 2017 during a maintenance drawdown when water levels were decreased. Water flow paths are from top to bottom. Individual process unit designations and locations of aeration devices are shown. Image obtained via small Unmanned Aerial System.

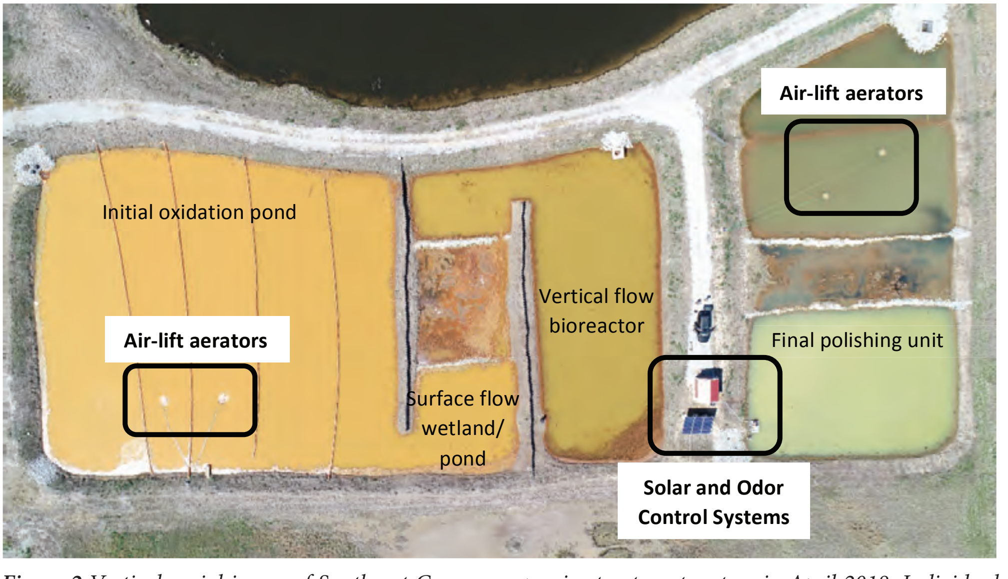

Figure 2 Vertical aerial image of Southeast Commerce passive treatment system in April 2018. Individual process unit designations and locations of aeration and other devices are shown. Note directional baffle curtains in the initial oxidation pond. Image obtained via small Unmanned Aerial System.

At Southeast Commerce, a custom-designed, solar-powered aeration and sulfide removal system was installed by BioMost Inc. This unique system includes a 3,180-W photovoltaic module, combiner box, two charge controllers, a bank of eight 6V/400 AH/20HR batteries, 1500-W 24V DC Inverter, two regenerative blowers with pressure kits and one regenerative blower with vacuum kit. This system drives four floating air-lift aerators (two in OX and two in FP) and a novel, closed Odor Control Structure (OCS) at the VFBR effluent. Gas (e.g., hydrogen sulfide) from the OCS outlets via suction through an Activated Carbon Filter (ACF) containing 180 kg of granular carbon media. This single combined system can provide air flows of more than 150 m^3/hour through the three subsystems (two sets of air-lift aerators in OX and FP, and the OCS).

Water quality and quantity data were collected on a monthly (MRPTS: 2009-2013; SECPTS: 2017-2018) and quarterly (MRPTS: 2013-2018) basis and included volumetric flow rates, physical parameters (pH, DO, temperature, specific conductance, ORP, alkalinity, turbidity), sulfate, sulfide, and a full suite of total and dissolved metals and base cations (Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, Pb, Si, Zn). Center for Restoration of Ecosystems and Watersheds (CREW) standard operating procedures follow US Environmental Protection Agency (USEPA) methods for all analyses.

Results

Both passive treatments systems addressed traditional mine water quality constituents, decreasing concentrations of targeted contaminants of concern (Table 1). Median annual mass retention values for Fe, Zn, Pb, Cd and As were 37000, 1670, 15, 3 and 13 kg/year, respectively, at Mayer Ranch. The Southeast Commerce system retained 24200, 1660, 5, 4, and 7 kg/year of Fe, Zn, Pb, Cd and As, respectively. Iron retention occurred in oxidative units (C1, C2N and C2S at Mayer Ranch, and OX and WL at Southeast Commerce) as well as substantial trace metal sorption to amorphous iron oxyhydroxide solids (Oxenford and Nairn 2010). Trace metals were further retained in the VFBRs (C3N and C3S at Mayer Ranch and VF at Southeast Commerce) by a suite of mechanisms including exchange, sorption, and sulfide precipitation (LaBar and Nairn 2018). Effluent Pb concentrations at Southeast Commerce were elevated, likely due to construction-related flow manipulations and are expected to decrease over time.

Table 3 presents selected data for passive treatment process units with renewable-energy driven aeration devices. Dissolved oxygen saturation and ORP increased significantly ($p<0.05$) in all units and sulfide, BOD5 and pCO2 decreased significantly ($p<0.05$). Sulfide and BOD5 were only evaluated for VFBR effluent reaeration. Increased dissolved oxy-

Table 2. Influent and effluent water quality for the Mayer Ranch and Southeast Commerce passive treatment systems in the Tri-State Lead-Zinc Mining District, Oklahoma, USA. Values less than the practical quantitation limit (PQL) are reported as <PQL. The number of sampling events is reported as n.

	Mayer Ranch		Southeast Commerce	
	In (n=82)	Out (n=43)	In (n=80)	Out (n=22)
pH	5.95	7.02	6.06	7.02
Total alkalinity (mg/L CaCO3)	393	224	350	117
Total Fe (mg/L)	192	0.13	127	0.79
Total Zn (mg/L)	11	0.25	6.15	0.69
Total Ni (mg/L)	0.97	0.15	0.52	0.06
Total Cd (µg/L)	17	<PQL	18	<PQL
Total Pb (µg/L)	60	<PQL	80	26
Total As (µg/L)	64	<PQL	38	<PQL
Total SO4-2 (mg/L)	2239	2057	2102	1956

gen concentrations and degassing loss of CO_2 have direct positive effects on iron oxidation rates (Kirby et al. 2009). Sulfide and oxygen demand may be considered nuisance constituents, which are typically not present in the untreated mine drainage but are created during passive treatment in sulfate-reducing bioreactors. Elevated concentrations may be directly ecotoxic to aquatic life. In the two studied systems, oxygen demand was never problematic, but sulfide concentrations were often well above the aquatic life criteria of 0.002 mg/L (USEPA 2018) even after re-aeration, especially in hot summer months in Oklahoma when air temperatures are often above 35°C.

All parameters showed substantial seasonality due to temperature variability and subsequent effects on biological activity. In addition, these data represent median measurements for the full lifetime of each system. During initial startup, the Mayer Ranch passive treatment system VFBRs exported substantial concentrations of nutrients leading to algal blooms, of which subsequent decomposition decreased dissolved oxygen concentrations in downstream process units. However, once the system reached a quasi-steady state after the first two growing seasons, these issues were no longer present. It is likely that the Southeast Commerce passive treatment system VFBR is still in this initial startup phase.

In addition, at the Southeast Commerce system, the novel solar-driven OCS installation pulled gaseous sulfide from the atmosphere above the VFBR effluent into the ACF. Gaseous sulfide concentrations through the fall and winter of 2017 and early spring of 2018 were decreased by essentially 100% (all ACF effluent gaseous concentrations were below detectable limits with influent concentrations ranging from 17 to 78 ppm). In two sampling events in spring 2018, ACF effluent gaseous sulfide concentrations showed an increase to 2.7 and 142 ppm as temperatures increased and influent concentrations reached 490 ppm. The performance of this unique system is the subject of ongoing research as are the novel air-lift aerators in the oxidation pond and final polishing unit at Southeast Commerce.

Conclusions

Both passive treatment systems produced circumneutral pH effluent waters containing concentrations of trace metals meeting in-stream, hardness-adjusted aquatic life criteria. Aeration in initial oxidation ponds showed seasonal and spatial variability in effectiveness, mainly due to air temperature changes and subsequent changes in dissolved oxygen saturation concentrations. Degassing of carbon dioxide by active aeration helped to increase pH and had positive effects on iron

Table 3. *Median measured dissolved oxygen saturation, oxidation-reduction potential (ORP), sulfide (S^{-2}) and five-day biochemical oxygen demand (BOD_5) values and median calculated partial pressures of carbon dioxide (pCO2) in and out of process units which included solar- or wind-powered aeration devices. pCO2 was calculated using a modified Henderson-Hasselbach equation including temperature compensation for KH and K_1.*

	DO Saturation (%)	pCO_2 (atm)	ORP (mV)	S^{-2} (mg/L)	BOD_5 (mg/L)
Mayer Ranch passive treatment system					
C1 In	13	0.528	-116	---	---
C1 Out	37	0.189	+121	---	---
C4N In	11	0.038	-80	31	2.89
C4N Out	51	0.023	+78	1.9	1.11
C4S In	14	0.035	-73	38	2.44
C4S Out	38	0.023	+77	4.2	1.21
C6 In	10	0.025	+5	---	---
C6 Out	41	0.021	+97	---	---
Southeast Commerce passive treatment system					
OX In	10	0.364	-43	---	---
OX out	80	0.130	+130	---	---
FP In	10	0.074	-184	85	3.51
FP Out	73	0.023	+91	12	3.30

oxidation rates. However, it is likely that the effects were limited in scope given the large surface areas of the pond-like process units. Although sulfate-reducing bioreactors produced biochemical oxygen demand, especially in initial growing seasons, these values were not sufficiently elevated to be considered problematic. Sulfide concentrations, however, were often elevated enough (> 1000 μg/L) to be considered both a nuisance odor and an aquatic toxicant. Renewable-energy driven re-aeration decreased sulfide concentrations substantially with both wind- and solar-powered technologies. Overall, sulfide concentrations decreased by 94% and 86% using solar power at Mayer Ranch and Southeast Commerce, respectively, and by 89% using wind at Mayer Ranch. At least initially, the larger custom-designed solar-powered unit at Southeast Commerce has demonstrated more consistent and effective performance.

Off-the-grid aeration devices may enhance water quality improvement effectiveness in passive treatment systems, addressing both oxidative iron removal and nuisance constituent treatment, especially in regions lacking substantial topographic variability to sustain effective cascade aeration or other hydraulic head-driven technologies. They may be especially attractive for use remote locations and/or at abandoned or derelict sites where operation and maintenance budgets are limited.

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