THE USE OF BENCH SCALE PERMEAMETERS FOR PRELIMINARY OF METAL REMOVAL FROM ACID MINE DRAINAGE BY WETLANDS[1]

by

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Abstract. Water drainage from abandoned mines in the Central City-Idaho Springs mining district has impacted the water quality of Colorado front-range water systems. To determine metal removal from mine drainage, permeameters with a high-alkalinity organic substrate were designed to operate in downflow and upflow configurations. Mine drainage from the National and Quartz Hill Tunnels were used in the permeameter testing. Initial flow rates were 10 mL/min and 1 mL/min for the National and Quartz Hill Tunnel drainages, respectively. Both drainages were tested in 3 parallel cells under varying initial conditions. One cell was initially dry, 1 was soaked with water for 1 week to attain anaerobic conditions, and 1 was soaked with water for 1 week and inoculated with established wetland substrate containing sulfate-reducing bacteria. Results indicate an increase of water pH from 5.6 to 7.7 and 2.5 to 7.4 at National and Quartz Hill Tunnels, respectively. Metal removal occurred within all cells for both drainages. The National Tunnel drainage contains metal levels of approximately 42 ppm Fe, 19 ppm Mn, 1 ppm Cu, and 7 ppm Zn. Removal of metals was over 95 %. The Quartz Hill Tunnel drainage contains metal levels of approximately 700 ppm Fe, 80 ppm Mn, 60 ppm Cu, and 140 ppm Zn. Results showed metal removal of over 99 %. Loading rates ranged from 2.1 to 3.8 grams per day per square meter (gdm^2) for the National Tunnel and 4.2 to 6.3 gdm^2 for the Quartz Hill Tunnel. Results indicate that bench scale permeameters can be used to evaluate metal removal from mine drainage and to attain design criteria for larger scale wetlands.

Additional Key Words: acid mine drainage, constructed wetland, wetland design, heavy metals remediation

Introduction

In the design of a wetland treatment system for mine drainage, various stages of experimentation can be performed to determine design criteria (Reynolds 1991). Lab analysis of microorganism activity has been successful for studying wetland treatment at the Big Five Tunnel mine drainage in Idaho Springs (Batal 1989, Machemer 1990, Reynolds 1991, Wildeman & Laudon, 1989). Bench scale permeameters were used to evaluate the hydraulic conductivity of specific substrates at the Big Five wetland and were found to be predictive of pilot scale operations (Lemke 1989). From evaluation of metal removal data, loading rates can be determined which provide design criteria for a treatment system (Hedin 1990, Wildeman 1990, Reynolds, 1991).

To evaluate mine drainages in the Central City-Blackhawk area, a part of the Idaho Springs-Central City Superfund area, bench scale permeameters were designed to evaluate metal removals, change in pH,

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system configuration, initial substrate conditions, and substrate loading rates.

The drainages chosen for analysis flowed from the National Tunnel and the Quartz Hill Tunnel. Both represent 2 completely different types of mine drainage in the Central City district (Wildeman 1974). Characteristics of the National Tunnel drainage are a slightly acidic pH of 5.6 and metal concentrations similar to that of the Big Five tunnel. Preliminary metal concentrations for iron, manganese, copper, and zinc were 42, 19, 0.18, and 7 ppm, respectively. Due to the pH, a significant problem with precipitation of iron hydroxide exists. The Quartz Hill Tunnel drainage represents the extremes of acid mine drainage for the area. The pH ranges from 2.3 to 2.7, while metal concentrations are comparatively high. The preliminary metal concentrations for iron, manganese, copper and zinc were 920, 63, 77, and 91 ppm, respectively.

The objectives were: 1) to evaluate metal removal efficiencies and the change in pH over time, 2) to evaluate an upflow configuration compared to a downflow configuration, 3) to evaluate the system by varying initial substrate conditions, and 4) to determine loading rates.

Materials and Methods

The permeameters for this study were constructed of 32 gallon plastic garbage cans fitted with PVC pipe and designed to operate without valve control in both upflow and downflow configurations. Flowrates were adjusted by raising or lowering the output level. Consideration was made for iron hydroxide clogging, adjustability of flowrates, and limited maintenance. Figure 1 is a diagram of the permeameters in the downflow configuration. Further details of the design and operation of this experiment are described in a report by Bolis and Wildeman (1990).

The permeameters for evaluation of the National Tunnel and Quartz Hill Tunnel mine drainages were setup in the field and in the lab, respectively. At each site, 3 downflow permeameters were setup and designated as Cell A, Cell B, and Cell C. Cell A contained the standard substrate and was considered to be a dry cell. This cell was not soaked or inoculated. Cell B contained the standard substrate and was soaked with city water for 1 week prior to operation. Cell C, which contained the standard substrate, was soaked for one week prior to operation, and was inoculated with substrate containing sulfate reducing bacteria from the Big Five constructed wetland (Batal 1989).

Previously, mushroom compost had been utilized as substrate at the Big Five constructed wetland (Batal 1989). After titrating the mixture with HCl, it was concluded that it may not provide sufficient buffering capacity for both mine drainages. The permeameter substrate selected was composed of cow manure and planter soil in a 3:1 ratio to provide a soil pH of approximately 8.7.

The permeameters at the National Tunnel were located near the adit with a PVC pipe running mine drainage to the system. A trough system was designed to feed mine drainage into each permeameter with both the trough and permeameters having an overflow system. Water was hauled from the Quartz Hill Tunnel site to the lab in 50 liter carboys. Each cell had an individual reservoir for mine drainage and an overflow system. Each permeameter had at least 1 inch depth of standing water on top of the substrate at all times.

Operation of both sites began in June 1990 and continued through October 1990. Cell A was changed from a downflow configuration to an upflow configuration at the end of 2-months operation at both sites. Fresh inoculated substrate was added to the permeameter and the flow direction was reversed and operated for approximately 2 months. At both sites, it was necessary to make regular checks on the system to adjust the permeameter flowrates, check the mine drainage, and rid the system of any iron hydroxide clogging.

The permeameters were operated at approximately 10 mL/min for National Tunnel and 1 mL/min for Quartz Hill Tunnel. The flowrates of the permeameters were determined by evaluating metal removal rates of the Big Five pilot treatment system in Idaho Springs, CO. The Big Five wetland operates at about 1/8 gpm/100 ft^2 and has shown to remove metals effectively (Wildeman 1990).

The heavy-metal concentration of the National Tunnel is approximately equal to that of the Big Five Tunnel. Table 1 shows a total of Fe, Mn, Cu, and Zn to be between 80 and 90 ppm for both drainages. Therefore, utilizing an effective flowrate of 1/8 gpm/100 ft^2, and a surface area of 0.204 m^2 for the permeameter, a new flowrate was calculated. The flowrate for the National Tunnel was determined to be approximately 10.0 mL/min.

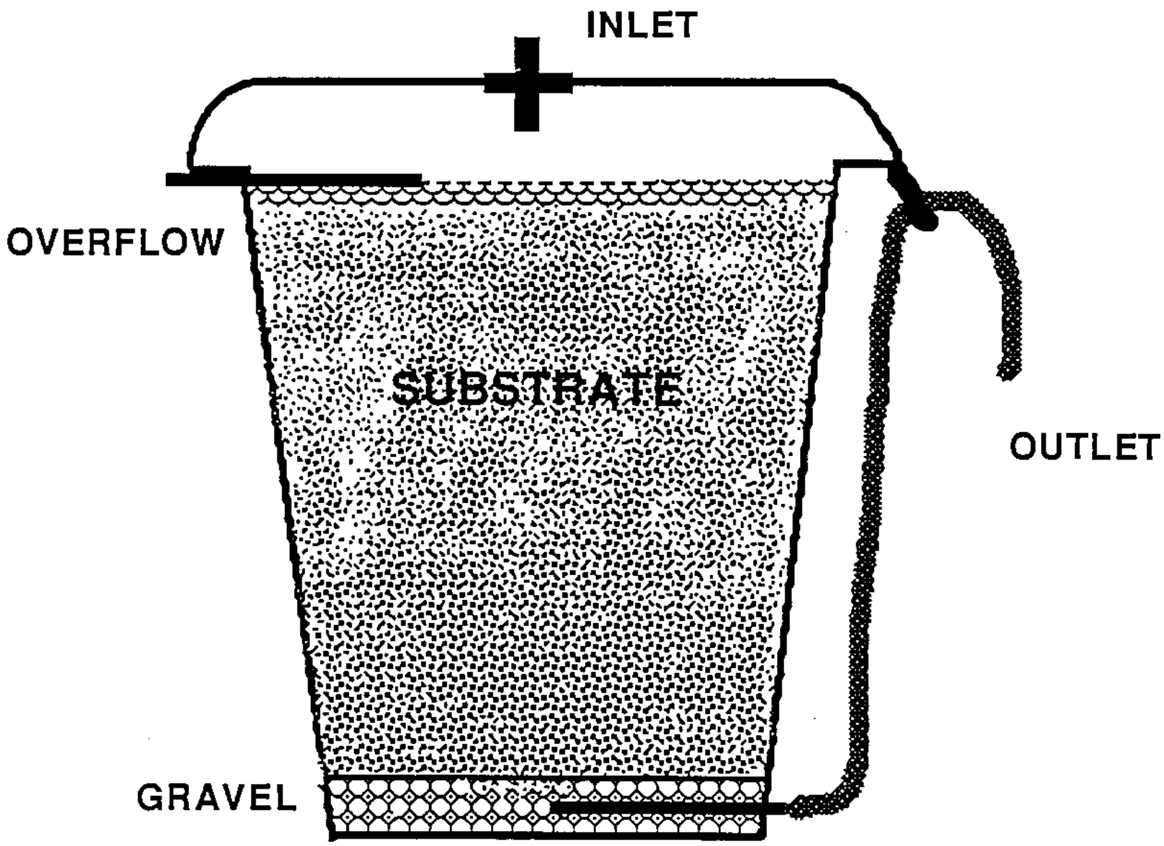


Figure 1. Typical bench scale wetland module in downflow configuration.

Table 1. Concentrations of Metals in Mine Drainage (ppm)

	Big Five	National Tunnel		Quartz Hill Tunnel	
	June, 1990	June, 1973	June, 1990	June, 1973	June, 1990
Eh	700	450	420	450	720
pH	3.0	4.6	5.8	2.6	2.7
Fe	50	50	42	820	920
Mn	32	28	19	80	63
Cu	0.9	1.4	.18	70	77
Zn	10	11	7	130	91

Similarly, the Quartz Hill Tunnel heavy-metal concentration is about 1060 mg/L as shown in Table 1. By comparing these concentrations with those of the Big Five and National Tunnel, the flowrate was reduced by a factor of 10. Therefore, a flowrate of 1 mL/min was selected for Quartz Hill permeameters.

Water sampling and field measurements were done on a weekly basis for the first 10 weeks of the experiment. The schedule was changed to bimonthly sampling when Cell A was changed to the upflow configuration. During sampling, water was filtered and treated with HNO_3. Duplicates of both the mine drainage and the cell outputs were taken on a regular basis. The results of the duplicates were averaged with the original sample for reporting. The Quartz Hill Tunnel mine drainage was sampled in the field and in the lab. There were no significant changes in the measurements of the metal concentrations. These values were averaged for data reporting.

The metal analyses for this project were done by flame atomic absorption and sulfate determinations were made gravimetrically by precipitation of $BaSO_4$.

Results

Tables 2 and 3 show the concentrations of mine drainage influent and permeameter effluent for the National and Quartz Hill Tunnels, respectively. Included in these tables are the percentages of the decrease in the metal concentrations for each permeameter relative to the mine drainage. Also included are the sulfate concentrations, pH's, and the effluent flowrates of each permeameter.

From the metal removal data in Tables 2 and 3, area-adjusted loading rates can be determined (Hedin 1990). Table 4 shows the area-adjusted removal rates for the National Tunnel and Quartz Hill Tunnel mine drainages. Ranges and averages are provided for both iron concentration and total metal concentrations in grams per day per square meter (gdm^2). The following calculation is performed to determine the loading rates (Hedin 1990):

$$\text{Rate} = ([M_{md}] - [M_{cell}])(Q)(CF)/A$$

where:

[M]	=	concentration of metal
md	=	mine drainage
cell	=	permeameter cell effluent
Q	=	flow rate of mine drainage into permeameter
CF	=	conversion factor of 1440 min/day
A	=	area of permeameter = 0.204 m^2

As shown in Table 4, the metal removal rates for the National Tunnel range from 3.0 to 6.0 gdm^2 with an average of 4.3 gdm^2. The average flow for the National Tunnel permeameters was 10 mL/min. The metal removal rates for the Quartz Hill Tunnel range from 5.4 to 8.5 gdm^2 with an average of 6.7 gdm^2. The average flow for the Quartz Hill Tunnel permeameters was 1 mL/min.

Discussion

The pH of the mine drainage and cell output for the National and Quartz Hill Tunnels are shown in Figure 2 for the 19-weeks of experimentation. The pH of the National Tunnel permeameter effluents parallel the fluctuations of the mine drainage from 5.2 to 5.8. The effluent pH's are maintained between 7.0 and 8.0 during the initial 4 weeks of experimentation. However, as the National flowrates cells were varied after week 6, to 2- and 3-times the original flow of 10 mL/min, the pH's show an overall decrease. Between weeks 9 and 13, Cell A was changed from downflow to upflow configuration and the cell maintained a higher pH for about 4-weeks.

For the Quartz Hill Tunnel, as the mine drainage pH fluctuated from 2.3 to 2.8, the permeameter effluent pH ranged from 6.2 to 8.2. An overall decline in pH occurred during the 19 weeks from around 8.0 to 6.5. In later weeks, the flowrate for Cells B and C, was increased from the established rate of 1 mL/min to 2-3 mL/min. After Cell A was changed from a downflow to upflow configuration in week 13, the effluent pH was approximately the same as Cells B and C.

By comparing the pH fluctuations at both sites, the start-up conditions of dry, soaking with water and inoculation show minor variation. Also, comparing the pH change in the upflow and downflow configurations show few differences.

The comparison of iron concentrations in the mine drainage and permeameter effluent for the National Tunnel and Quartz Hill Tunnel is shown in Figure 3. Cells B and C of National Tunnel had a slower start-up removal rate of about 5 to 7 weeks than Cell A. However, in week 13, as Cell A was changed to an upflow configuration, the removal was similar to Cells B and C in weeks 1-6. Note that the upflow Cell A was inoculated while downflow Cell A was not, perhaps indicating that the inoculin impedes immediate iron

Table 2. National Tunnel concentrations of mine drainage and permeameter output in mg/L, flowrate in mL/min.

	Cu	% dec.	Fe	% dec.	Mn	% dec.	Zn	% dec.	SO_4^{2-}	pH	flow rate
Week 1											
MD	.45		50.3		20.5		8.8		938	5.7	
Cell A	--		--		--		--		--	--	
Cell B	.3	33.3	4.7	90.6	1.1	94.6	.6	93.2	3260	7.4	--
Cell C	.2	55.5	13.9	72.4	1.6	92.2	.4	95.5	1200	7.0	--
Week 2											
MD	.2		40.9		20.3		8.2		899	5.2	
Cell A	.05	97.5	.8	98.0	.9	95.6	.05	99.4	871	7.2	38
Cell B	.2	--	18.8	54.0	1.5	92.6	.5	93.9	825	7.3	7.5
Cell C	.05	75.0	5.9	85.6	1.4	93.1	.2	97.6	462	7.0	7.5
Week 3											
MD	.3		44.0		20.3		8.5		935	5.4	
Cell A	.05	98.3	2.1	95.3	11.0	45.8	0.5	94.1	906	6.6	25
Cell B	.08	73.3	14.7	66.6	1.6	92.1	.3	96.5	341	7.5	10
Cell C	.05	98.3	4.3	90.2	1.9	90.6	.2	97.6	86	7.7	2
Week 4											
MD	.2		39.3		20.8		8.5		926	5.9	
Cell A	.05	75	2.6	93.4	12.4	40.4	.05	99.4	871	7.7	30
Cell B	.05	75	11.1	71.8	1.6	92.3	.2	97.6	197	7.7	15
Cell C	.05	75	2.5	93.6	1.3	93.8	.08	99.1	106	7.7	--
Week 5											
MD	.4		42.5		21.6		8.4		947	5.5	
Cell A	.05	87.5	2.4	94.4	14.0	35.2	.08	99.0	687	7.4	22
Cell B	.07	82.5	7.4	82.6	1.3	94.0	.2	97.6	47	7.3	1
Cell C	--		--		--		--		--	--	-
Week 6											
MD	.3		41.4		21.0		8.4		936	5.6	
Cell A	.05	83.3	1.4	96.6	17.0	19.0	.07	99.2	778	6.7	25
Cell B	.05	83.3	3.6	91.3	.7	96.7	.1	98.8	417	7.3	15
Cell C	.05	83.3	.7	98.3	1.9	91.0	.06	99.3	710	6.8	1
Week 7											
MD	.3		41.6		19.0		8.0		936	5.4	
Cell A	.05	83.3	2.2	94.7	14.1	25.8	.06	99.2	738	7.1	15
Cell B	.07	76.7	2.1	95.0	.8	85.8	.1	98.8	272	7.0	9
Cell C	.05	83.3	.6	98.6	1.8	90.5	.04	99.5	804	7.0	5
Week 9											
MD	.2		34.1		20.0		8.4		--	5.5	
Cell A	.05	97.5	2.0	94.1	18.5	7.5	.1	98.8	--	6.7	19
Cell B	.05	97.5	1.3	96.2	8.7	56.5	.05	99.4	--	7.0	38
Cell C	.05	97.5	1.2	96.5	7.9	60.5	.05	99.4	--	6.4	24

Table 2. (continued) National Tunnel concentrations of mine drainage and permeameter output in mg/L, flowrate in mL/min.

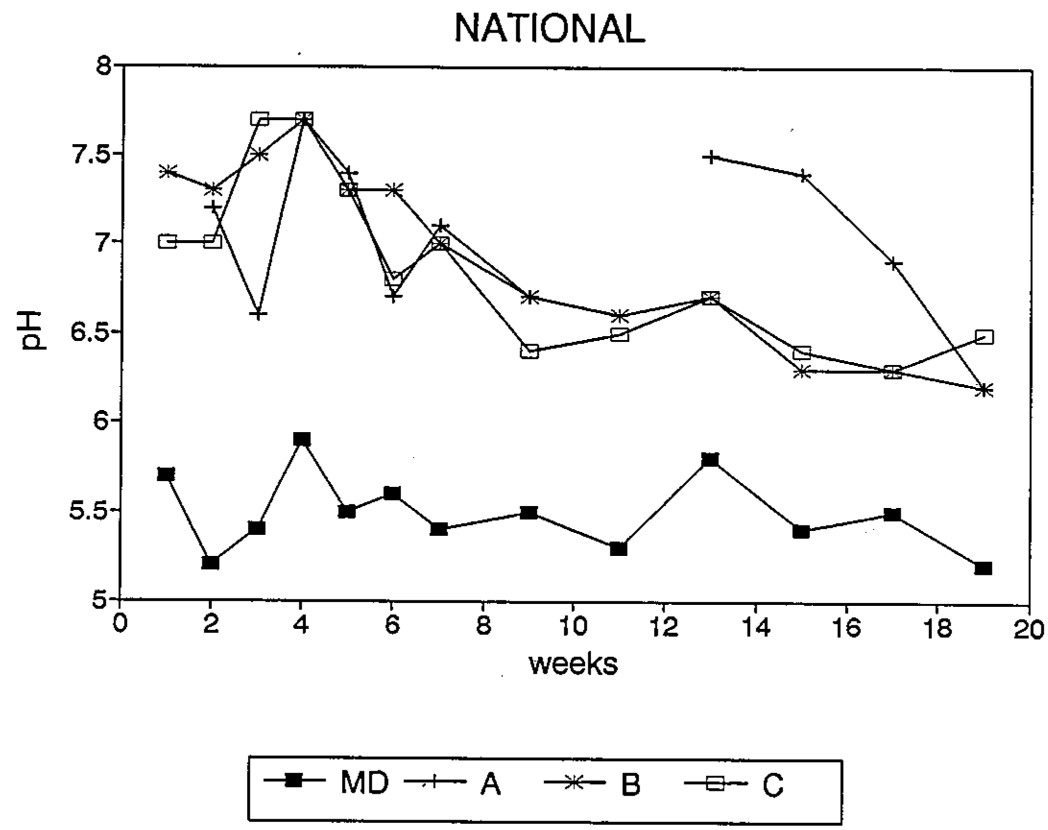
	Cu	% dec.	Fe	% dec.	Mn	% dec.	Zn	% dec.	SO_4^{2-}	pH	flow rate
Week 11											
MD	.2		39.9		21.8		8.9		995	5.3	
Cell A	--		--		--		--		--	--	
Cell B	.07	65	1.5	96.2	17.2	21.1	.1	98.9	941	6.6	130
Cell C	.05	75	.1	99.7	13.7	37.2	.01	99.9	873	6.5	35
Week 13											
MD	.2		41.9		22.8		9.1		772	5.8	
Cell A	.05	75	7.4	82.3	1.5	93.4	.5	94.5	1317	7.5	12
Cell B	.07	65	.2	99.5	16.0	29.8	.07	99.2	923	6.7	--
Cell C	.05	75	.1	99.8	17.8	21.9	.2	97.8	908	6.7	20
Week 15											
MD	.1		42.3		23.1		7.9		860	5.4	
Cell A	.08	20	5.5	87	.3	98.7	.3	96.2	664	7.4	7
Cell B	.05	50	--		--	--	.3	96.2	--	6.3	30
Cell C	.05	50	.3	99.3	13.1	43.3	.01	99.9	507	6.4	26
Week 17											
MD	.1		54.8		24.8		9.5		1027	5.5	
Cell A	.3	--	2.9	94.7	.4	98.4	.1	98.9	752	6.9	9
Cell B	.05	50	1.5	97.3	18.6	25	.07	99.3	929	6.3	24
Cell C	.05	50	.3	99.5	13.1	47.2	.01	99.9	507	6.4	30
Week 19											
MD	.08		49.2		24.4		9.0		1010	5.2	
Cell A	.05	62.5	2.9	94.1	2.6	89.3	.4	95.5	1001	6.2	43
Cell B	.05	62.5	.05	99.9	3.4	86.1	.05	99.4	--	6.2	42
Cell C	.05	62.5	.2	99.6	18.8	23.0	.04	99.6	922	6.5	24

Table 3. Quartz Hill concentrations of mine drainage and permeameter output in mg/L, flowrate in mL/min.

	Cu	% dec.	Fe	% dec.	Mn	% dec.	Zn	% dec.	SO_4^{2-}	pH	flow rate
Week 1											
MD	55.7		672		82.5		136.2		4340	2.7	
Cell A	--		--		--		--		--	--	
Cell B	.3	99.5	7.6	98.9	1.5	98.2	.5	99.6	2410	6.9	.7
Cell C	.2	99.6	15.3	97.7	2.9	96.5	.4	99.7	1300	6.5	--
Week 2											
MD	56.2		666		84.2		141.6		4380	2.6	
Cell A	.4	99.3	8.7	98.7	1.4	98.3	.9	99.4	515	8.6	.9
Cell B	.3	99.5	6.8	99.0	1.7	98.0	.6	99.6	188	7.9	.7
Cell C	.1	99.8	4.8	99.3	1.7	98.0	.2	99.9	109	8.2	.7
Week 3											
MD	56.2		680		84.9		143.2		4300	2.6	
Cell A	.3	99.5	2.6	99.6	1.5	98.2	.6	99.6	280	7.5	1.0
Cell B	.12	99.8	4.5	99.3	1.4	98.4	.3	99.8	520	7.4	1.4
Cell C	.05	99.9	3.8	99.4	1.4	98.4	.1	99.9	237	7.3	1.2
Week 4											
MD	47.5		636		79.4		132.6		4190	2.4	
Cell A	.06	99.9	1.6	99.7	.9	98.9	.3	99.8	450	7.4	1
Cell B	.05	99.9	1.9	99.7	.9	98.9	.2	99.8	773	7.5	1.1
Cell C	.05	99.9	1.0	99.8	1.0	98.7	.2	99.8	412	7.4	.8
Week 5											
MD	54		681		78.2		138.0		4280	2.3	
Cell A	.05	99.9	1.2	99.8	.7	99.1	.2	99.9	640	7.5	.6
Cell B	.05	99.9	1.3	99.8	.7	99.1	.2	99.9	812	7.3	.9
Cell C	.05	99.9	.8	99.9	.8	99.0	.2	99.9	306	7.3	.3
Week 7											
MD	48.4		626		78.2		133.3		4300	2.5	
Cell A	.05	99.9	.9	99.9	1.0	98.8	.2	99.9	1080	7.2	1
Cell B	.05	99.9	1.0	99.8	.6	99.2	.2	99.8	660	7.4	.9
Cell C	.05	99.9	.5	99.9	1.6	98.0	.1	99.9	1180	7.2	.9
Week 9											
MD	55.2		628		78.8		160		3800	2.7	
Cell A	.05	99.9	.46	99.9	1.5	98.1	7.4	95.4	1312	7.1	1.3
Cell B	.05	99.9	.43	99.9	.5	99.4	9.1	94.3	995	7.3	1.4
Cell C	.05	99.9	.3	99.9	3.5	95.5	5.2	96.8	1332	6.9	1.4
Week 11											
MD	69.8		806		70.5		101.5		3992	2.9	
Cell A	--		--		--		--		--		--
Cell B	.05	99.9	--		.5	99.3	.2	99.8	1067	8.0	.6
Cell C	.05	99.9	--		1.6	97.7	.3	99.7	556	7.9	.7

Table 3. (continued) Quartz Hill concentrations of mine drainage and permeameter output in mg/L, flowrate in mL/min.

	Cu	% dec.	Fe	% dec.	Mn	% dec.	Zn	% dec.	SO_4^{2-}	pH	flow rate
Week 13											
MD	63.5		900.5		82.1		167.9		3829	2.6	
Cell A	.08	99.9	3.0	99.7	.9	98.9	.5	99.7	732	7.5	.4
Cell B	.05	99.9	.3	99.9	1.4	98.3	.2	99.9	1006	7.3	.5
Cell C	.05	99.9	.3	99.9	3.7	95.5	.2	99.9	725	7.2	.6
Week 15											
MD	57.1		692		76.8		159.1		3090	2.5	
Cell A	.4	99.3	3	99.6	.9	98.8	.5	99.7	1777	7.7	.9
Cell B	.05	99.9	.1	99.9	8.5	88.9	.2	99.9	2842	7.0	1.5
Cell C	.05	99.9	.1	99.9	15.7	79.6	.1	99.9	2929	6.8	1.7
Week 17											
MD	54.4		702.9		79.7		177.4		4027	2.5	
Cell A	.04	99.9	1.8	99.7	.6	99.2	.4	99.8	2207	7.7	.7
Cell B	.05	99.9	3.3	99.5	22.0	72.4	.2	99.9	3342	6.6	2.4
Cell C	.24	99.6	--		--		.1	99.9	3089	6.4	2.9
Week 19											
MD	59		633.8		95.9		190		3438	2.3	
Cell A	.26	99.6	1.6	99.7	1.2	98.7	.1	99.9	3430	7.1	1.2
Cell B	.6	98.9	119.2	82.2	58.9	38.6	.1	99.9	3574	6.4	2.1
Cell C	.8	98.6	38.5	93.9	50.5	47.4	.1	99.9	3340	6.4	1.5



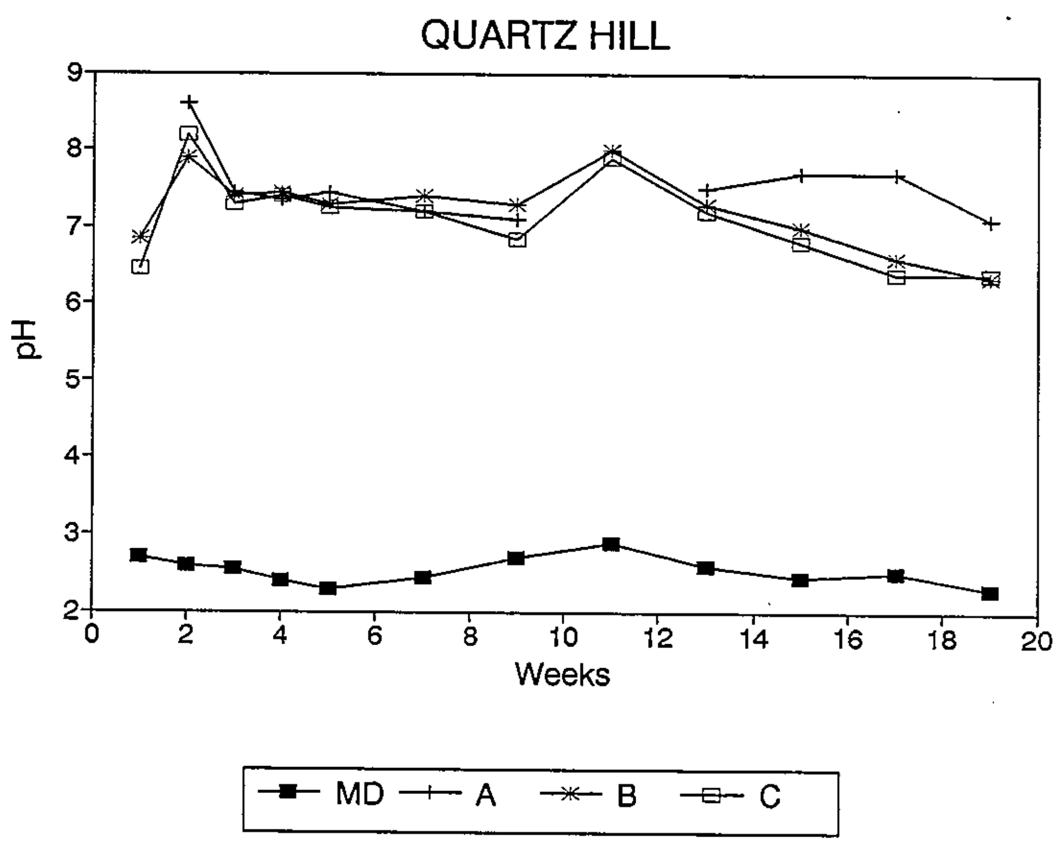


Figure 2. pH of mine drainage and permeameter effluents for National Tunnel and Quartz Hill Tunnel.

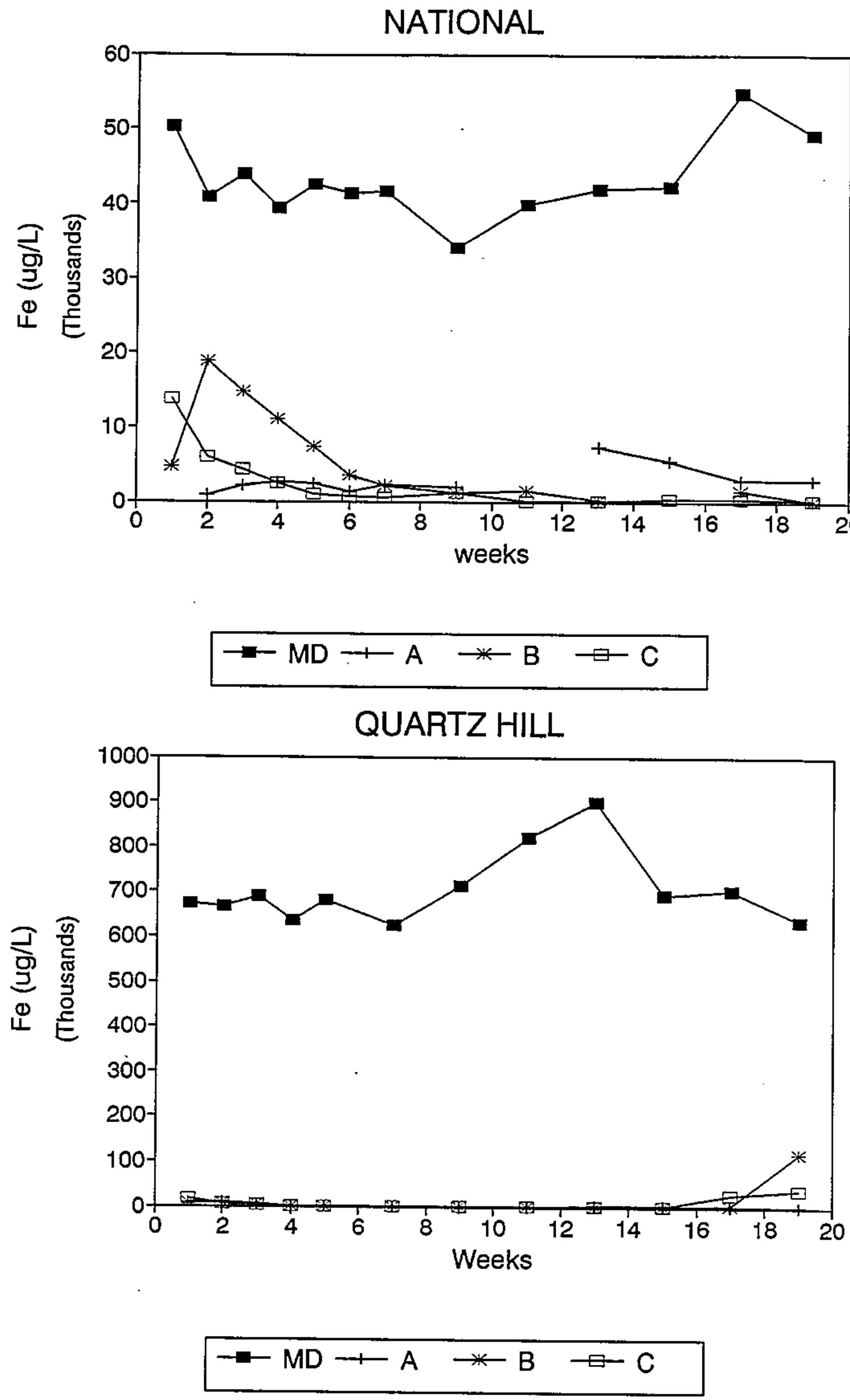


Figure 3. Iron content of mine drainage and permeameter effluents for National Tunnel and Quartz Hill Tunnel.

removal. However, the inoculated and soaked permeameters are expected to work better. This difference in removal may be due to the National Tunnel permeameters being on-site in the field. During the first 4-weeks, flows were found to be quite variable and the removal may have been affected.

Quartz Hill Tunnel iron-removal data shows nearly 100 % removal of iron from all 3 cells during the experimentation. Variations of the flowrate of 1 mL/min showed no apparent effect on the removal of iron. Again, no significant changes are shown by varying substrate conditions and direction of flow. The consistency of this removal pattern, compared with the removal of iron from the National Tunnel permeameters, may be due to the experiments being run in the laboratory and the flows were monitored daily for the first 4 weeks.

Figure 4 shows a comparison of the removal of manganese for the field experiment at the National Tunnel and the lab experiment for the Quartz Hill Tunnel. As the other figures have illustrated, the fluctuations of metal removal in the field are much greater than the lab experiment. For Cells B and C, the removal of manganese from the National Tunnel water was high in the first 7 weeks of the experiment, while it was poor from Cell A. This may be attributed to the variation in the flowrate of Cell A early in the experiment. After week 7, the decrease in the removal of manganese from Cells B and C may be due to the increased flowrate of the system. Note that in week 13, the upflow configured Cell A shows high removal of manganese. The reason for manganese variability in the National Tunnel permeameters is uncertain. However, Machemer and Wildeman (1991) found that Mn can be removed by adsorption onto the substrate in the early stages of wetland operation. After about 8 weeks, when the substrate sites are saturated, Mn concentration in the effluent increases.

Manganese removal for Quartz Hill Tunnel mine drainage was much more consistent. It averaged over 95 % until week 13 when Cells B and C show an apparent decrease. This is best attributed to the increase in permeameter flowrate, which causes a drop in effluent pH, or to the sorption site being saturated by Mn. The change of Cell A to an upflow configuration shows consistent manganese removal for the remaining 6 weeks. Again, this cell was soaked and inoculated and can be compared with Cell C.

For other heavy metals, the National Tunnel permeameter effluent data indicate nearly 4 weeks is needed to attain a less-than detection limit for copper as shown in Tables 2 and 3. The copper removal tended to vary with the amount of copper in the mine drainage. Despite fluctuations in the Quartz Hill Tunnel mine drainage, copper removal was near 100% for the entire 19 weeks. Zinc removal from both mine drainages was very effective, as shown in Tables 2 and 3. The data show no apparent differences between the dry, soaked, and inoculated cells, as well as between the upflow and the downflow configurations.

Summary

The conditions of the lab were much more favorable than the field for testing due to weather and maintenance problems. The variation in the soaked and inoculated substrate may only be apparent in the iron and manganese removals of the National Tunnel mine drainage. The dry substrate initiated high iron removal immediately, while the soaked and inoculated substrate initiated manganese removal immediately. Both the upflow and downflow configurations showed equally effective removal of metals and increase in pH.

As shown with both drainages, an increase in the flowrate will cause a decrease in the overall pH of the effluent. Total metal removal of Quartz Hill Tunnel mine drainage was not as sensitive to the flowrate change as the National Tunnel mine drainage. Removal of copper, iron, manganese, and zinc from the mine drainages was nearly 100 % throughout the experiment. The exception was manganese removal, which declined in the last 8 weeks. Declines in manganese removal may be explained by an increase in flowrate, decline in pH, and overloading of the system. The flowrates of 10 mL/min for National Tunnel and 1 mL/min for Quartz Hill Tunnel were sufficient to insure an increase in pH and attain a high metal removal.

Finally, loading rates of the substrate were determined. Metal removal rates for the National Tunnel permeameters range from 3.0 to 6.0 gdm^2, with an average of 4.3 gdm^2. The Quartz Hill Tunnel permeameter metal removal rates range from 5.4 to 8.5 gdm^2, with an average of 6.7 gdm^2.

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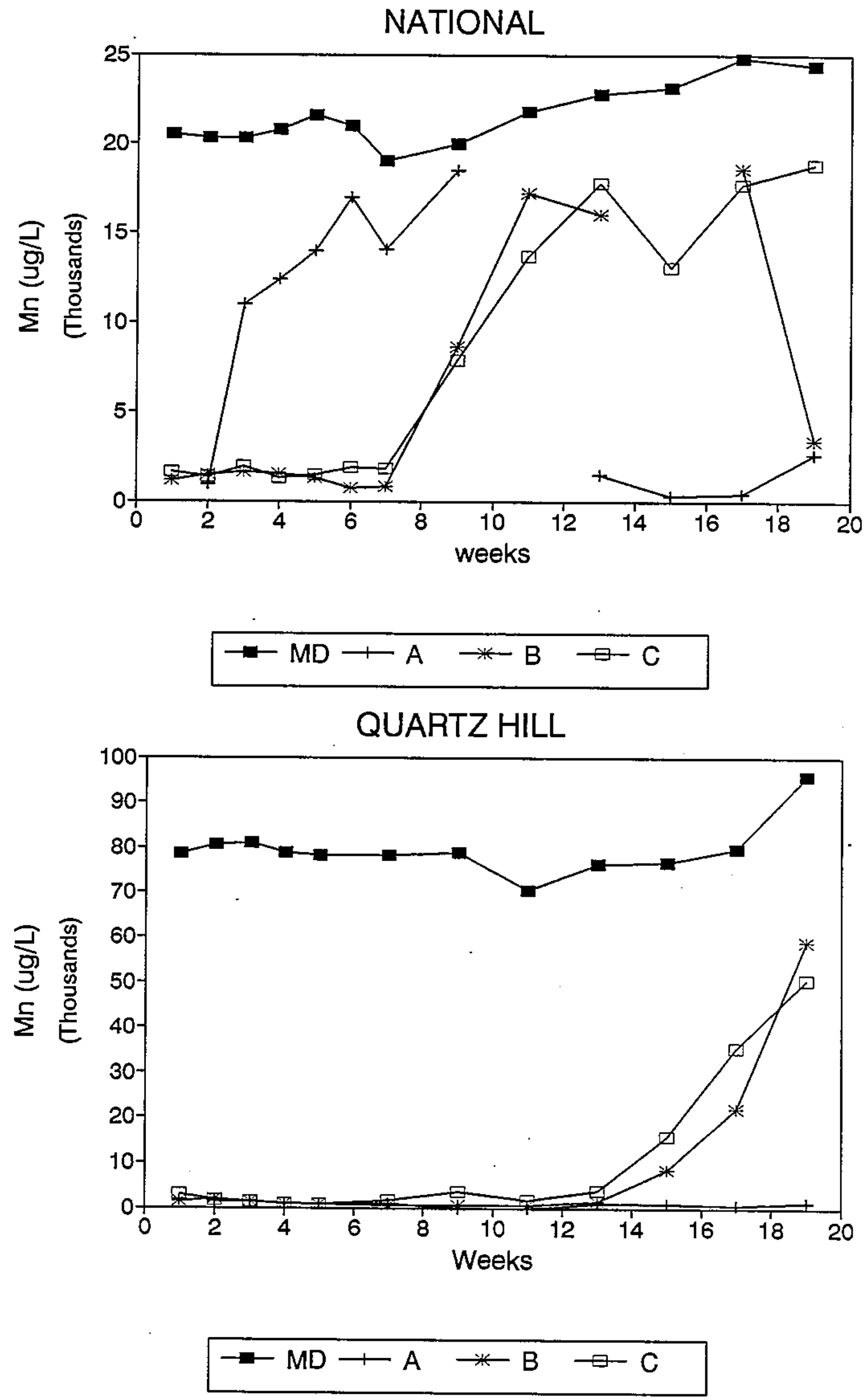

Figure 4. Manganese content of mine drainage and permeameter effluents for National Tunnel and Quartz Hill Tunnel.

Table 4. Area Adjusted Removal Rates for National and Quartz Hill Tunnels (grams/day/meter^2)

		National gdm^2	Quartz Hill gdm^2
Iron	Range	2.1 - 3.8	4.2 - 6.3
	Average	2.8	4.8
Total Metals	Range	3.0 - 6.0	5.4 - 8.5
	Average	4.3	6.7

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