EFFECTS ON THE UNDERLYING WATER COLUMN BY ECOLOGICALLY ENGINEERED FLOATING VEGETATION MATS[1]

W.H. Strosnider[2] and R.W. Nairn[2]

Abstract. Engineered floating vegetation mats are emerging applications of ecological engineering that have promising water quality improvement and habitat creation applications. However, relatively little research has been published regarding their construction or effects on the underlying water column. The objectives of this study were to determine appropriate design characteristics and the effect of ecologically engineered floating vegetation mats (EFVM) on the underlying water column. Four EFVM designs were constructed of drainpipe, burlap, mulch, utility netting, and reused polyethylene bottles, and then planted with *Typha* spp. and *Juncus effusus*. The water column beneath EFVM in two test ponds was compared to that in an open water control pond. Dissolved oxygen concentrations and pH were lower, diurnal temperature range was dampened, and sulfate/nitrate reduction was greater under the EFVM with respect to the control. Alkalinity was also greater under EFVM. Results reinforced previous findings indicating that *Typha* spp. is a suitable species for EFVM creation. However, a more robust planting matrix is necessary to encourage faster growth and protect against wind and wave action damage. Although plant propagation was limited, results suggest that EFVM may be applied to encourage reducing, thermally insulated conditions for passive treatment of acid mine drainage a wide range of other pollutants. Specifically, they may be employed to improve short and long-term performance of vertical flow bioreactors for acid mine drainage treatment by lowering dissolved oxygen concentrations in the water column and providing a continual source of organic carbon to the underlying substrate.

Additional Key Words: acid reduction using microbiology, acid mine drainage, vertical flow bioreactor

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Introduction

Naturally occurring floating vegetation mats (NFVM) are relatively common in various climates and settings (Hunt, 1943; Mitsch and Gosselink, 2000; Mallison et al., 2001; Scheffer et al., 2003; Somodi and Botta-Dukat, 2004; van Duzer, 2004; Kadlec and Wallace, 2009). NFVM often develop as the rhizomes of wetland plants colonize horizontally from the shoreline, from masses of vegetation delaminated from the underlying substrate or colonization of floating organic substrates (Somodi and Botta-Dukat, 2004; Kadlec and Wallace, 2009). Examples of NFVM range from free-floating *Typha* spp. tussocks in Florida (Mallison et al., 2001), floating sedge fens in Alaska (Racine and Walters, 1994), *Panicum hemitomon*-dominated floating marshes of the Mississippi River Delta Plain (Sasser et al., 1996), floating *Cyperus papyrus* L. marshes of equatorial Africa (Gaudet, 1977; Boar et al., 1999), to boreal quaking bog vegetation (Mitsch and Gosselink, 2000). *Typha* spp. can form stable, buoyant and productive NFVM in a wide variety of climates and hydro-geochemical settings (Hunt, 1943; Racine and Walters, 1994; Sasser et al., 1996; and Mallison et al., 2001). *Typha* spp. NFVM are resilient and can recover quickly from drying and even burning regimes (Krusi and Wein, 1988).

NFVM have demonstrated effects on water quality that may be conducive to treating certain types of effluent. NFVM can create anoxic conditions in the underlying water column (Mallison et al., 2001; Scheffer et al., 2003). Vascular plants with photosynthetic tissue above the water surface often deplete dissolved oxygen (DO) in the underlying water column (Kadlec and Wallace, 2009; Janse and Van Puijenbroek, 1998; Caraco et al., 2006). Dense growth of floating vegetation reduces the water surface available for oxygen diffusion as well as lowers turbulence in the neighboring uncovered water surface (Scheffer et al., 2003). NFVM can also decrease DO levels in the water column by shading submersed vegetation (Janse and Van Puijenbroek, 1998; Mallison et al., 2001). Decaying plant material forms loose layers of organic sludge beneath NFVM (Swarzenski et al., 1991). Alam et al. (1996) found water below NFVM to have depressed DO levels and higher organic matter concentrations when compared to nearby open water. Generally, previous findings indicate that NFVM can help create anaerobic, organic-rich systems in the underlying water column. Similar to NFVM, floating aquatic plant systems of *Eichhornea crassipes* and *Lemna*, *Spirodela* and *Wolffiella* spp. have been successfully established for municipal wastewater treatment (Kadlec and Wallace, 2009). Like NFVM, these systems of free-floating aquatic plants are generally anaerobic because photosynthesis occurs above the water's surface while oxygen diffusion is limited by vegetative cover (Kadlec and Wallace, 2009).

EFVM (Ecologically-engineered floating vegetation mats) take advantage of the properties of NFVM to provide a desired water quality effect and/or habitat improvement. EFVM are generally constructed of a framework promoting the growth of emergent macrophytes, such as *Typha* spp., suspended in the water column. Although tests and/or full-scale applications have been few, EFVM have been applied to treat meat processing effluent (Van Oostrom, 1995), improve lake water quality (Boutwell, 2001), and treat dilute de-icers from airport runoff (Revitt et al., 2001; Richter et al., 2003).

EFVM have been applied in multiple instances to treat AMD by providing a continual carbon source to bacteria in systems dubbed ARUM (Acid Reduction Using Microbiology) (Smith and Kalin, 2000; Kalin and Caetano Chaves, 2003; Kalin, 2004). These systems have been primarily applied to either flooded pits associated with mining disturbances or in treatment wetlands. Canada hosts EFVM wetlands treating zinc/lead rich contaminated open pits in Buchans, Newfoundland, nickel/copper tailings runoff in Sudbury, Ontario, nickel/arsenic waste rock runoff in Northern Saskatchewan, and aqueous aluminum oxide and coke particles in Kitimat, British Columbia (Smith and Kalin, 2000). Anaerobic (reducing) conditions beneath the EFVM are reported to enable sulfate and iron reduction reactions that remove acidity and metals from solution while increasing alkalinity (Kalin et al., 2006).

Nevertheless, comprehensive EFVM performance data and design specifications are lacking in the refereed literature, information that is necessary to determine their suitability to treat AMD as well as other effluents. Beyond the exploration of the structural stability and maturation of four EFVM designs, this experiment allowed the comparison of water quality parameters between control and test ponds to provide indications of how passive treatment cells with EFVM may perform. The objectives of this study were to determine appropriate design characteristics and the effect of EFVM on the underlying water column.

Methods

Experimental Design

EFVM trials occurred in newly HDPE-lined ponds cleared of any debris and filled with well water at the University of Oklahoma Aquatic Research Facility. Three approximately 200 m^2

University of Oklahoma Aquatic Research Facility ponds, one control and two experimental were used (Fig. 1). The open water control pond had the same general dimensions and volume, approximately 140 m^3, as the test ponds. The ponds were each a closed controlled hydrologic system, receiving very little surface runoff. All ponds were periodically refilled with approximately equal volumes of well water to offset losses from evapotranspiration not compensated by precipitation.

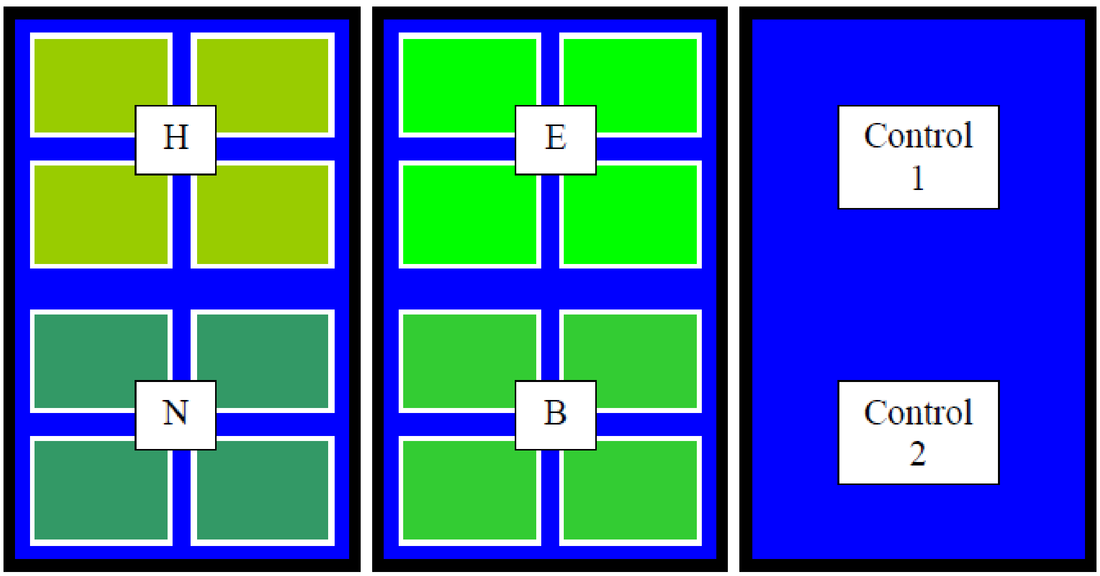

Figure 1: Experimental pond layout

Four EFVM designs were installed in the test ponds (Fig. 1, Table 1), each with four replicates. Designs were designated “E”, “H”, “B” and “N”. EFVM “H” had the most intensive planting medium, with corn stover hydromulch sandwiched by burlap accompanying the mulched *Typha* spp. that all designs shared. The “B” design had a medium-intensive planting media. The “E” was a minimalist low embodied energy design defined by a frameless bed supporting minimal planting media overlain by burlap. “N” had the least intensive planting media, with no supportive burlap. Each EFVM had one water sampling unit aligned in its center with fixed sampling ports located 10 cm below the water surface, 40 cm below the water surface and 10 cm above the bottom of the pond.

Table 1: EFVM design description

Design Feature	Design			
	H	N	E	B
15 x 17 ft ABS drainpipe frame	X	X		X
15 x 17 ft 3/4 in utility net	X	X	X	X
7oz untreated burlap - over rhizomes	X		X	X
7oz untreated burlap - under rhizomes	X			
45 kg corn stover hydromulch	X			
1.5 x 6 ft access slot centered and perpendicular to long axis	X	X	X	X
7 kg of long cut Typha spp. shoots	X	X	X	X
4 kg of mulched Typha spp. shoots and seed heads	X	X	X	X
2 sealed 16oz float bottles placed at each corner	X	X	X	X
4 sealed 16oz float bottles placed around central access slot	X	X	X	X
1 sealed 16oz float bottle placed at each edge midpoint			X	
Tension applied at corners directed away from the center			X	

On June 13-16, 2006 the EFVM were constructed and initially planted with 52 *Typha* spp. rhizomes (~7.6 g dry weight each) at regularly spaced intervals and four *Juncus effusus* culms, one at each corner. Locally harvested rhizomal plantings were chosen following the observations of Mitsch and Gosselink (2000) that this is a viable planting method and Kadlec and Knight (1996) that locally harvested plants may have a more fitting genotype for the applied setting. All EFVM were designed to support the plantings at water depths between 5 and 30 cm following the findings of Grace (1989) that *Typha* spp. have higher productivity in this range. High winds and multiple storm events blew over and killed some of the established vegetation. Following the findings of Van Oostrom (1995) that interlocked emergent macrophytes patches can be separated from terrestrial substrate and successfully set upon floating frames, seven (10 x 10 cm, 54 g dry weight each) sections and one large (~60 x 60 cm, 1500 g dry weight each) section of rhizomally interlocked *Typha* spp. were added to each mat on May 20-21, 2007. The EFVM were qualitatively and quantitatively monitored until deconstruction on October 10, 2008.

Data Collection

Vegetation growth and any structural degradation were monitored monthly by elevated photography using a 3.6-m stepladder and digital camera. Diurnal DO, pH, Eh and temperature (T) were continuously logged for an average of three days in duration at two or five minute intervals using YSI 600QS multiparameter sondes and YSI 650MDS displays. Diurnal data were gathered by hanging the sondes at the middle of a randomly determined EFVM with sensors located approximately 35 cm below the water surface. Control diurnal data was gathered by hanging sondes in the same fashion at the center of either half of the control pond.

Waters were sampled from the fixed sampling ports for 13 monthly sampling events. The same sondes and displays were coupled with a peristaltic pump and flow-through cell for the monthly sampling events. Sampling generally occurred from 11:00 to 17:00 over consecutive days. One level of all stations (all EFVM replicates and both control) was sampled a day, over the three day sampling event. The order of sampling was randomized to avoid systemic error due to the diurnal range of various parameters. Alkalinity titrations were conducted with samples from the fixed sampling ports following standard methods (APHA, 1998) and Hach Method 8203 (Hach, 2006). Following Sharp et al. (1995), water samples for dissolved organic carbon (DOC) and dissolved total nitrogen (DTN) were gathered from the fixed sampling ports, immediately filtered through 0.45-μm nylon filters, then stored at <-4°C in 40-mL amber glass EPA vials with polypropylene caps and Teflon septa until quantification with an Analytik Jena multi N/C 2100. DOC and DTN samples were processed from five events that were evenly spread among the 13 overall sampling events.

Grab samples for anion concentrations were taken from the well heads and the center of each pond at irregular temporal intervals throughout the experiment using 250-mL HDPE containers. These samples were stored at 4 °C until filtered through Dionex OnGuard® II H cartridges and 0.2 μm nylon filters. A MetrOhm® 761 compact ion chromatograph unit was used to quantify anion concentrations following EPA method 300.

Data Analysis

Due to the non-normality yet relatively similar distribution and equal variances of the diurnal data sets, the Mann-Whitney test was applied for statistical comparisons of diurnal DO, pH and T. A one-tailed homoscedastic Student's *t*-test was applied to compare the diurnal T range differences between the control pond and under the EFVM. To do so, the absolute value between each sequential daily maximum and minimum T during diurnal sampling periods were compiled. Prior to statistical analysis, each monthly sampling event's alkalinity, pH, DO, Eh and T of the control and each EFVM type were averaged, pooling each level and replicate. As the reduced data sets were normal with similar variances, each EFVM was tested against the control using two-tailed homoscedastic Student's *t*-tests. Due to the small size of the DOC and DTN data sets from the monthly sampling events, they were not reduced and medians of the full non-normal data sets were compared with the Mann-Whitney test. One-tailed homoscedastic Student's *t*-tests were applied to means test anion data. All statistical tests employed an alpha of 0.05.

Results

Structural Performance

Various design lessons were learned from qualitative observation of each EFVM (Fig. 2 and 3). From observation of EFVM "H", it was deduced that a stronger, more buoyant frame was necessary to support the mass of more intensive planting medium. From observation of the other EFVM, more durable finer mesh netting is recommended to allow vegetation to firmly establish. Plant survival and propagation was limited. However, interlocked continual rhizomes were more productive, and are thus preferable over singular separated *Typha* spp. rhizomes. *Juncus effusus* displayed survivability yet remained isolated at the corners of the mats and did not propagate. The depth of planting should be kept at a minimum to avoid any additional unnecessary vegetative stressors. All designs suffered damage from high winds, and consequential wave action, that frequent central Oklahoma. Boutwell (2001) observed the same difficulty with EFVM in Nevada. More robust planting matrices to firmly root plantings are suggested for applications in regions commonly experiencing high winds.

Figure 2. The central pond with EFVM set "E" in the foreground and "B" in the background

Figure 3. EFVM "E" approximately one year after construction and installation

Anions

Well water (influent) NO_3^- concentrations averaged 11.5 ±1.0 mg/L, yet NO_3^- was consistently below detection limits (<0.5 mg/L) in the EFVM ponds. In the control pond, NO_3^- was greater than detection limits (0.65 and 0.67 mg/L) for two out of the six anion sampling events. Well water SO_4^{2-} averaged 59 ±5.5 mg/L and was significantly less in the EFVM and control ponds. However, control pond SO_4^{2-} (28 ±2.1 mg/L) was found to be significantly greater than the ponds with EFVM "E" and "B" (24 ±2.0 mg/L) and "N" and "H" (20 ±2.8 mg/L). Phosphate was consistently below detection limits (<0.75 mg/L) in the well water and all ponds.

Denitrification and SO_4^{2-} reduction are the likely mechanisms for the observed decrease of NO_3^- and SO_4^{2-} concentrations within the test and control ponds. Dilution is unlikely because the only possible pond outflow was evapotranspiration, which would serve to concentrate dissolved constituents. Denitrification and SO_4^{2-} reduction require labile organic electron donors and reducing conditions to proceed. Van Oostrom (1995) observed that EFVM successfully promoted denitrification as well. Because the waters beneath the EFVM were not strongly reduced, it is likely that denitrification and SO_4^{2-} reduction occurred in the organic-rich benthos beneath the EFVM. The occurrence of denitrification and SO_4^{2-} reduction to a greater extent in the EFVM ponds indicates that EFVM can help create more reduced organic-rich conditions beneath.

Diurnal Results

Median diurnal T was significantly greater in the control than the EFVM ponds, except for the diurnal sampling period during the coldest period of the study (Table 2). DO was significantly less under the EFVM for the majority of diurnal logging periods (Table 3). The pH was also significantly lower under the EFVM for most periods (Table 4). The Eh was consistently significantly less under each EFVM than the control (Table 5). Although the differences are not large in magnitude, the DO, pH and Eh data combine to indicate the presence of less oxidizing conditions with lower oxidation reduction potential under the EFVM than in the control pond. It can be expected that greater differences would be noted for mature EFVM with more intensive planting media, established root mass and productive emergent vegetation.

Table 2. Median T (°C) for each diurnal sampling period. EFVM values are bolded or underlined where statistically greater or less than the control, respectively. Mean air T data are from the Oklahoma Climatological Survey (2010). The "-" denotes that no data were taken at this station.

Logging Period	Station					
	Air	Control	"N"	"B"	"E"	"H"
04/25/08 - 04/27/08	18.83	20.36	<u>18.94</u>	<u>19.50</u>	-	-
03/20/08 - 03/22/08	21.28	15.07	-	-	<u>13.99</u>	<u>14.18</u>
12/28/07 - 12/30/07	0.89	4.17	-	-	-	**4.44**
10/26/07 - 10/29/07	11.47	15.42	-	-	<u>14.27</u>	<u>14.43</u>
10/18/07 - 10/21/07	18.47	19.64	-	-	<u>18.61</u>	-
09/28/07 - 10/01/07	17.04	25.10	-	<u>23.42</u>	-	-
09/18/07 - 09/21/07	25.13	27.06	-	-	-	<u>25.19</u>
08/21/07 - 08/24/07	27.88	31.41	-	-	<u>29.06</u>	<u>29.22</u>
08/8/07 - 08/13/07	29.76	33.83	<u>31.17</u>	<u>30.88</u>	-	-
07/21/07 - 07/23/07	26.39	33.07	-	<u>30.49</u>	<u>30.42</u>	-
07/08/07 - 07/11/07	25.63	31.10	-	<u>27.88</u>	<u>27.90</u>	-
06/30/07 - 07/01/07	23.58	26.98	-	-	-	<u>25.53</u>

Table 3. Median percent saturation of DO for each diurnal sampling period. EFVM values are bolded or underlined where statistically greater or less than the control, respectively. The "-" denotes that no data were taken at this station.

Logging Period	Station				
	Control	"N"	"B"	"E"	"H"
04/25/08 - 04/27/08	102.2	77.3	**103.5**	-	-
03/20/08 - 03/22/08	99.0	-	-	**101.3**	96.2
12/28/07 - 12/30/07	91.0	-	-	-	96.4
10/26/07 - 10/29/07	85.6	-	-	**93.1**	**100.2**
10/18/07 - 10/21/07	102.0	-	-	88.2	-
09/28/07 - 10/01/07	124.6	-	94.4	-	-
09/18/07 - 09/21/07	134.1	-	-	-	83.3
08/21/07 - 08/24/07	119.6	-	-	99.9	66.0
08/08/07 - 08/13/07	125.5	52.2	98.0	-	-
07/21/07 - 07/23/07	102.4	-	94.2	96.1	-
07/08/07 - 07/11/07	94.1	-	74.7	74.1	-

Table 4. Median pH for each diurnal sampling period. EFVM values are bolded or underlined where statistically greater or less than the control, respectively. The "-" denotes that no data were taken at this station.

Logging Period	Station				
	Control	"N"	"B"	"E"	"H"
04/25/08 - 04/27/08	8.64	7.95	**9.11**	-	-
03/20/08 - 03/22/08	8.51	-	-	8.46	8.46
12/28/07 - 12/30/07	8.13	-	-	-	**8.45**
10/26/07 - 10/29/07	8.71	-	-	8.47	8.10
10/18/07 - 10/21/07	8.99	-	-	8.35	-
09/28/07 - 10/01/07	8.77	-	8.23	-	-
09/18/07 - 09/21/07	8.12	-	-	-	7.63
08/21/07 - 08/24/07	9.22	-	-	8.81	8.05
08/08/07 - 08/13/07	9.22	7.73	8.72	-	-
07/21/07 - 07/23/07	8.94	-	8.59	8.60	-
07/08/07 - 07/11/07	8.93	-	8.28	8.34	-
06/30/07 - 07/01/07	9.17	-	-	-	7.66

Table 5. Median Eh (mV) for each diurnal sampling period. EFVM values are bolded or underlined where statistically greater or less than the control, respectively. The "-" denotes that no data were taken at this station.

Logging Period	Location				
	Control	"N"	"B"	"E"	"H"
04/25/08 - 04/27/08	334	242	-	-	-
03/20/08 - 03/22/08	332	-	-	267	-
12/28/07 - 12/30/07	367	-	-	-	309
10/26/07 - 10/29/07	352	-	-	-	251
10/18/07 - 10/21/07	369	-	-	257	-
09/28/07 - 10/01/07	348	-	247	-	-
09/18/07 - 09/21/07	440	-	-	-	242
08/21/07 - 08/24/07	373	-	-	205	-
08/08/07 - 08/13/07	311	-	196	-	-
07/21/07 - 07/23/07	262	-	213	-	-
07/08/07 - 07/11/07	305	-	227	-	-
06/30/07 - 07/01/07	280	229	-	-	-

Diurnal Temperature Range

Temperature profiles were dampened beneath the EFVM through all seasons with respect to the control. Figure 4 presents a representative logging period. EFVM designs "B" and "H" demonstrated statistically greater diurnal T range for all five and four of their diurnal logging periods, respectively. EFVM "N" only displayed statistically significant dampening for one of three diurnal logging periods. However, its T ranges were numerically greater, and a longer logging period would likely reveal statistical significance. EFVM "E" demonstrated significantly greater T ranges for five of six logging periods. Overall, it is likely that greater insulative effects would be noted for mature EFVM with more intensive planting media, established root mass and productive emergent vegetation.

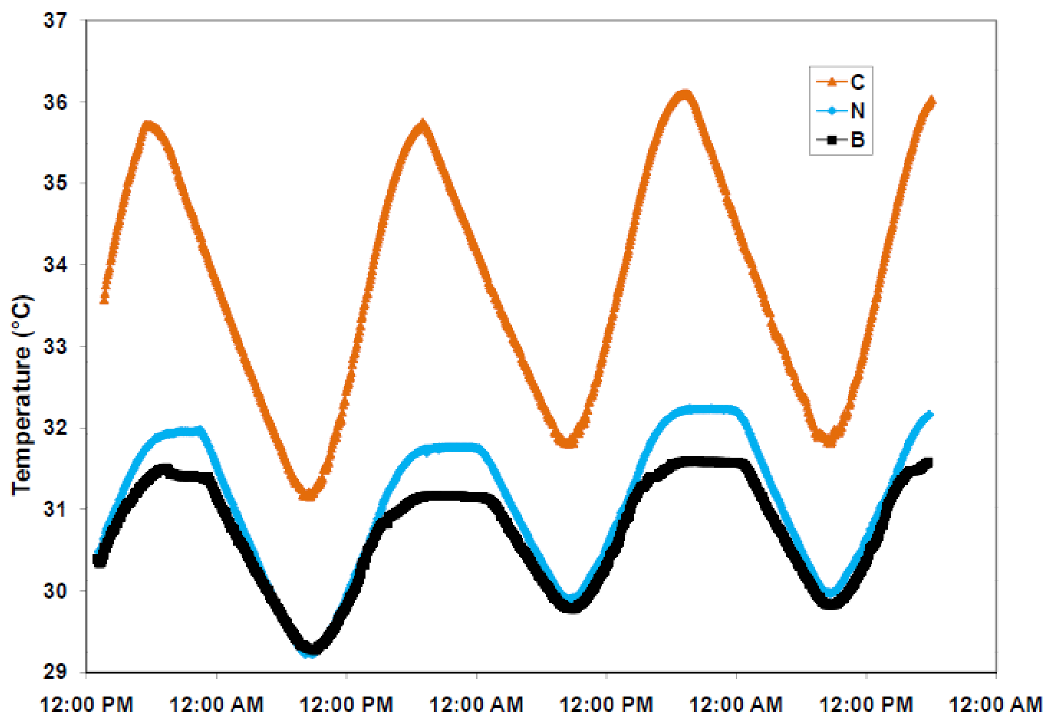

Figure 4. Diurnal T variation for August 8-13, 2007 demonstrating the statistically significantly greater range for the control versus the EFVM "N" and "B". "C" is representative of the control.

<u>Monthly Sampling Results</u>

There was no statistical difference in mean T between any of the EFVM and the control (Table 6). Mean T was not significantly different between EFVM and the control possibly due to the small size of the data set (n = 13). "N" and "H" had mean DO less than the control (Table 7). However, "E" and "B" mean DO was not significantly different than the control. "N" and "H" had mean alkalinity less than the control (Table 8). However, "E" and "B" mean alkalinity was not significantly different than the control. Increased alkalinity under "N" and "H" was likely due to the increased presence of organic ligands in the pond from the hydromulch in the "H" design. The hydromulch also likely helped further deplete DO in the water column. The other EFVM may have shown statistically greater alkalinity and lower DO if the size of the data set was expanded. All EFVM had mean pH less than the control (Table 9), generally reflecting the diurnal pH results. Median DOC was not significantly different between EFVM and the control (Table 10). It may be that the bulk of organic matter released by the mats was in particulate form and was deposited in the benthos. Median DTN was slightly, yet significantly less under "N" and "H".

Table 6. Mean T for each monthly sampling period. Mean air T data are from the Oklahoma Climatological Survey (2010). Note that air T is a daily mean, while water T was recorded only during the daytime/evening sampling windows.

Sampling Period	Air	Control	B	N	E	H
		Temperature (° C)				
10/7/2006-10/9/2006	18.4	23.2	21.4	20.7	21.5	20.6
1/9/2007-1/11/2007	9.8	9.9	8.3	9.3	9.3	9.5
2/10/2007-2/12/2007	3.6	5.4	4.5	5.2	5.0	5.3
6/9/2007-6/11/2007	25.5	31.1	28.6	29.2	28.8	29.4
7/21/2007-7/23/2007	26.4	33.5	30.6	30.6	30.7	30.4
8/21/2007-8/23/2007	27.8	32.7	30.8	30.9	31.4	31.1
9/29/2007-10/1/2007	23.2	27.1	25.6	25.9	25.9	25.8
10/26/2007-10/28/2007	10.5	16.2	15.7	15.4	16.2	15.7
11/29/2007-12/4/2007	6.3	10.6	9.9	9.5	9.8	9.9
12/28/2007-12/30/2007	0.9	5.5	5.0	5.0	5.4	4.8
1/26/2008-1/28/2008	9.0	8.0	7.1	6.5	8.4	7.0
2/27/2008-3/1/2008	10.7	11.7	11.2	11.7	11.0	11.8
3/20/2008-3/22/2008	14.1	17.0	16.5	16.0	16.5	16.5
Mean	**14.3**	**17.8**	**16.6**	**16.6**	**16.9**	**16.7**
Standard Deviation	**9.1**	**10.5**	**9.8**	**9.8**	**9.7**	**9.8**

Table 7. Mean DO for each monthly sampling period.

Sampling Period	Control	B	N	E	H
		DO (%)			
10/7/2006-10/9/2006	142	151	101	153	92
1/9/2007-1/11/2007	117	108	120	119	124
2/10/2007-2/12/2007	95	90	90	93	84
6/9/2007-6/11/2007	146	98	79	99	77
7/21/2007-7/23/2007	120	96	68	98	46
8/21/2007-8/23/2007	126	114	99	127	97
9/29/2007-10/1/2007	142	113	108	112	105
10/26/2007-10/28/2007	103	102	97	105	97
11/29/2007-12/4/2007	96	93	93	92	95
12/28/2007-12/30/2007	97	93	97	95	97
1/26/2008-1/28/2008	100	98	103	100	104
2/27/2008-3/1/2008	100	104	108	103	108
3/20/2008-3/22/2008	103	115	107	113	105
Mean	**114**	**106**	**98**	**108**	**95**
Standard Deviation	**19**	**16**	**13**	**17**	**19**

Table 8. Mean alkalinity for each monthly sampling period.

Sampling Period	Control	B	N	E	H
	Alkalinity (mg/L as $CaCO_3$ eq.)				
1/9/2007-1/11/2007	179	214	218	214	220
2/10/2007-2/12/2007	177	208	213	212	218
6/9/2007-6/11/2007	136	167	176	166	179
7/21/2007-7/23/2007	91	108	127	106	125
8/21/2007-8/23/2007	73	88	109	87	109
9/29/2007-10/1/2007	125	145	154	144	156
10/26/2007-10/28/2007	114	137	167	141	168
11/29/2007-12/4/2007	161	181	200	179	197
12/28/2007-12/30/2007	154	169	179	169	179
1/26/2008-1/28/2008	161	177	179	177	176
2/27/2008-3/1/2008	171	181	171	180	169
3/20/2008-3/22/2008	170	161	158	161	157
4/25/2008-4/27/2008	161	116	173	115	173
Mean	**144**	**158**	**171**	**158**	**171**
Standard Deviation	**34**	**38**	**30**	**38**	**31**

Table 9. Mean pH for each monthly sampling period.

Sampling Period	Control	B	N	E	H
	pH (s.u.)				
10/7/2006-10/9/2006	8.11	7.91	7.36	7.93	7.32
1/9/2007-1/11/2007	8.54	8.50	8.24	8.49	8.18
2/10/2007-2/12/2007	8.05	8.00	7.99	8.04	7.92
6/9/2007-6/11/2007	8.89	7.83	7.71	7.77	7.60
7/21/2007-7/23/2007	8.72	8.16	7.70	8.27	7.63
8/21/2007-8/23/2007	8.74	8.23	7.97	8.39	7.73
9/29/2007-10/1/2007	8.52	7.70	7.45	7.57	7.51
10/26/2007-10/28/2007	8.17	7.62	7.36	7.66	6.85
11/29/2007-12/4/2007	7.62	7.52	7.54	7.58	7.31
12/28/2007-12/30/2007	8.13	8.19	8.28	8.13	8.23
1/26/2008-1/28/2008	7.98	7.99	8.20	7.90	8.18
2/27/2008-3/1/2008	7.85	7.85	8.07	7.92	7.92
3/20/2008-3/22/2008	8.16	8.18	8.17	8.19	8.13
Mean	**8.27**	**7.98**	**7.85**	**7.99**	**7.73**
Standard Deviation	**0.38**	**0.28**	**0.34**	**0.30**	**0.42**

Table 9. Median DOC and DTN from monthly sampling.

	Control	B	N	E	H
	mg/L				
DOC	15.4	14.1	15.6	14.3	15.5
DTN	1.05	0.91	1.11	0.96	0.93

Discussion

EFVM have promising passive AMD treatment applications. For example, organic carbon availability and temperature influence the effectiveness of vertical flow bioreactors (VFB), which are also known as reducing and alkalinity producing systems (RAPS) or successive alkalinity producing systems (SAPS). VFB generally consist of a layer of limestone with drainage piping overlain by organic material with a ponded depth of approximately 1 m overtop (Watzlaf et al., 2004). Influent flows vertically down through the water column, organic matter, and limestone sequentially. The organic material in VFB serves to deplete oxygen and fuel sulfate reduction, which generates alkalinity and removes metals from solution. The limestone generates yet further alkalinity. VFB are typically followed by oxidation ponds where Fe or Mn can be optimally removed from the buffered solution.

Several studies have shown a sulfate reduction rate decline over time in treatment cells that rely on organic matter oxidation (Drury, 2000; Chang et al., 2000; Gibert et al., 2003; Eger and Wagner, 2003). VFB treatment efficiency decreases with age before organic carbon sources are fully depleted as the supply of short chain organics decreases and supplemental carbon is currently introduced to address this issue (Eger and Wagner, 2003; Kalin et al., 2006). *Typha* spp. and *Juncus effusus* contribute labile dissolved organic carbon to their surroundings during senescence or via root exudates which can be readily used by sulfate reducing bacteria and fermenters, key consortia of VFB (Mann and Wetzel, 1996; Johnson and Hallberg, 2002).

Emergent macrophytes are among the most productive plant communities worldwide (Mitsch and Gosselink, 2000) and Eger and Wagner (2003) suggest that decaying wetland plants could provide a renewing carbon source to VFB. Batty and Younger (2007) showed that wetland plant litter in AMD treatment systems can be a key source of organic and inorganic nutrients to bacterial populations, even under conditions of depressed pH (6.5-3.0). *Typha latifolia* productivity ranged from 0.76 to 2.7 kg dry wt m^{-2} yr^{-1} in data compiled by Cronk & Fennessy

(2001). Average *Juncus effusus* productivity is similar (Mitsch and Gosselink, 2000). However, *Typha* spp. productivity is reported to be roughly halved in wetlands receiving mine drainage (Mitsch & Jorgensen, 2004). Neculita et al. (2007) note optimal VFB field conditions at 0.3 mol SO_4/m^3-d and this comports well with data from Dvorak et al. (1992) and McCauley et al. (2009). In sulfate reduction, for each mole of SO_4^{2-} reduced, two moles of C are required (Neculita et al., 2007). From samples of *Typha* spp. at an AMD passive treatment system, it was determined that 90% of dry wt. is organic matter (Nairn, unpublished data). By halving the productivity of the range noted by Cronk and Fennessy (2001), applying the approximation from Mitsch and Gosselink (2000) that approximately 50% of the dry wt. of organic matter is C with the percent organic matter from Nairn (unpublished data) it was calculated that EFVM in AMD could provide 0.04-0.14 mol C/m^2-d of the 0.6 C/m^2-d that an optimally functioning VFB of 1 m substrate depth would require. EFVM as productive as *Typha* spp. in optimal growth settings could, in theory, fix half the C required by VFB.

Aside from the organic matter contributions, EFVM ability to increase alkalinity, promote of reducing conditions, and temperature insulating effects could be a welcome addition to VFB. Passive AMD treatment systems, such as VFB, require strategies to limit the impact of low ambient temperatures (Heal and Salt, 1999; Johnson and Hallberg, 2002; Watzlaf et al., 2004; Champagne et al., 2005; Gusek, 2005), especially in extreme latitudes or higher elevations. The results suggest that in a colder climate, EFVM would insulate the underlying water column and substrate from the cooler temperatures that often limit the preferential biogeochemical reactions central to VFB performance. VFB sizing is often based on the conservative expected cold-weather removal/processing rates. The insulative effects of EFVM could inhibit bacterial activity during warmer periods when activity may otherwise be unnecessarily elevated, consuming more substrate than is needed and producing excess hydrogen sulfide gas, which can be a nuisance odor and environmental toxin. The reduction of the water column by EFVM would allow more of the organic substrate’s vertical profile to be allocated to sulfate reduction, other than oxygen stripping, which could increase sulfate reduction and therefore alkalinity production and metal removal rates. Continual additions of organic matter and nutrients from the EFVM to the VFB would help renew essential labile substrate. Increased sulfate reduction and hence alkalinity production before VFB waters contact the underlying limestone could decrease the reliance on limestone for alkalinity production, enabling cost-savings. All these factors would combine to increase the lifetime, efficiency, and overall sustainability of VFB while decreasing necessary land footprint and seasonal odors with an aesthetically pleasing addition of floating emergent wetland vegetation.

Another possible use for EFVMs may be to condition mildly AMD-impacted waters with dissolved and particulate organic material to encourage metals complexation with organic matter. According to the Biotic Ligand Model, this would decrease the toxicity of various ecotoxic metals (Paquin et al., 2000). In this application, EFVMs may remove metals from solution by metals complexation with particulate organic matter.

However, there is the possibility of creating a wildlife attraction that may increase exposure to whatever ecotoxic constituent is present. Floating islands are an attractive habitat for many species (van Duzer, 2004). For example, in Minnesota, floating *Typha* spp. mats are prime nesting substrate for Red-necked Grebes (*Podiceps grisegena*) because of their isolation from predators (Nuechterlein et al., 2003). However, overall the selection of *Typha* spp. should decrease the chance of biomagnification because it is of limited value to wildlife when compared to many other macrophyte species (Mitsch & Jorgensen, 2004).

Conclusions

Results indicate that EFVM are a suitable ecological engineering tool for influencing water quality and temperature that may have a wide variety of applications. EFVM can encourage more reducing conditions in the underlying water column with greater alkalinity as well as provide insulation from extreme temperatures. EFVM performance can likely be enhanced by employing more intensive planting media, joined rhizomal plantings, and stronger more buoyant frames than those presented in this study. Future studies should investigate incorporation of EFVM into VFB for AMD treatment and other applications where organic-rich, thermally insulated, and reducing conditions are advantageous. Pilot studies to investigate the possibilities of passively treating the constituents listed in the previous paragraph are also suggested. Testing EFVM over flow-through systems is necessary to determine the rate at which EFVM can alter the underlying water column.

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