

FINAL REPORT

USE OF A CONSTRUCTED WETLAND
FOR THE TREATMENT OF ACID MINE DRAINAGE
AT THE FRIENDSHIP HILL NATIONAL HISTORIC SITE, FAYETTE COUNTY, PA

Interagency Agreement #4000-5-0010

between

National Park Service

and

U.S. Bureau of Mines

R. S. Hedin, D. H. Dvorak, S. L. Gustafson,
D. M. Hyman, P. E. McIntire, R. W. Nairn,
R. C. Neupert, A. C. Woods and H. M. Edenborn

Biotechnology Section
Environmental Technology Group
U.S. Bureau of Mines, Pittsburgh Research Center
Pittsburgh, PA

September 30, 1991

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EXECUTIVE SUMMARY

Ice Pond Run, a stream that flows through the Friendship Hill National Historic Site in Fayette County, PA, is severely polluted with acidic water draining from an abandoned coal mine. The U.S. Bureau of Mines, in cooperation with the National Park Service, evaluated the feasibility of treating the acid mine drainage with a constructed wetland. A pilot-scale wetland was constructed in 1988 that consisted of cattails (*Typha latifolia*) growing in a limestone and spent mushroom compost substrate. The pilot wetland was designed to allow replicated loading experiments. Acid mine drainage flowed through three parallel, hydrologically-isolated wetland lanes. The flow rate of drainage into each lane was controlled with valves. Experiments were conducted that determined the contaminant removal capabilities of the wetland, the processes that result in water quality amelioration, and the seasonal variation in these processes.

Removal of acidity (the sum of proton and mineral acidity) averaged $7.2 \text{ g m}^{-2}\text{day}^{-1} \text{ CaCO}_3$ equivalent and ranged from 3 to $10 \text{ g m}^{-2}\text{day}^{-1}$. Removal rates were highest in summer months and lowest in winter months. When flow rates were adjusted so that contaminant loading rates approximated predicted summer contaminant removal rates, the wetland transformed highly acidic water (pH 2.6; Fe 175 mg L^{-1} ; Al 50 mg L^{-1} ; Mn 8 mg L^{-1} ; acidity $945 \text{ mg L}^{-1} \text{ CaCO}_3$ equivalent) to near-neutral condition (pH 6.0; Fe 35 mg L^{-1} ; Al $<1 \text{ mg L}^{-1}$; Mn 4 mg L^{-1} ; alkalinity $88 \text{ mg L}^{-1} \text{ CaCO}_3$ equivalent).

Acidity was removed from the water by a combination of limestone dissolution and bacterial sulfate reduction. On average, bacterial sulfate reduction produced $4.3 \text{ g m}^{-2}\text{day}^{-1}$ of alkalinity (CaCO_3 equivalent), while limestone dissolution produced $2.5 \text{ g m}^{-2}\text{day}^{-1}$ of alkalinity. Limestone dissolution rates displayed little variation between seasons, while bacterial sulfate reduction ranged markedly between the coldest winter periods ($0\text{-}1 \text{ g m}^{-2}\text{day}^{-1}$ of alkalinity generation) and warm summer periods ($6\text{-}9 \text{ g m}^{-2}\text{day}^{-1}$ of alkalinity generation).

The measurements of acidity removal capabilities of the pilot wetland, in combination with measurements of acidity production by the abandoned coal mine, allowed calculations of the size of wetland area necessary to treat the acid mine drainage. Because acidity-removal processes by the wetland and acid production by the mine both varied seasonally, the optimum size of the effective wetland also varied. Calculations indicated that a $50,000 \text{ m}^2$ wetland would be necessary to treat average summer flows, while $150,000 \text{ m}^2$ wetland would be necessary to treat average winter flows. The estimated cost of these wetland systems would be between \$500,000 and \$1,500,000.

Other treatment options for Ice Pond Run were also considered. These include no treatment, re-mining, piping of the untreated mine water through most of the park, chemical treatment, and the use of a containerized passive treatment system. Total costs are lowest for the first three of these options, but each has associated disadvantages,

including continued pollution of Ice Pond Run and/or the Monongahela River. It may also be possible to use combinations of these treatment options to improve water quality and provide an educational display for visitors to the park.

INTRODUCTION

Friendship Hill National Historic Site (NHS) is located in southern Fayette County, PA, near the towns of New Geneva and Point Marion (fig. 1). The historic site protects and displays the former country home of Albert Gallatin, U.S. Secretary of the Treasury under Thomas Jefferson. The property consists of 661 acres of land adjacent to the Monongahela River. The park was created in 1978 and now annually receives approximately 15,000 visitors who visit the park museum and the historic Gallatin home, and also use the park for a variety of outdoor activities, such as hiking and cross-country skiing.

Ice Pond Run, which runs through the park, is severely impacted by acid mine drainage coming from an abandoned coal mine. The stream is too polluted to support fish and many other aquatic organisms, and thus has a negative impact on the environmental quality of the park. The U.S. Department of Interior, Bureau of Mines, with the cooperation of the National Park Service, has carried out fundamental and pioneering research on the use of constructed wetlands for the treatment of acid mine drainage at Friendship Hill NHS since 1986. Two constructed wetland projects have been built and studied intensively since that time, and much of the current knowledge about the efficiency of constructed wetlands in treating severely polluted acid mine drainage is a direct result of the studies carried out at the Friendship Hill site. The existing wetland at Friendship Hill is the most routinely and intensively studied constructed wetland in the world.

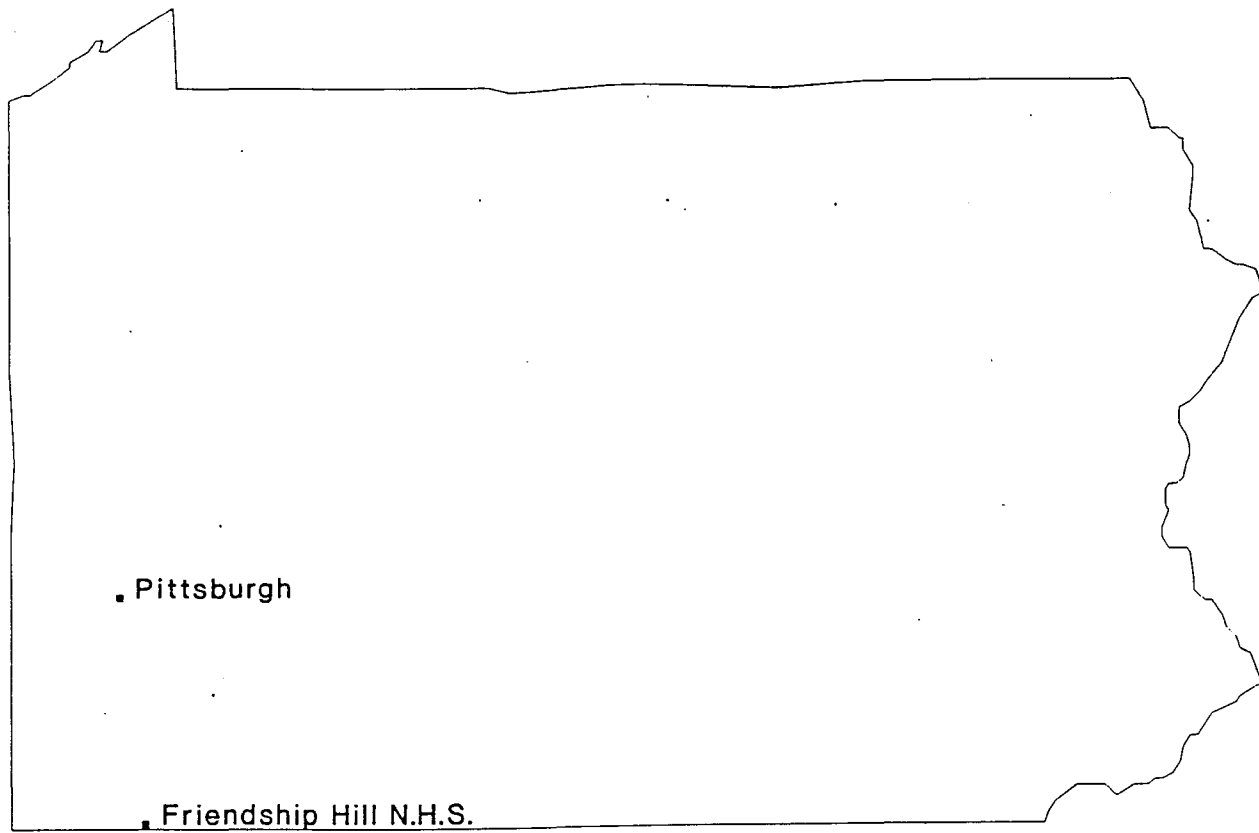


Fig. 1. Location of Friendship Hill National Historic Site.

In this report we describe aspects of the Bureau's work at Friendship Hill that are applicable to the question that precipitated our involvement at the site: can the acid mine drainage in Ice Pond Run be treated with a low-cost, low-maintenance constructed wetland? To answer this question, we constructed a small pilot-scale wetland at the park. Research at this wetland focused on the identification of chemical and bacterial processes that ameliorate acid mine drainage, and the measurement of the summed effect of these processes through the calculation of contaminant removal rates. In separate studies by the Bureau, rates of contaminant production by the abandoned deep mine at the Friendship Hill site have been measured. The combination of rates of contaminant production and contaminant removal can be used to estimate the size of wetland necessary to treat acid mine drainage at the site.

METHODS

Surface water was sampled by collecting water discharging from influent and effluent pipes at the constructed wetland. Raw and acidified water samples were collected in 250-mL plastic bottles at each sampling point. Samples were acidified in the field with 2 ml of concentrated HCl to preserve metal concentrations. Measurements of pH and temperature were made in the field using an Orion SA230 portable pH meter.

Surface areas of the wetland cells were determined from field measurements. Water depths (free water lying on top of the substrate) were determined in August 1990 at 12-16 random locations in each cell. Water flows were determined by collecting the outflow of a pipe in a bucket for 30-60 seconds, and then measuring the volume of water collected with a large graduated cylinder. Three to five measurements were made on each sampling date and mean values are reported.

Concentrations of total cations (Fe, Mn, Al, Ca, Mg, and Na) were determined for the acidified samples using Inductively Coupled Argon Plasma Spectroscopy (ICAP, Instrumentation Laboratory Plasma 100 model). Ferrous iron was determined by titrating a mixture of 50 mL acidified sample and 9 mL of a sulfuric acid-phosphoric acid solution with potassium dichromate. Diphenylamine sulfonic acid was added as an endpoint indicator, which was determined using a redox electrode.

Sulfate concentrations were determined for raw samples by a barium chloride titration with thorin as the end-point indicator. Samples were passed through a cation exchange resin before sulfate analysis.

Acidity was determined for 50-mL raw samples that were first boiled with 1.0 ml of 30% hydrogen peroxide and allowed to cool. The samples were then titrated to a pH of 8.3 with 0.1 N NaOH. Alkalinity was measured by titrating 50-ml samples with 0.2 N sulfuric acid to pH 4.8.

For each set of samples, a duplicate, standard, and spiked sample was analyzed for quality control purposes. The relative standard deviation of the duplicates was always less than 1% and standards were always within 3% of each other. A known amount of standard was added to one of the samples to calculate percent spike recovery. Spike recoveries were always within 5% of the expected value.

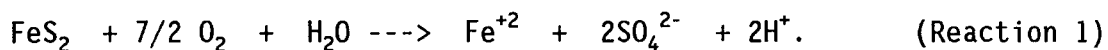
All chemical concentrations are expressed as mg L^{-1} , which is equivalent to ppm. Acidity and alkalinity are presented as $\text{mg L}^{-1} \text{CaCO}_3$ equivalent. This is the standard acidity unit used in most evaluations of acid mine drainage. Alkalinity was treated as negative acidity, and vice versa. To translate $\text{mg L}^{-1} \text{CaCO}_3$ equivalents to milliequivalents, the standard units for acidity and alkalinity in other research fields, simply divide by 50.

Water samples were not filtered before acidification, so reported metal concentrations describe the sum of dissolved and particulate species. Comparisons of acidic surface water samples that were treated normally (unfiltered) and filtered through a 0.22 μm membrane filter before acidification yielded results that differed by less than 10%. Thus, although total metal concentrations are reported, the values closely approximate dissolved concentrations.

BACKGROUND

PASSIVE TREATMENT OF ACID MINE DRAINAGE

When water flows through an environment disturbed by mining activity, its chemistry is sometimes degraded. The primary cause of most mine water degradation is the oxidation of iron sulfide minerals, such as pyrite (FeS_2). When FeS_2 is exposed to water and oxygen, it oxidizes to form an acidic solution that contains high concentrations of ferrous iron and sulfate:

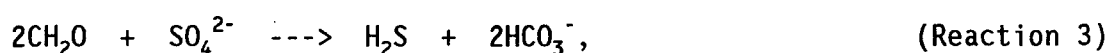
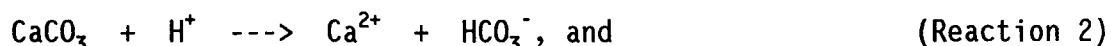


As this solution moves through abandoned mine workings or spoils, it undergoes secondary reactions that raise pH, decrease concentrations of iron, and increase the concentrations of other cations. Contact with clays releases aluminum, while contact with carbonate minerals releases calcium, magnesium, and manganese. The effects that these reactions have on the chemistry of the mine drainage varies depending on the volume of water, the amount of pyrite oxidized, and the extent and variety of secondary chemical reactions. Often water seeps from abandoned mines without significant degradation. In some cases, water seeps from abandoned mines with circumneutral pH (6-8), but with high concentrations of dissolved iron and manganese. In other cases, mine drainage is acidic and contains high concentrations of dissolved iron, aluminum, and manganese.

As contaminated mine drainage flows into and through receiving systems (streams, rivers, and lakes), its toxic characteristics decrease naturally as a result of chemical and biological reactions and dilution with uncontaminated waters. Under the aerobic conditions found in most surface waters, iron, manganese, and aluminum precipitate as oxides and hydroxides. Ferrous iron oxidizes to ferric iron, which hydrolyzes and precipitates as iron oxyhydroxide (FeOOH). This compound stains the bottom of many streams orange, often accumulating to sufficient depths to suffocate most benthic organisms. Manganese oxidizes and hydrolyzes to MnOOH or MnO_2 , and precipitates as a black particulate. Aluminum hydrolyzes to $\text{Al}(\text{OH})_3$ and precipitates as a white particulate. The extent of these reactions is largely dependent on the pH of the water. Little precipitation of manganese occurs when the pH is less than 6; little precipitation of aluminum occurs when pH is less than 4; and little precipitation of iron occurs when pH is less than 3.

The goal of passive mine drainage treatment systems is to accelerate natural amelioration processes so that they occur within the treatment system, not in the receiving stream or lake. For alkaline mine drainages that are contaminated with iron and manganese, treatment requires aeration and adequate retention time. Aeration provides the oxygen that stimulates oxidative reactions, while retention provides the time necessary for the reactions to proceed to the desired level as well as to precipitate suspended solids.

For acidic mine drainages, alkalinity must be generated in the treatment system to neutralize the acidity. Two processes that can generate alkalinity in constructed wetlands are the dissolution of limestone and the bacterial reduction of sulfate:



where HCO_3^- is bicarbonate alkalinity and CH_2O represents organic matter.

Limestone dissolution generates alkalinity by directly neutralizing proton acidity (H^+) and producing bicarbonate. Flow of iron-containing mine water over limestone in an aerobic environment commonly results in limited dissolution because the limestone is quickly armored and inactivated by ferric hydroxides. However, in an anaerobic environment, where iron usually exists only in the ferrous state, armoring does not occur and limestone dissolution proceeds.

Sulfate reduction generates alkalinity through the production of hydrogen sulfide and bicarbonate. Bicarbonate neutralizes proton acidity while hydrogen sulfide precipitates iron as a sulfide (e.g. FeS), which decreases mineral acidity (the concept of mineral acidity is discussed in the next section). Sulfate reduction is a common bacterial process in marine sediments and wetlands where sulfate is present in

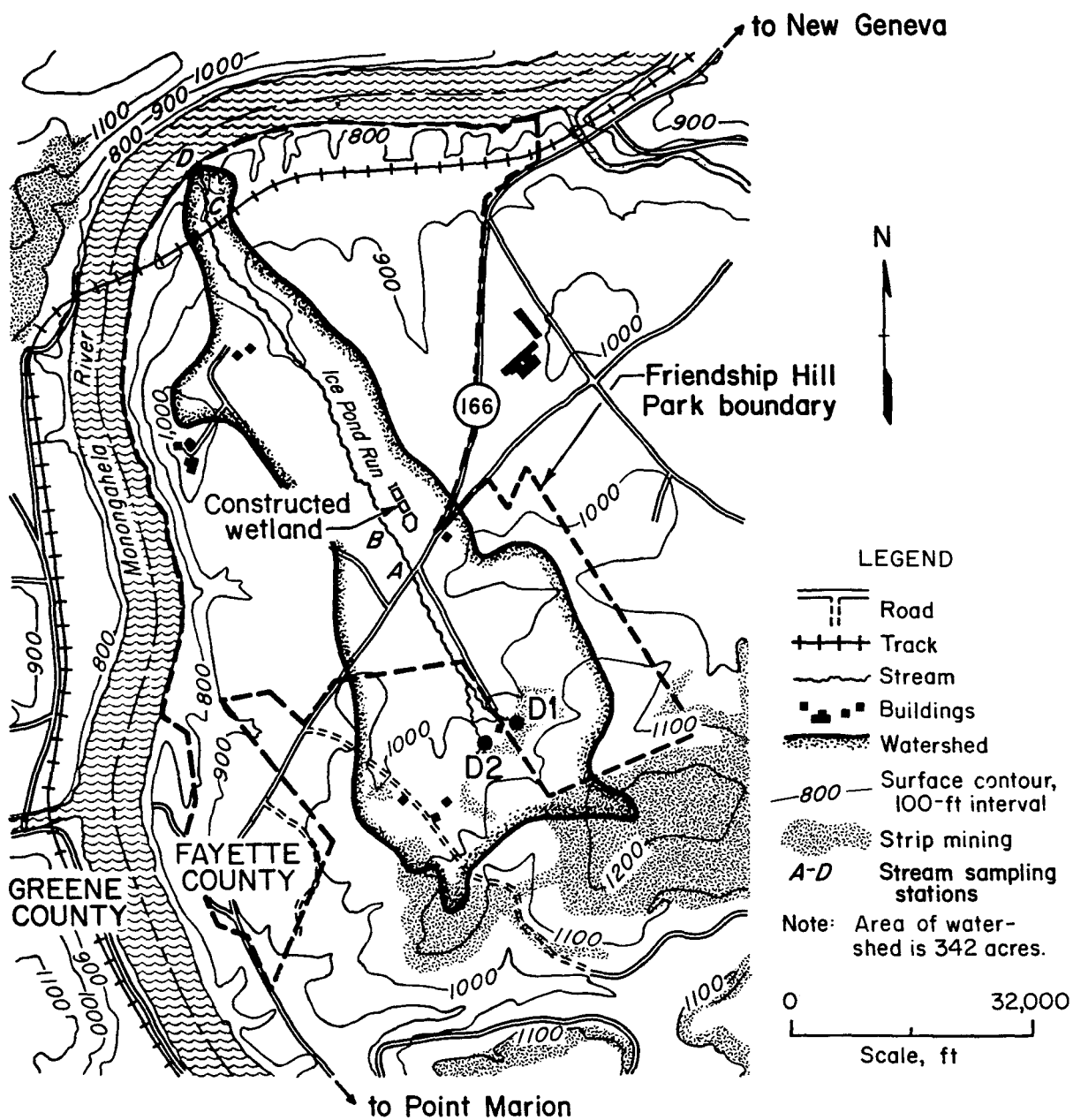
high concentrations ($2,000 \text{ mg L}^{-1}$). In most freshwater wetlands, where sulfate concentrations are typically less than 30 mg L^{-1} , sulfate reduction is less important. Wetlands that receive mine drainage often receive high concentrations of sulfate and, if a suitable organic substrate is present, the potential for high rates of bacterial sulfate reduction exist. Sulfate reduction rates similar in magnitude to those reported for marine systems have been measured at the Friendship Hill site and at other constructed wetlands in northern Appalachia (McIntire et al. 1990; McIntire et al., in preparation).

The most common organic substrate used in the construction of wetlands for mine drainage treatment is spent mushroom compost. This substrate is a waste product of mushroom farming and is a balanced mixture of nitrogenous materials (manures) and carbonaceous materials (wood chips, hay, corn cobs). It is a good general microbial substrate, and it supports bacterial sulfate reduction activity better than *Sphagnum* peat, rotted manure, woodchips, or rotten hay. Spent mushroom compost also contains about 10% limestone (dry weight). This limestone is soluble under the anaerobic conditions that develop when compost is flooded. Thus, spent mushroom compost can potentially generate alkalinity through both microbial and chemical processes.

Acid Mine Drainage at Friendship Hill NHS

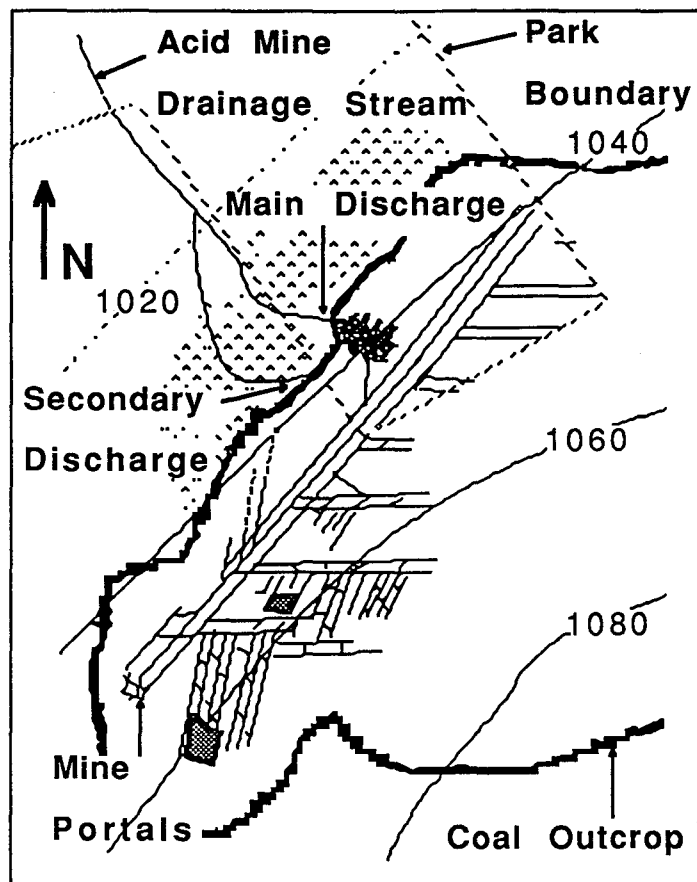
Ice Pond Run is contaminated by severely polluted acid mine water draining from an abandoned drift mine at two main discharge points (D1 and D2; fig. 2). The mine was located in the Pittsburgh coal seam and was operated by the Winstead Coal Co. in the 1920's and 30's. The main mine discharge originates from a partially collapsed opening of a very small unnamed mine surrounded by the larger Winstead mine (fig. 3). The location of this mine suggests that it was used to drain water away from the Winstead mine, and it is likely that it continues to drain this mine as well as other mines to the southeast that may all be interconnected. The total flooded area drained by these two discharges has been estimated to be between 1.0 and 2.7 ha (2.5 and 6.6 acres), with a total mine pool volume of between 12 and 40 million liters (Aljoe and Hawkins, 1991).

Mine discharge flow rates and the water chemistry of the primary (D1) and secondary (D2) mine discharges were measured between May 1989 and September 1990 (table 1; Aljoe and Hawkins, 1991). During this time, flow rates ranged from approximately 14 to 732 L min⁻¹; the highest flows occurred in the winter and spring months, and the lowest flows in the early fall. The response of the mine discharge to precipitation events was likewise strongest in the winter and spring months. Water quality determinations for the mine discharge during this period indicated that acidity, sulfate, and metal concentrations changed marginally as flow rates increased or decreased.



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Fig. 2. Ice Pond Run Watershed. D1 and D2 are points of primary and secondary mine water discharge into Ice Pond Run, respectively.



Winstead Mine

Entries and projections
from 1929 map

Structure contours from
Hickok and Moyer (1940)

 Strip Mine Spoil

Scale in Feet



Fig. 3. Location of drainage discharge points with respect to the Winstead Mine.

The water from the secondary discharge was always of lesser volume than the primary discharge, but more contaminated with acid mine drainage pollutants. Nevertheless, the primary discharge always contributed the greatest total amount of pollutants to Ice Pond Run. On days when both discharges were sampled, the primary discharge produced, on average, 3.5 times as much acidity as the secondary discharge (table 2).

Because of the chemical differences in the water from the two discharges, it is believed that they come from different locations within the same mine pool (Aljoe and Hawkins, 1991). The percentage of ferrous iron detected in the discharge water at both points never exceeded 30% and was consistently below 5% during months of high flow. This implies that the mine pool is well-oxygenated, allowing the fairly complete chemical and biological oxidation of ferrous iron prior to discharge.

Water from the mine discharges flows approximately 3 km via Ice Pond Run through the Friendship Hill National Historic Site prior to flowing into the Monongahela River (fig. 2). The water quality of Ice Pond Run improves slightly over this distance (table 3). As will be discussed later, magnesium ion concentration in the water can be used to accurately estimate dilution effects within the Friendship Hill wetland system. Calculations using data in table 3 indicate that most of the observed decreases in acid mine drainage pollutants are due to dilution alone (table 4).

Table 1.--Water chemistry and flow rate of the
two main mine drainage discharges impacting
Ice Pond Run, 5/12/89 - 9/4/90.

	Primary Discharge (D1)				Secondary Discharge (D2)			
	mean	sd	min	max	mean	sd	min	max
pH.....	2.8	0.1	2.3	3.0	2.5	0.1	2.4	2.8
Acidity.....	1178	94	977	1379	1883	196	1192	2292
Fe ^{tot}	245	29	140	296	403	18	354	436
Fe ²⁺	24	25	1	130	21	1	2	72
Fe ³⁺	221	23	124	255	381	20	350	416
Al	70	6	56	84	97	4	87	105
Mn	10	1	8	13	12	1	11	13
Ca	269	37	120	385	253	14	218	278
Mg	114	10	90	133	120	7	106	138
Na	5	1	4	7	4	<1	3	4
Cl	7	8	2	13	2	na	na	na
Sulfate.....	2277	190	1887	2650	2989	132	2675	3200
sum [+]....	45.2	4.0	35.5	53.2	57.5	2.2	51.7	61.9
sum [-]....	47.4	4.0	39.3	55.2	62.3	2.7	55.7	66.7
flow	203	124	68	732	50	39	14	147
(L min ⁻¹)..								
n.....	61 ¹				23 ²			

¹ except Cl, n = 2; and flow, n = 58

² except Cl, n = 1; and flow, n = 17

All units are mg L⁻¹ except pH (standard units) and flow rates which are L min⁻¹.

sum [+] refers to the total milliequivalent charge of measured cations.

sum [-] refers to the total milliequivalent charge of measured anions.

Table 2.--Comparisons of acidity and flow at the primary (D1)
and secondary (D2) discharges when samples were
taken from both discharges on the same day.

Parameter	Acidity ¹		Flow ²		Acidity Load ³		
	D1	D2	D1	D2	D1	D2	D1/D2
average...	1175	1864	126	25	216,273	65,234	3.5
sd.....	81	231	33	9	56,733	22,133	0.9
min.....	977	1192	93	14	143,474	42,175	2.7
max.....	1262	2293	182	36	323,547	96,632	4.9
n.....	14	14	8	8	8	8	8.0

¹ Acidity concentrations are mg L⁻¹ CaCO₃ equivalent.

² Flow rates are L min⁻¹.

³ Acidity loads are g day⁻¹.

Table 3.--Changes in Ice Pond Run water chemistry with flow toward Monongahela River, January 30, 1991.

Sample Location	pH	Acid	Fe ^{tot}	Fe ²⁺	Ca	Mg	Al	Na	Mn	Sulfate
Primary discharge (D1)...	2.49	1008	198	2	222	98	61	5	9	1925
Road Culvert (A).....	2.60	582	110	3	110	48	34	4	5	1000
Wetland In (B).....	2.72	484	85	3	90	39	28	5	4	800
Waterfall (C).....	2.73	418	79	4	85	37	13	4	4	725
Monongahela River (D)....	6.63	-9	1	1	23	6	1	8	<1	85

All concentrations are mg L⁻¹ except pH, which is standard units.

Table 4.--Percentage change in concentrations of measured water quality parameters (no pH) between sampling points, January 30, 1991.

Comparison	Mg	Acid	Fe ^{tot}	Ca	Al	Sulfate
waterfall (C)/D1 discharge.....	38*	41	40	38	21	38
waterfall (C)/road culvert (A).....	77	72	72	77	38	73

All concentrations are mg L⁻¹ except pH, which is standard units.

* Indicates that concentrations of magnesium at the waterfall station were 38% of concentrations at the primary discharge station.

While the data presented in tables 3 and 4 provide a snapshot of Ice Pond Run water quality on a single day, data presented in figure 4 illustrate changes in quality over one year (1990) between its headwaters at the primary mine discharge and at the influent to the constructed wetland, a distance of about 1 km. Differences between concentrations of acidity at the primary discharge and the wetland influent reflect dilution with freshwater. On most sampling occasions, significant inputs of freshwater were indicated because the wetland influent contained 25-75% less acidity than the primary mine discharge. However, during summer and early autumn, concentrations of acidity at the sampling points were similar. During these drier portions of the year, almost all of the water contained in Ice Pond Run at the wetland location was derived from the deep mine.

Construction of Wetlands at Friendship Hill NHS

The Bureau's research into wetland treatment of acid mine drainage at Friendship Hill evolved significantly over the five year life of the project (see Appendix A). Initially, a wetland was constructed that consisted of *Sphagnum* moss and cattails. No organic substrate was contained in the original wetland. This design resulted from observations of amelioration of acid mine drainage in natural *Sphagnum* bogs (Huntsman et al. 1978; Wieder and Lang 1982), and preliminary research by the Bureau and others that indicated significant iron-removal capabilities of *Sphagnum* (Kleinmann et al. 1983; Burris et al. 1984). By 1988, the limited capabilities of *Sphagnum* were

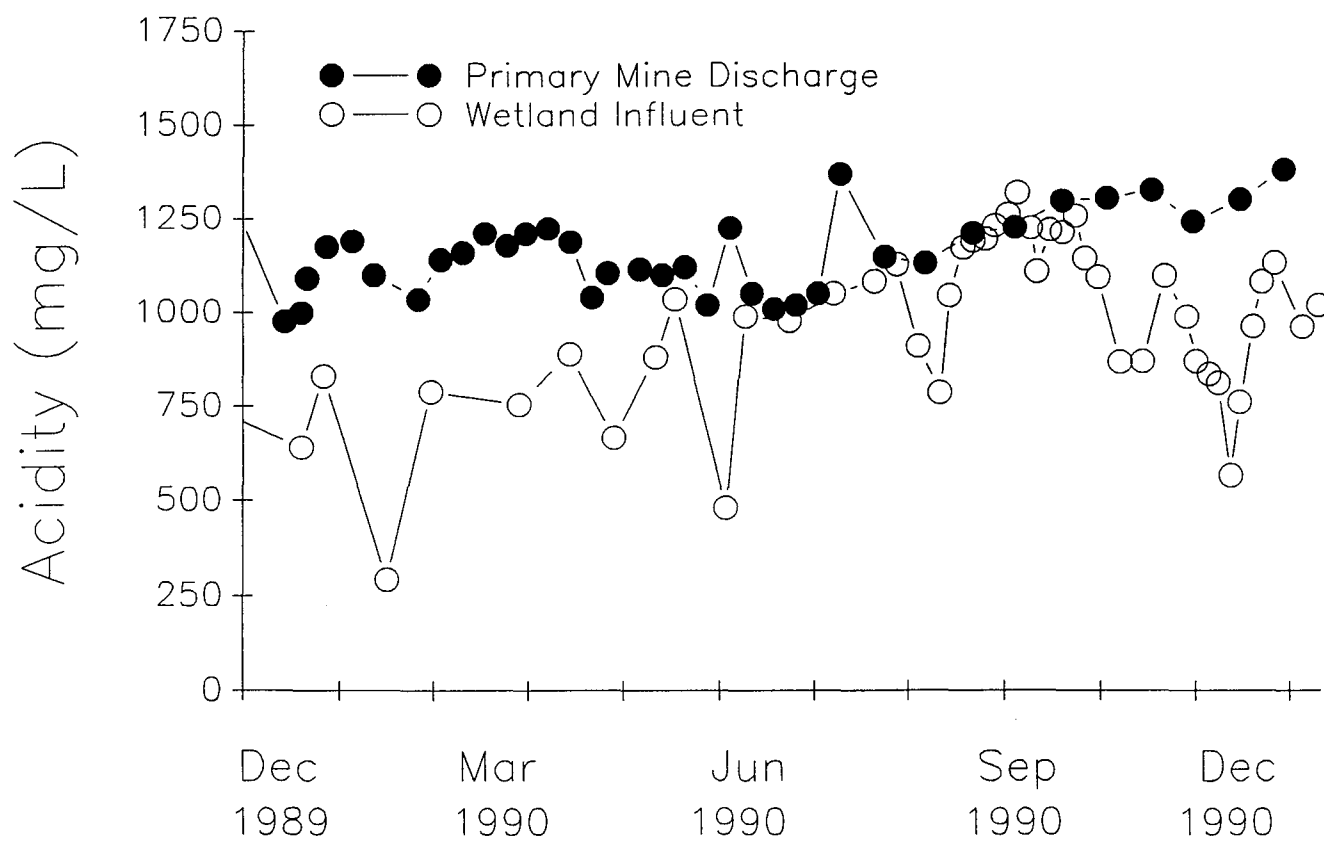


Fig. 4. Concentration of acidity at the primary mine discharge and at wetland influent between December 1989 and January 1991.

evident at the pilot wetland and elsewhere. Increasing numbers of wetlands were being constructed by planting cattails in spent mushroom compost, and growing emphasis was placed on understanding microbial processes in these wetlands. Thus, during the summer of 1988 the wetland was reconstructed with spent mushroom compost and cattails. Changes in the system's general design improved research opportunities at the site. While originally only a single wetland had been constructed, the second system was built as three side-by-side, hydrologically separate, wetland systems. An improved method for controlling influent flow rates was incorporated, as was a novel plumbing system that allowed water to be injected into the compost, in addition to passively flowing on the surface.

Research at the second constructed wetland can be divided into two phases. Early in 1988, research at other constructed wetlands had established the occurrence of sulfate reduction and its theoretical potential for the treatment of acid mine drainage (Hedin et al. 1988; Hedin et al. 1989). During the first phase of research at the reconstructed pilot wetland, emphasis was placed on documenting the activity of sulfate-reducing bacteria. Measurements were made of bacterial sulfate reduction rates and flow regimes were manipulated to test whether forcing mine drainage through the compost could increase bacterial activity. This phase of our research established that sulfate

reduction occurred in mushroom compost at rates high enough to make the treatment of acidic mine drainage feasible, although all of our engineering efforts to manipulate flow paths were unsuccessful (McIntire et al. 1990; McIntire et al., in preparation).

The second phase of research at the reconstructed wetland addressed contaminant removal rates. Contaminant loadings (grams of contaminant entering the wetland per day) were manipulated by adjusting flow rates, resulting in the collection of baseline data describing contaminant removal under various loading conditions. The results of these experiments are particularly germane to questions about the size of wetland needed to treat acid mine drainage at the Friendship Hill NHS.

First pilot-scale wetland

This wetland was constructed in the summer of 1986 by Bureau of Mines and National Park Service personnel. An excavation was made 97 m (316 ft) long by 12 to 20 m (40-70 ft) wide, encompassing a total of about 1,420 m² (15,000 square feet) (fig. 5). The flow through the wetland was intended to be 75 L min⁻¹ (20 gal min⁻¹), although the area of the wetland could, based on accepted wetland construction practices at the time, treat about 110 L min⁻¹ (30 gal min⁻¹). The initial depth of the wetland was set between 20 and 30 cm (.7-1.0 ft). The base of the excavation, on natural clay, provided an average 1% grade from inflow to outflow. Seven sets of boards were placed across the width of

FRIENDSHIP HILL CONSTRUCTED WETLAND

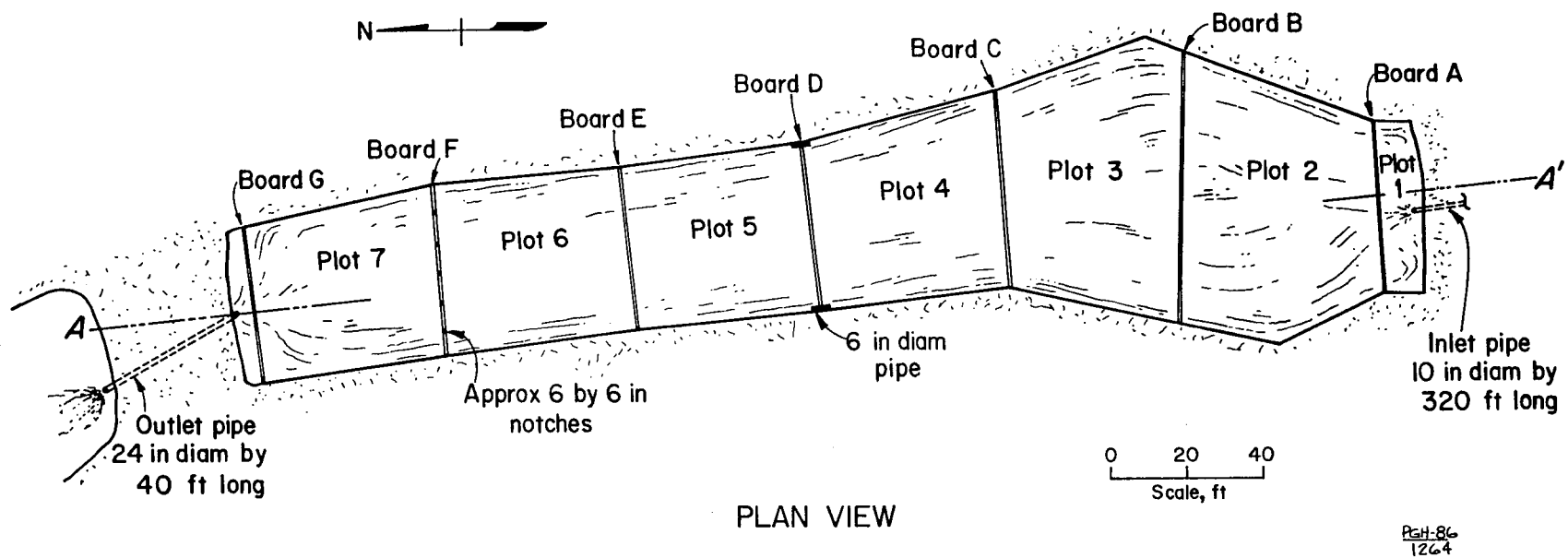


Fig. 5. Layout of the first pilot-scale wetland.

the wetland to separate it into seven plots and regulate water depth. Water flowed between the plots by running over the boards.

Locally-collected *Typha* were planted in late August 1986 in five of the seven wetland plots. Plants were collected from a freshwater seepage area and from a stand of volunteer *Typha* growing in a local coal yard. Individual plants consisted of roots and emergent leaves, and were planted on 1 m centers directly in the clay base of the wetland. In September 1986, a small section of plot 4 was planted with a variety of emergent aquatic plants obtained from a nursery in Wisconsin. These included softstem and hardstem bulrushes, three species of *Carex*, wild iris, and bluestem jointgrass. In November 1986, plots 2 and 3 were planted with 18,000 kg (40,000 lb) of live *Sphagnum* purchased from a Wisconsin peat moss quarry. The moss was set directly on top of previously added and inundated hay bales. The only amendments made to the wetland vegetation were slow-release fertilizer tablets buried in the clay around each cattail in April 1987.

Upstream from the wetland, a dam was built across Ice Pond Run to provide a pool from which water could be diverted into the wetland. Flow ran through an adjustable sluice gate into 100 m (320 ft) of buried 10-inch plastic pipe, and emptied into plot 1. A 24-inch pipe was placed down-gradient from the last set of boards to channel the outflow from the system for sampling and flow measurement. The dam performed well until the spring of 1987. During severe rainstorms in April 1987, serious erosion occurred around and under the dam. Flow into the

wetland was not lost, but concerns about the effects of further erosion prompted repair efforts. In August 1987, the pool was deepened and the dam increased in size. At the same time, a concrete gauging flume was built below the wetland. Outflow water from the wetland flowed through this flume.

The pilot-scale wetland became operational in September 1986, when water was diverted into the system. Maintenance activity consisted mainly of water flow and depth regulation. Water depths in the cattail sections were initially too high for good cattail establishment. Consequently, water levels were reduced to between 9 cm and 15 cm (0.3-0.5 ft) deep. By late 1987, it was apparent that plant growth could not be sustained and that the wetland was basically ineffective at treating Ice Pond Run acid mine drainage. Data collection was then discontinued and the design of the wetland was reassessed.

Second pilot-scale wetland

The present constructed wetland was built in the summer of 1988 on the site of the previous constructed wetland and was divided into three cells (fig. 6). The first cell is a holding pond that does not treat the AMD. A large flow of Ice Pond Run flows into this pond, part of which is diverted into the experimental wetlands. Most of the flow, however, discharges through an overflow pipe back into Ice Pond Run. This design results in constant water levels in the pond, regardless of the amount of water diverted into the wetland system. The remaining two

cells (designated 2 and 3) are each divided into three different treatment lanes (designated A, B, and C) separated by fiberglass sheeting. Water flows into the wetland lanes through three submerged plastic pipes. The inflow of each pipe is inside a plastic barrel that has numerous holes drilled in it. The purposes of the barrel are to ensure that each pipe draws similar water, and to minimize the likelihood that leaves or sticks are drawn into and clog the pipes. The amount of water flowing from these pipes into each wetland lane is regulated with plastic ball valves. Because of the extremely low pH of influent water, little precipitation of iron occurs in the pipes and clogging with iron hydroxides has not been a problem.

In cell 2, no efforts were made to direct a flow path, and most AMD flows across the surface of the organic substrate. The effluent of cell 2 wetlands is taken from the surface by an adjustable plastic pipe whose height determines the depth of water in each cell. In cell 3, subsurface infusion pipes were placed beneath the compost in each lane so that AMD could be introduced to the wetland at the bottom of the organic substrate layer (fig. 6). When the pipes are operational, water enters the wetland underneath the compost and then diffuses to the surface, where it exits through a plastic pipe positioned at the wetland surface. A ball valve at a Y-connection controls whether water entering the cell 3 lanes is directed into the subsurface pipes or spills out of a pipe onto the surface of the organic substrate.

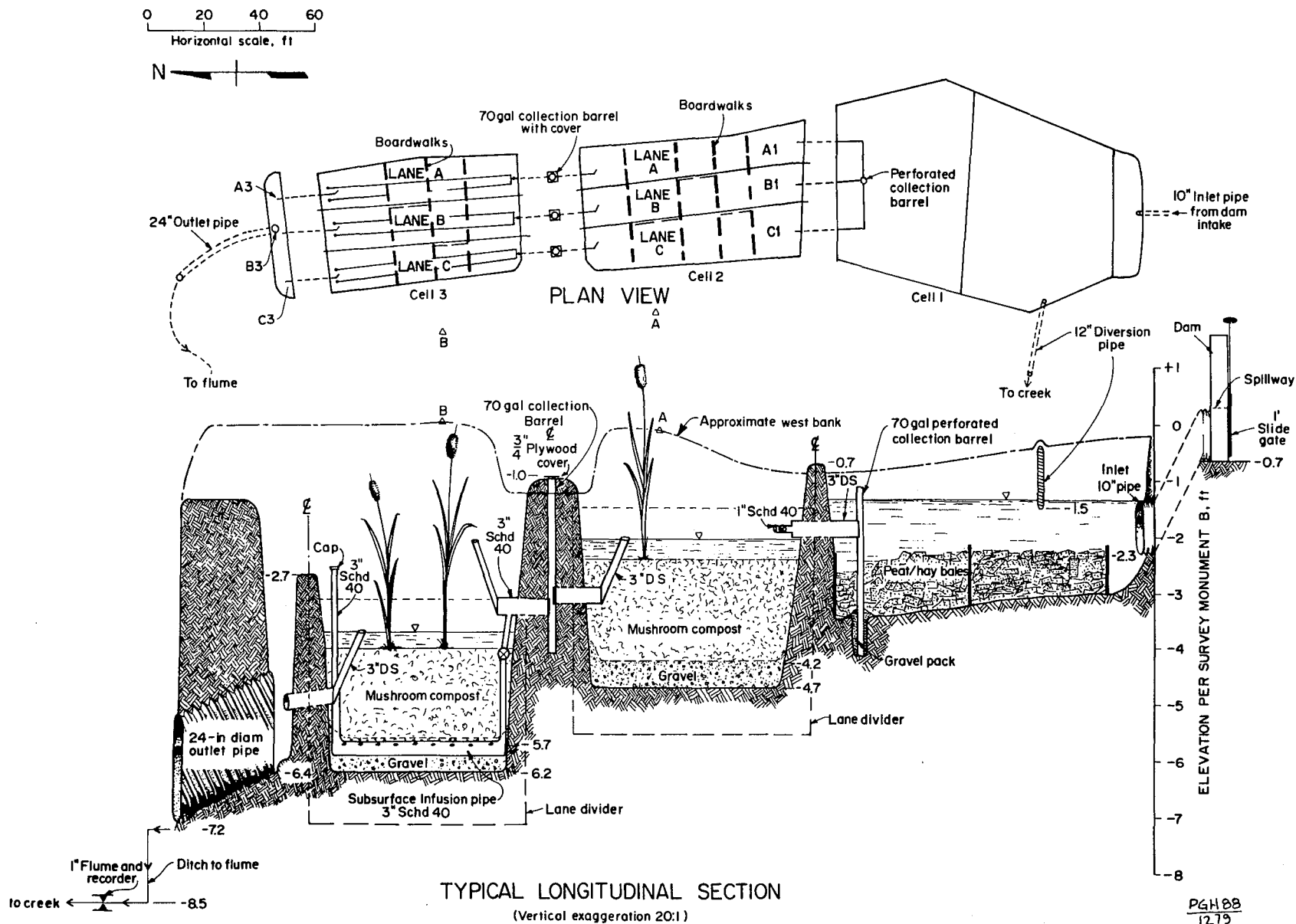


Fig. 6. Layout of the second pilot-scale wetland.

The three wetland treatment lanes (A, B, C,) each consisted of 2 cells constructed with a 15 cm (6 in) layer of gravel on the bottom and covered by a 45 cm (18 in) layer of spent mushroom compost obtained from a mushroom farm near Worthington, PA. The basal gravel layers in the cells consisted of limestone gravel in lanes B and C, and noncalcareous river gravel in lane A. Whole cattail plants were transplanted to all cells and the compost was flooded on November 15, 1988 with 8 to 20 cm (3 - 8 in) of AMD water. Although attempts were made to ensure that all three wetland lanes were the same size, contained the same amount of compost, and had equivalent water depths, variability between the cells existed (table 5). Lane B was smaller than the other two lanes, but contained the largest volume of surface water because it contained the deepest water depths.

Table 5.--Dimensions of the wetland cells and lanes.

Cell	Surface Area m ²	Mean Depth cm	Surface Water L
A2.....	119	8.3	9,852
B2.....	117	11.9	13,971
C2.....	147	7.9	11,571
A3.....	98	6.3	6,174
B3.....	87	12.1	10,515
C3.....	99	8.8	8,738
Lane A*..	217	7.3	16,026
Lane B...	204	12.0	24,486
Lane C...	246	8.4	20,312

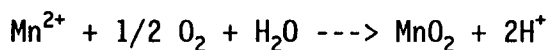
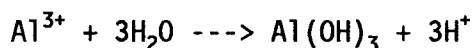
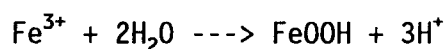
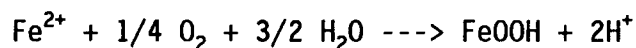
* The sum of cells A2 and A3.

During the summer of 1990, a minor modification was made to the watershed immediately surrounding the wetland cells. Freshwater seeps developed during certain times of the year when rainfall accumulated in trenches behind berms built during wetland construction. These seeps caused inputs of freshwater into lane A that were not present in the other lanes. An additional trench was dug to divert this accumulated water to the holding pond above the wetland cells. This modification lessened inputs of freshwater to lane A, but did not prevent them entirely.

The Concept of Acidity

A good understanding of the concept of acidity is central to understanding the water pollution problem at Friendship Hill and any water treatment considerations. Acidity is a measurement of the base neutralization capacity of a volume of water. In studies of uncontaminated natural waters, the term "acidity" is commonly used as a synonym for low pH. For mine waters, this use of the term is incorrect. Mine water acidity arises from low pH and the presence of iron, aluminum, and manganese. These metals are considered acidic because they participate in hydrolysis reactions that produce hydrogen ions (table 6).

Table 6.--Common acidic metal-removing reactions
in coal mine drainage.



When trying to explain what is responsible for the measured acidity of a mine water sample, or when trying to estimate the total acidity of a sample based on its chemical composition, the pH, ferrous iron, ferric iron, aluminum, and manganese concentrations in the water must all be determined. As an example, acidity of coal mine drainages can be estimated by the following equation:

$$\text{Estimated Acidity} = 50 \left(2\text{Fe}^{2+}/56 + 3\text{Fe}^{3+}/56 + 3\text{Al}/27 + 2\text{Mn}/55 + 1000 (10^{-\text{pH}}) \right) \quad (4)$$

where mineral acidity is expressed as $\text{mg L}^{-1} \text{CaCO}_3$ equivalent, all metal concentrations are in mg L^{-1} , and 50 is the term that transforms meq of acidity into $\text{mg L}^{-1} \text{CaCO}_3$ equivalent. We have found that for water samples with $\text{pH} < 4.5$ (no alkalinity present), equation 4 predicts measured mine water acidity accurately. Table 7 shows concentrations of metals, predicted acidities and measured acidities for synthetic mine drainage. Predicted acidity values differed from measured values by less than 10%.

Table 7.--Calculated and measured acidities for synthetic acidic mine water.¹

<u>Synthetic Mine Water Composition</u>					<u>Acidity</u>	
pH	Fe ²⁺	Fe ³⁺	Al	Mn	Calculated	Measured
3.9	98	1	0	0	181	184
3.9	0	0	106	0	598	578
3.6	0	0	0	97	192	186
3.8	13	0	47	42	370	335

¹ All values are the average of three tests. Metal concentrations are mg L⁻¹. Acidities are mg L⁻¹ CaCO₃ equivalent.

Equation 4 accurately characterized mineral acidity at the Friendship Hill pilot-scale wetland as well. For water samples with pH < 4.5, the mean measured acidity was 693 mg L⁻¹ (s.d.= 302, n= 496), while the predicted acidities for these samples averaged 655 mg L⁻¹ (s.d. = 270, n = 496), a difference of only 6%.

Equation 4 can be used to partition total acidity into its individual constituents. On average, the wetland influent contained 956 mg L⁻¹ of measured acidity (table 8). Although the pH of this water was extremely low (2.65), hydrogen ions accounted for only 13% of the total acidity. Most of Ice Pond Run acidity arose from dissolved ferric iron and aluminum. The dominance of mineral acidity (that due to metals), as opposed to proton acidity (that due to H⁺), indicates that evaluations of the wetland for water treatment should not focus excessively on water pH as an indicator of general water quality. It is

Table 8.--Breakdown of estimated Ice Pond Run acidity into acidic components.

Acidic parameter	Mean* value	Acidity equivalent	Percent of total estimated
Total measured.....		956	
Total estimated.....		892	
Ferric iron.....	162	434	49
Aluminum.....	57	317	36
pH.....	2.65	112	13
Ferrous iron.....	7	13	1
Manganese.....	9	16	1

*Except for pH, all mean values are mg L⁻¹.
For all analyses, n = 50.

possible for the wetland to raise pH to circumneutral levels, but for the mineral acidity to remain the same. Likewise, it is possible for total acidity to be decreased by 50%, while the pH only increases by several tenths of a unit.

It is not a coincidence that the components of acidity--Fe, Mn, Al, and pH--are also the contaminants that make the water in Ice Pond Run toxic. The tendency for these metals to oxidize and hydrolyze under aerobic conditions gives them toxic ecological features. When we discuss acidity in this report, we are referring to a summation of the toxic features of acid mine drainage in Ice Pond Run.

Evaluating Wetland Performance

The performance of the second pilot scale wetland was evaluated through the calculation and interpretation of contaminant removal rates. This approach involved the calculation of contaminant removal in terms of grams of contaminant removed per day, and then dividing that amount by the size of wetland. The units of the resulting rate expression are $\text{g m}^{-2} \text{ day}^{-1}$, or grams of contaminant removed per square meter of wetland per day. These rates are believed to be specific to the type of wetland constructed; e.g., a cattail wetland with a 45 cm layer of spent mushroom compost as its base substrate.

Contaminant removal rates were calculated from measurements of flow rates and water chemistry at the influent and effluent sampling points of each wetland cell. Although the determination of these parameters is straightforward, their subsequent interpretation is not. Evaluations of wetland performance through comparisons of a set of influent and effluent water samples and flow rates carry several implicit assumptions about the relationships between the samples. Two important assumptions of direct comparisons are:

- 1) The measured flow rates are assumed to approximate the flow rates that existed at the sampling points between sampling periods.
- 2) The chemistry of the influent sample is assumed to represent the original chemistry of the effluent.

If these assumptions are accepted, then contaminant removal rates are determined by simply calculating contaminant loads for the influent and effluent stations, and then adjusting for wetland surface area:

$$\text{Daily Acidity Removal Rate} = \frac{1.44 \times ((\text{Acidity}_{\text{in}} \times \text{Flow}_{\text{in}}) - (\text{Acidity}_{\text{out}} \times \text{Flow}_{\text{out}}))}{\text{Wetland surface area (m}^2\text{)}} \quad (5),$$

where concentrations are mg L^{-1} , flows are L min^{-1} and 1.44 is a factor that converts milligrams to grams and minutes to days, and wetland surface area is in m^2 .

If either of the assumptions is not considered appropriate, then an alternative method for estimating the contaminant removal rate must be developed. In cases where effluent flow rates are considered undependable, influent flow rates may be used if a method of accounting for dilution with freshwater is incorporated into the calculation. A simple dilution adjustment method is to monitor concentrations of an element that is present in high concentrations in the contaminated drainage, in low concentrations in diluting freshwater, and is chemically conservative in the wetland.¹ In western Pennsylvania, magnesium often meets these criteria (Hedin, in preparation). Changes in the concentration of the conservative element are used to calculate a dilution factor, which is then used to adjust influent contamination

¹ Chemically conservative elements are not affected by chemical or biological reactions operative in the wetland. Concentrations of conservative elements change only due to dilution with freshwater or evaporation.

concentrations down, effluent concentrations up, or some combination. A typical calculation, where magnesium is considered the conservative element, is shown below.

$$\text{Acidity Removal Rate} = \frac{1.44 \times \text{Flow}_{\text{in}} \times (\text{Acidity}_{\text{in}} \times \text{Mg}_{\text{out}}/\text{Mg}_{\text{in}} - \text{Acidity}_{\text{out}})}{\text{wetland surface area}} \quad (6),$$

where the units are the same as in equation 5.

In some circumstances the pairing of influent and effluent samples is not appropriate because the chemistry of the influent changes rapidly. In these circumstances, "sample pairing" errors result. When the influent water is becoming more contaminated, the performance of the wetland will be overestimated. When the influent chemistry is becoming less contaminated, the performance of the wetland will be underestimated. It is possible under the latter circumstances that the wetland could be erroneously judged to be producing contaminants. Although the highly variable nature of the chemistry of particular mine drainages is well known, the errors that this variability may introduce into evaluations of wetland performance are rarely acknowledged.

Two approaches are available for use in situations where variability in influent drainage chemistry is suspected to be high enough to result in sample pairing errors. If water sampling is done on a schedule that is independent of weather conditions (the most likely source of rapid changes in influent chemistry), then underestimation and overestimation

errors should average out over a long sampling period. The error can be ignored, with the caveat that importance must not be placed on particular measurements of contaminant removal rates. A second approach explores the possibility that chemical characteristics of the effluent sample can provide an accurate indication of the original contaminant concentrations. At many mine sites, strong statistical relationships exist between concentrations of magnesium and concentrations of contaminants in the raw mine drainage. If magnesium is judged to be conservative in the wetland system, then its concentration in the effluent sample can be used to estimate the original influent contaminant concentrations. Only an influent flow rate is necessary for this calculation;

$$\text{Acidity Removal Rate} = \frac{1.44 \times \text{Flow}_{\text{in}} \times ((b_1 \times \text{Mg}_{\text{out}} + b_0) - \text{Acidity}_{\text{out}})}{\text{wetland surface area}} \quad (7),$$

where b_1 and b_0 are regression coefficients that relate influent concentrations of magnesium to influent concentrations of acidity. This method is only useful when the regression equations relating acidity and magnesium have very high r^2 (correlation) values.

Our studies indicate that both of the assumptions discussed above are violated on a regular basis at the pilot scale wetland. Effluent flow rates were found to be very high relative to influent flow rates during rainfalls. In all cases, the assumption that these inflow rates were indicative of effluent flow conditions during the 3-14 days between

sample collections was considered unreasonable. The chemistry of influent water samples was also found to be highly variable on short time scales (Hedin, in preparation). This condition resulted from our withdrawal of contaminated water from Ice Pond Run, not directly from the mine discharge (as occurs for most wetlands constructed to treat mine drainage). During periods of rainfall, inputs of freshwater to Ice Pond Run were considerable and the chemistry of the stream changed very rapidly.

RESULTS AND DISCUSSION

SELECTION OF A CONTAMINANT REMOVAL RATE CALCULATION METHOD

Contaminant removal rates were initially calculated for the individual wetland lanes by using three methods: 1) a direct comparison of influent loadings and effluent loadings, 2) a dilution adjustment method that adjusted contaminant concentrations for dilution using a factor calculated from changes in magnesium, and 3) a contaminant prediction method that predicted, for effluent samples, the original contaminant concentrations using regression equations that related concentrations of magnesium to influent contaminant concentrations.

Both the dilution adjustment method and the contaminant prediction method were based on the observations that mine drainage at the site contained high concentrations of magnesium, diluting water contained very low concentrations of magnesium, and magnesium exhibited conservative chemical behavior at the pilot wetland and other constructed wetlands. Concentrations of magnesium in the influent averaged 77 mg L^{-1} and only ranged as low as 25 mg L^{-1} . Our chemical analyses of rainwater at sites in western Pennsylvania have never detected magnesium ($<1 \text{ mg L}^{-1}$). A sample of a shallow seep that occasionally flowed into Lane A contained only 5 mg L^{-1} magnesium.

Magnesium is expected to behave conservatively in acidic mine water (Hem 1985). However, because the wetland contained an organic substrate that typically contained alkaline pore water (McIntire et al. 1990), it was theoretically possible that magnesium carbonates could form and precipitate in highly alkaline pockets. If this process was important, magnesium concentrations would have decreased during periods of dry weather (no dilution by rainfall). No such evidence was found. During dry weather periods, flow of drainage through the wetland resulted in no detectable decrease in concentrations of magnesium (table 9).

Table 9.--Concentrations of magnesium at the study wetlands during periods of no precipitation.

Date	Weather	Common Influent	Effluent		
			Lane A	Lane B	Lane C
08/07/90	Dry	100	102	102	100
08/10/90	Dry	105	107	107	105
08/14/90	Dry	113	112	111	113
08/17/90	Dry	117	118	118	118

Dilution adjustment rate calculations were made by calculating a dilution factor from changes in magnesium concentration between the influent and effluent sampling locations, and then adjusting influent contaminant concentrations downward and effluent concentrations upward. In the absence of a point source of dilution whose location is known, this is the most equitable method of making dilution adjustments. Loadings were then calculated by multiplying the adjusted changes in contaminant concentrations by the influent flow rate.

The contaminant prediction method made use of regression equations developed between magnesium and contaminant concentrations at the wetland influent (table 10). Despite highly variable influent chemistry, very strong relationships ($r^2 > 0.85$) existed between magnesium and concentrations of acidity, total iron, aluminum, manganese, calcium, and sulfate. These strong relationships indicated that the chemistry of the mine drainage was largely conservative as it flows from the deep mine discharge points to the wetland influent. Changes in concentrations resulted from dilution with freshwater, a process that affected all contaminants equally and did not decrease their relative concentrations.

Table 10.--Relationships between concentrations of magnesium and other chemical parameters at the wetland influent station, January 3, 1990 - March 15, 1991.

		Equation*	r^2
Acidity	=	10.5 Mg + 141	.92
Fe ^{tot}	=	1.68 Mg + 38.4	.86
Fe ³⁺	=	1.63 Mg + 35.0	.83
Al	=	0.65 Mg + 5.7	.95
Mn	=	0.10 Mg + 1.3	.93
Ca	=	2.31 Mg + 5.3	.99
Na	=	0.02 Mg + 3.2	.34
Sulfate	=	19.2 Mg + 186	.96
H ⁺ (lab)	=	0.02 Mg + 0.88	.57

* For all regression equations, n = 62.

The strong relationship between magnesium and acidity (fig. 7) was especially useful because, in conjunction with the conservative behavior of magnesium in the wetland, it allowed confident prediction of original

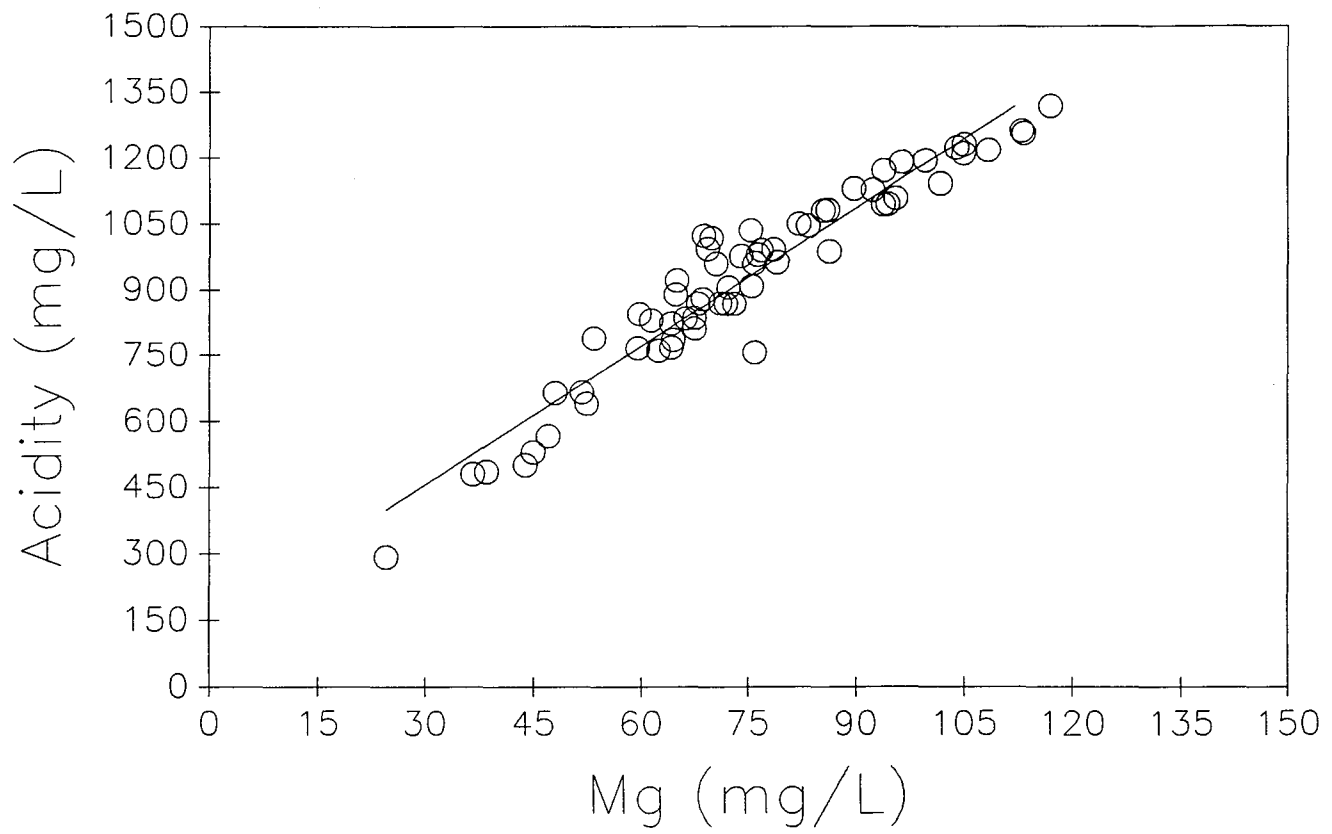


Fig. 7. Concentrations of acidity and magnesium for wetland influent water samples, December 1989 - March 1991 (n = 52).

influent acidity concentrations for each effluent sample. These predicted influent acidity concentrations were then compared to observed effluent acidity concentrations to determine removal or addition. Acidity removal rates were calculated from the change in concentration, the influent flow rate and the wetland size.

Comparisons of removal rates calculated by the three methods for each wetland lane are shown in figures 8, 9 and 10. In general, the methods resulted in similar estimates of acidity removal. However, on several occasions the loading comparison method resulted in highly negative rates while the other methods did not. Investigation of these negative rates indicated that each resulted from flow rates aberrations (table 11). On each of these days, effluent concentrations of acidity were lower than the influent sample, but because flow rates were higher at the effluent than the influent, acidity loadings (concentration times flow) were higher at the effluent station. Higher effluent flow rates on each of these occasions resulted from the measuring of flow rates during rain storms. Because these high flow rates were not sustainable for the entire inter-sampling period (3-14 days), these highly negative removal rates were considered temporary and anomalous phenomena.

Average acidity removal rates for each lane, calculated for the entire study period (November 1, 1988 - March 15, 1991) are shown in table 12. All methods indicated a net removal of acidity (positive value). The dilution adjusted method resulted in the highest rates, the

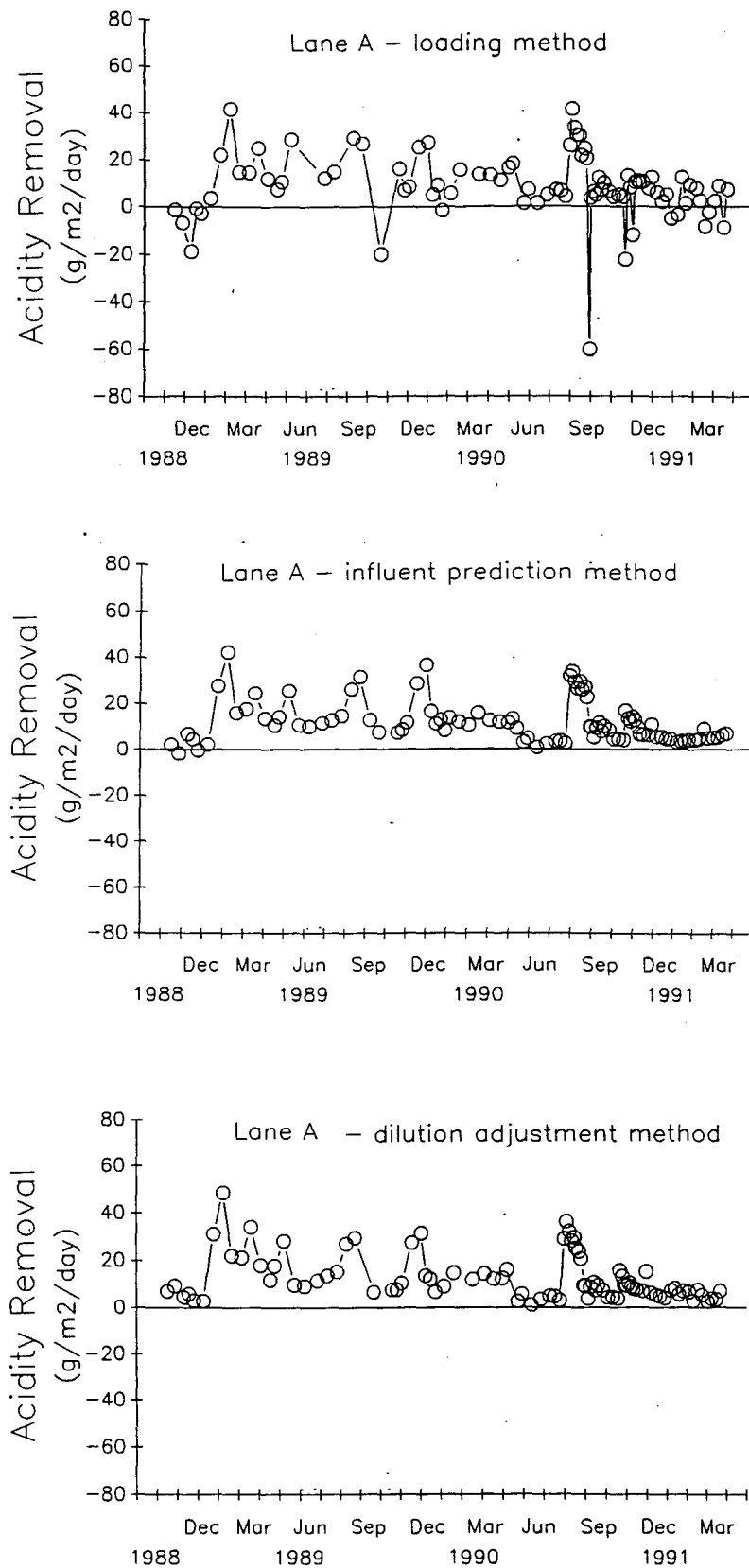


Fig. 8. Acidity removal rates for Lane A calculated by the loading method, influent prediction method, and dilution adjustment method.

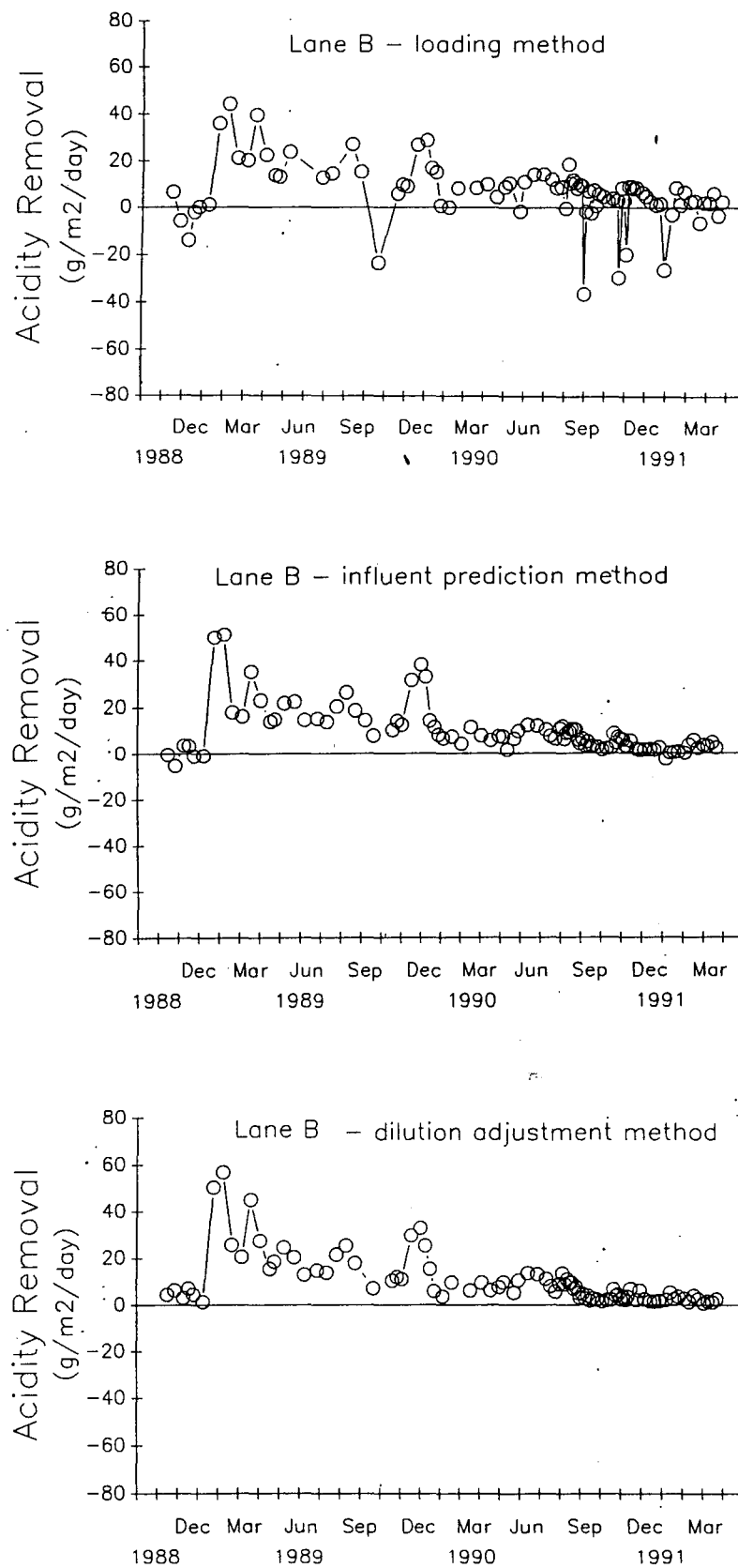


Fig. 9. Acidity removal rates for Lane B calculated by the loading method, influent prediction method, and dilution adjustment method.

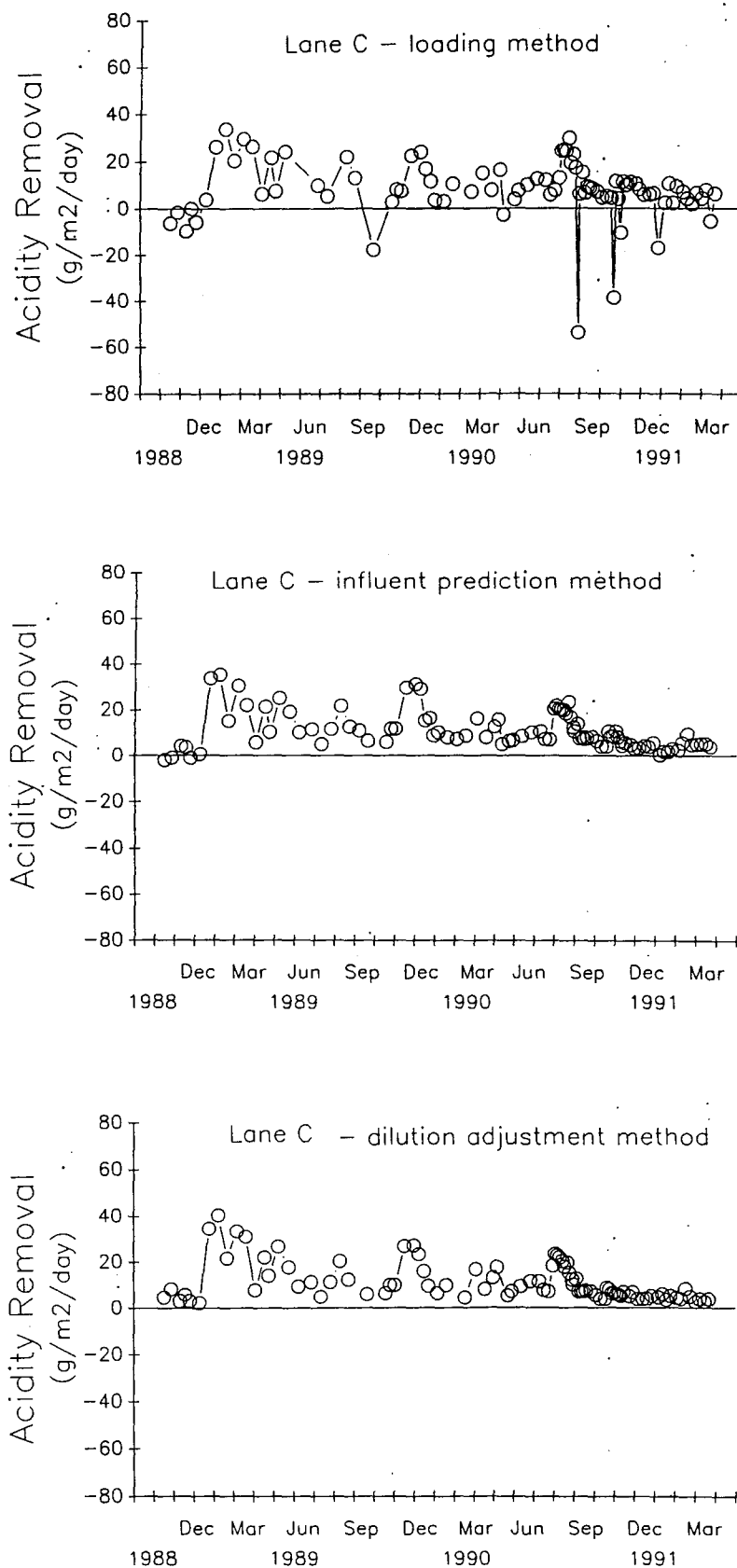


Fig. 10. Acidity removal rates for Lane C calculated by the loading method, influent prediction method, and dilution adjustment method.

Table 11.--Flow rates and concentrations of acidity for the lane A on days when the loading method indicated a net release¹ of more than 5 g m⁻² day⁻¹ of acidity.

Date	Weather	Acidity Removal Rate ²	Flow rate ³		Acidity ⁴	
			in	out	in	out
Oct 17, 1989	unknown	-19.9	3.8	10.7	567	480
Aug 21, 1990	heavy rain	-60.0	5.6	20.7	1224	770
Oct 12, 1990	heavy rain	-22.1	10.4	25.1	870	492
Oct 23, 1990	light rain	-11.8	10.6	15.2	566	509
Feb 6, 1990	light rain	-8.3	14.4	17.9	666	605
Mar 6, 1991	light rain	-9.0	4.7	11.7	501	316

¹ Negative removal rates.

² Acidity removal rates are g m⁻² day⁻¹.

³ Flow rates are L min⁻¹.

⁴ Acidities are mg L⁻¹.

Table 12.--Comparison of mean estimated acidity removal rates by the wetland lanes calculated by different methods between November 1988 and March 1991.

Lane	Acidity-removal Rate Calculation Method			
	Influent Prediction	Dilution Adjustment	Loading (modified)*	
A.....	11.0	12.4	8.7	(11.0)
B.....	9.0	10.0	6.7	(8.9)
C.....	10.5	11.4	8.4	(10.6)

*Six highly negative values were deleted. See text for details.

Mg-prediction method resulted in slightly lower rates, and the direct loading method resulted in the lowest rates. The low rates for the direct method were strongly influenced by the presence of the six negative values discussed above. When these values were deleted from the data set, the average removal rates calculated by the direct loading method were almost identical to the Mg-prediction method (see modified column in table 12).

In the rest of this report, we will only report contaminant removal rates calculated by the influent prediction method. This method was selected because of the highly variable nature of the constructed wetland influent. A study of variability of the influent water samples over a 300 hour period during the summer of 1990 indicated that significant changes in influent chemistry occurred over short time periods (12 hours), suggesting that a method which accounted for this variability needed to be used (Hedin, in preparation). During dry weather, influent concentrations of acidity varied by as much as 75 mg L⁻¹ over 12 hour periods. During a rainstorm event, concentrations varied as much as 150 mg L⁻¹ over 12 hour periods. Concentrations of magnesium in the influent samples varied in parallel with the changes in acidity, and retained the strong statistical relationship discussed previously.

REMOVAL OF ACIDITY BY THE PILOT-SCALE WETLAND

Acidity loading and removal rates² for the three wetland lanes between November 1983 and March 1991 are shown in figure 11. During the first 3 months of the wetland operation, its effects on mine water chemistry were distinct from the following 24 months. During this initial period, the wetland acted as a source of cations and anions. Water flowing through the wetland was enriched with calcium, magnesium, sodium, iron, and sulfate. Because of increases in metal concentrations, acidity sometimes increased with flow through the wetland. The wetland effluent during this period also had a very high dissolved organic carbon content.

The production of chemically-enriched, highly organic water during the first weeks or months of operation is a common feature of wetlands constructed with spent mushroom compost. This substrate, which contains gypsum (CaSO_4) and limestone, is maintained in a moist, but not flooded, condition during its use on mushroom farms and it accumulates high concentrations of salts. When flooded, the salts and gypsum dissolve and are leached. In addition, as the flooded compost becomes more reduced, iron oxides and hydroxides dissolve, and diffuse into the overlying waters.

²Loadings are the grams per day of acidity that a square meter of wetland was exposed to, while removals are the grams per day of acidity removed per square meter of wetland.

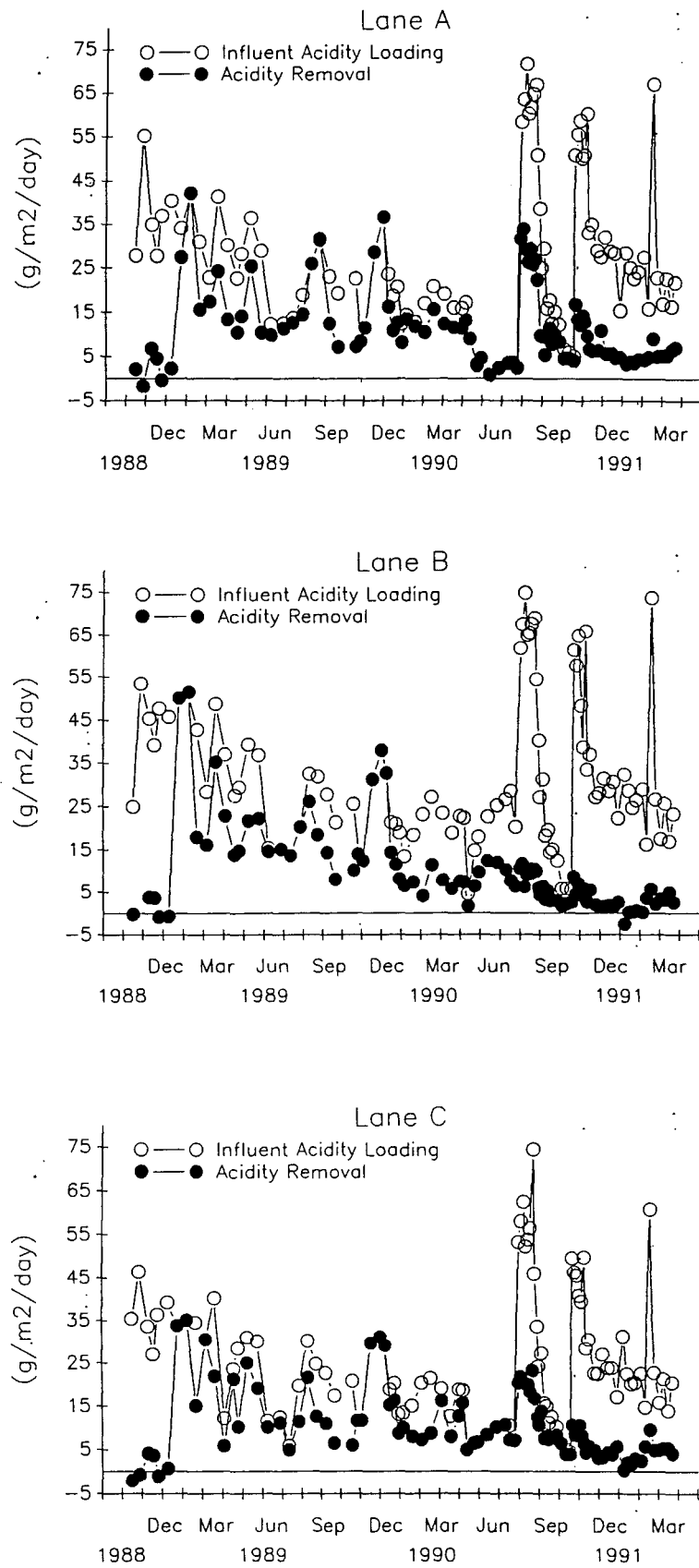


Fig. 11. Rates of acidity loading and removal for lanes A, B, and C, November 1988 - March 1991.

We will ignore the first 100 days of the wetland's operation because its short-term role as a source of metals is contrary to its long-term role as a sink for metals contained in the mine drainage. We do not intend to dismiss this period as trivial. The biochemical oxygen demand of the highly organic effluent during this period would be a serious pollutant to a high quality stream. Ice Pond Run is not such a stream. However, were compost wetlands to be built in areas where the effluent flowed into ecologically valuable receiving waters, concern about the impact of early wetland effluents would be warranted.

From February 1989 to March 1991, the wetland lanes were sinks of mine water metals and thus decreased acidity. Between February 1989 and May 1990, the wetland was used primarily for sulfate reduction research. Rates of bacterial sulfate reduction were measured periodically by the sulfate isotope ($^{35}\text{SO}_4$) method. Experiments were conducted to determine whether the beneficial attributes of sulfate reduction could be stimulated by increasing contact between the mine water and the compost substrate. Manipulations included the use of the subsurface infusion pipes, the lowering of water levels, and the construction of Plexiglas dams. Details of the rate measurements and the results of these experiments are presented in McIntire, Edenborn and Hammack (1990). In summary, the research determined that high rates of sulfate reduction occurred in the compost substrates. Attempts to increase contact between mine water and compost always resulted, initially, in alkaline effluents and very high rates of acidity removal (see peaks in fig. 11). However, the beneficial effects of these manipulations proved temporary.

Apparently the high rates of acidity removal occurred primarily through the dissolution of alkaline compounds that, once exhausted, allowed the substrate pH to fall below five. As sulfate reducing bacteria are inactive below this pH, the beneficial by-products of their activity were no longer produced. As a result, it appears prudent to allow passive exchange of acidic surface water and alkaline substrate pore water, as occurs naturally in "surface flow" wetlands. Since May 1990, all flow of water through the constructed wetlands has been by surface routes.

ACIDITY REMOVAL RATE EXPERIMENTS

Between May 1990 and July 1991, research at the constructed wetlands focused on the measurement of acidity removal rates, so that sizing criteria could be developed for this site and others where acid mine drainage exists. The approach used was to vary loadings through manipulations of influent mine drainage flow rates. The goals were: 1) to identify a loading rate at which the wetland could successfully treat the mine waters, 2) to determine how variable acidity removal was between the lanes, and 3) to determine whether removal of acidity varied seasonally.

Our first objective, identification of the optimal acidity loading rate (where removal = loading), was approached by performing a loading experiment. Previous work at the wetland suggested that, on average, a flow rate of 2 L min^{-1} appeared optimal for a single wetland lane. We

predicted that less flow would result in incomplete utilization of acidity-removal capabilities, while more flow would result in incomplete removal of the acidity load.

The predictions were tested by setting the influent flow rates to the individual experimental lanes at different rates, so that the lanes were exposed to different loads of acidity. Lane A was assigned a flow rate of 1 L min^{-1} , lane C was assigned 2 L min^{-1} , and lane B was assigned 4 L min^{-1} .³ For two months, water samples were collected and flow rates were measured at the influent and the effluent of each lane. Acidity loading rates and acidity removal rates were calculated as discussed previously.

Summary statistics for the experiment are shown in table 13. Flow rates were lower than originally planned, but were consistent within lanes between sampling days. Influent water chemistry (which was common to each lane) varied during the experiment because of the weather conditions.

Effluent water chemistry during the loading experiment was distinct for lane B, but similar for lanes A and C (fig. 12). The latter lanes produced effluents with $\text{pH} > 5$, markedly decreased concentrations of aluminum and iron, and were either alkaline or only marginally acidic. Acidity removal rates, however, varied between lanes A and C

³Assignment of flow rates to lanes was random.

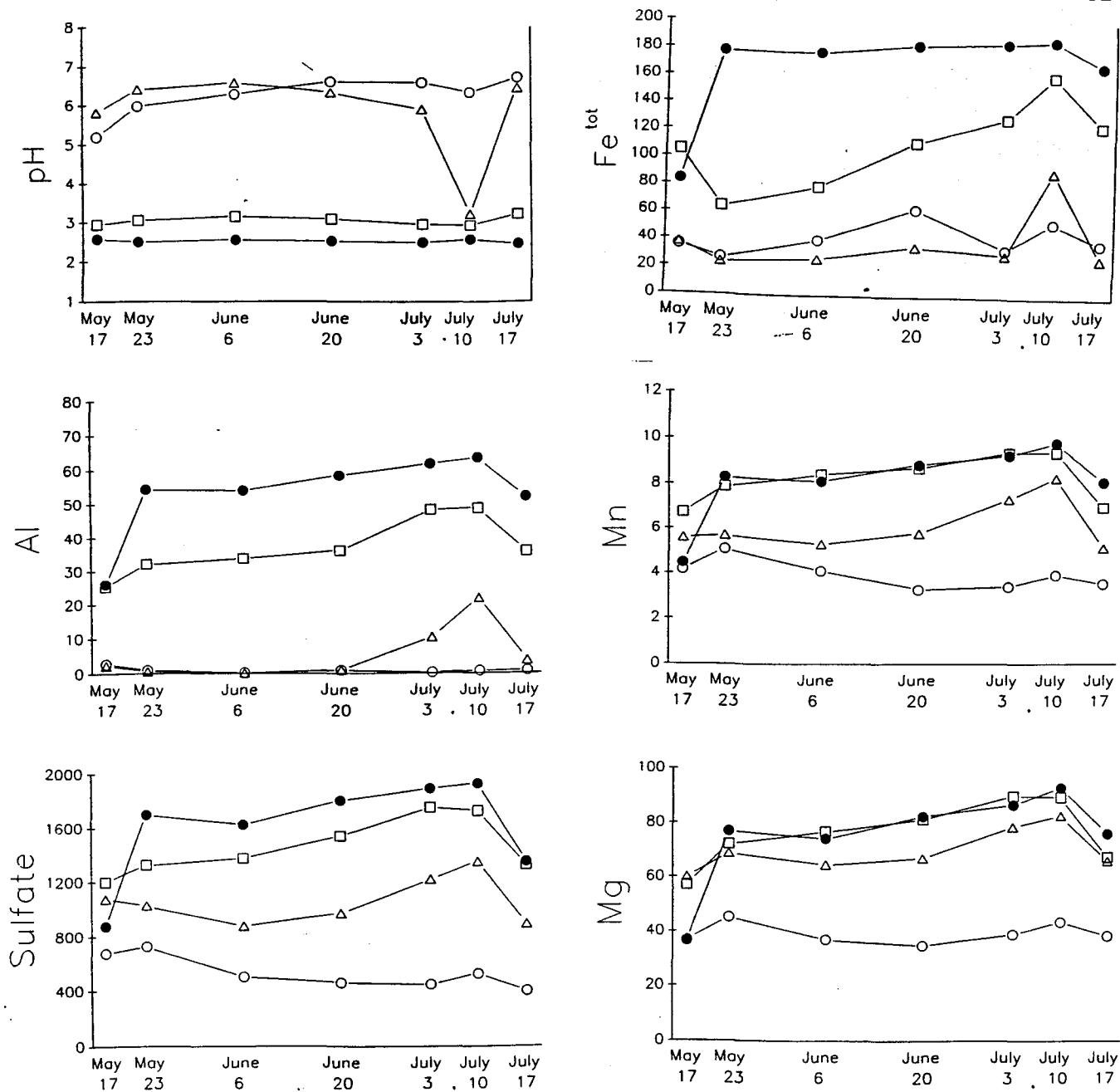


Fig. 12. Water chemistry for the wetlands lanes, May 17, 1990 - July 17, 1990.
 Symbol key: solid circles, influent; open circles, lane A;
 triangles, lane C; squares, lane B.

Table 13.--Summary statistics for loading experiment,
May 17 - July 17, 1990.

Parameter	Unit	Lane A	Lane C	Lane B
Flow _{in}	L min ⁻¹	0.9 (0.2)	1.7 (0.3)	3.3 (0.4)
pH _{in}		2.7 (0.7)	2.7 (0.7)	2.7 (0.7)
Acidity _{in}	mg L ⁻²	945 (217)	945 (217)	945 (217)
Acid load _{in} ...	g m ⁻² day ⁻¹	3.8 (0.9)	12.5 (2.2)	25.8 (5.8)
pH _{out}		5.9 (1.0)	5.7 (1.3)	3.1 (0.1)
Acidity _{out}	mg L ⁻¹	-93 (86)	-88 (204)	542 (141)
Acid rem _{out} ...	g m ⁻² day ⁻¹ -1	3.9 (0.8)	9.4 (2.1)	9.3 (2.5)

Values in parentheses are standard deviations. For all values, n = 7.
"In" refers to water that was collected at the influent of each lane.
"Out" refers to water that was collected at the effluent of each lane.

fig. 13, table 13). The average removal rate for lane A was 3.9 g m⁻² day⁻¹, while lane C averaged 9.4 g m⁻² day⁻¹.

If the lanes are assumed to have equal acid-removal capabilities (an assumption evaluated shortly), then lane A's lower removal rate can be simply attributed to load limitation. With only 3.8 g m⁻² day⁻¹ of acidity loading entering the wetland, removal of much more than this is impossible⁴. At 3.8 g m⁻² day⁻¹ of acidity loading, the wetland was being underutilized. Lane C's acidity loading rate averaged 12.5 g m⁻² day⁻¹, of which 9.4 g m⁻² day⁻¹ was removed. The rate would be higher, almost equal to the loading, except for one sample collected July 10, 1990. This anomalous sample cannot be explained. Lane B discharged acidic water with pH 2.8 - 3.2 and acidities of 400 - 800 mg L⁻¹. The wetland never removed more than 58% of its acidic load. Thus, this lane

⁴Removal of acidity slightly in excess of load occurs because we treated alkalinity as negative acidity.

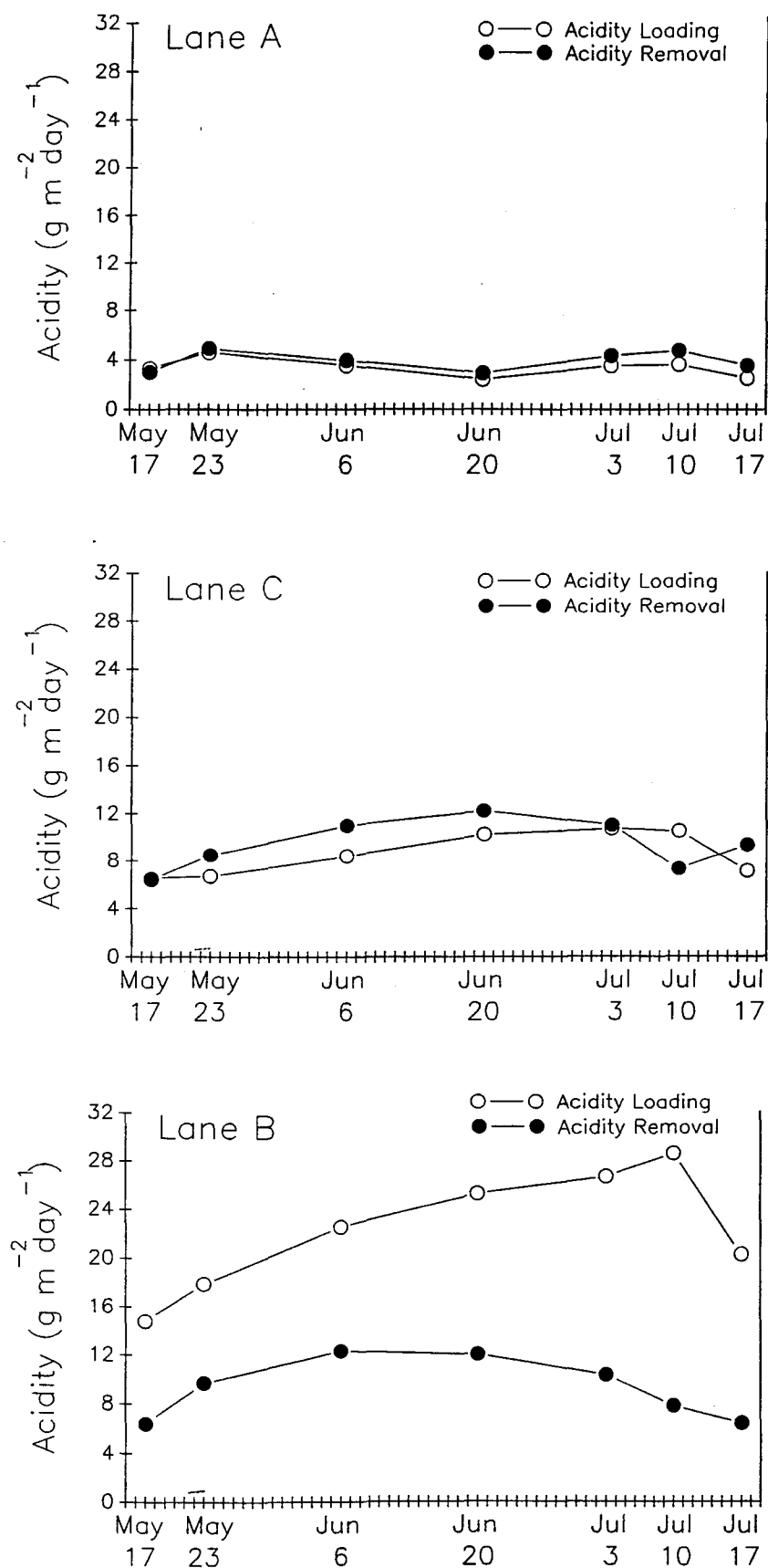


Fig. 13. Acidity removal rates for the wetland lanes, May 17 - July 17, 1990.

was undersized with respect to its influent acidity load. However, the average rate of removal of $9.4 \text{ g m}^{-2} \text{ day}^{-1}$ was the same rate as observed for lane C. This similarity indicates that during early summer months, the wetlands were capable of removing approximately $9 \text{ g m}^{-2} \text{ day}^{-1}$ of acidity.

Variability in Acidity Removal by the Wetland Lanes

The results of the first loading experiment established that Ice Pond Run water could be treated successfully by a constructed wetland, given the proper loading rate. An acidity removal capability of about $9 \text{ g m}^{-2} \text{ day}^{-1}$ was indicated for summer months. To better understand the variability in acidity removal at the constructed wetland, experiments were designed that utilized the three lanes as replicate wetland systems. Between July 24, 1990 and October 9, 1990, influent acidity loadings were periodically adjusted by changing influent flow rates. During any single period, however, the influent flow rates into each lane were approximately equal. Thus, on each sampling day all three lanes were exposed to similar loadings of acidity. Initially, flow rates were set at 10 L min^{-1} , a high rate that resulted in very high acidity loadings ($50\text{-}80 \text{ g m}^{-2} \text{ day}^{-1}$). Over the next two months, the flow rates were decreased every 10-14 days by $1\text{-}2 \text{ L min}^{-1}$ increments. The lowest flow rate tested was 1 L min^{-1} .

Summary statistics of the experiment are shown in table 14.

Influent acidity loadings were similar between all lanes on all dates (fig. 14). Slight variability in acidity loadings resulted from unequal area adjustments necessary to produce rates ($\text{g m}^{-2} \text{ day}^{-1}$). Lane C had the largest surface area and, thus, the lowest area-adjusted acidity loads. This minor variation in loading rates between the lanes was not considered large enough to invalidate the use of the lanes as replicates during this experiment.

Acidity removal rates varied markedly between lanes (table 14, fig. 15). Lane B consistently removed less acidity than the other two lanes. Lane A removed more acidity than lane C at higher loading rates, but removed similar amounts of acidity when loadings were less than $25 \text{ g m}^{-2} \text{ day}^{-1}$.

Table 14.--Summary statistics for the loading variability experiment, July 24, 1990 - Oct 9, 1990.

Lane	Acidity Loading		Acidity Removal	
	mean	(s.d.)	mean	(s.d.)
A.....	35.9	(24.7)	16.4	(10.8)
B.....	37.9	(25.9)	6.3	(3.4)
C.....	32.8	(23.0)	13.3	(6.5)

All units are $\text{g m}^{-2} \text{ day}^{-1}$. For all values, $n=19$.

Based upon the results of previous experiments, we expected that acidity removal rates during the current experiment would be limited to about $9 \text{ g m}^{-2} \text{ day}^{-1}$. This prediction was only realized in lane B.

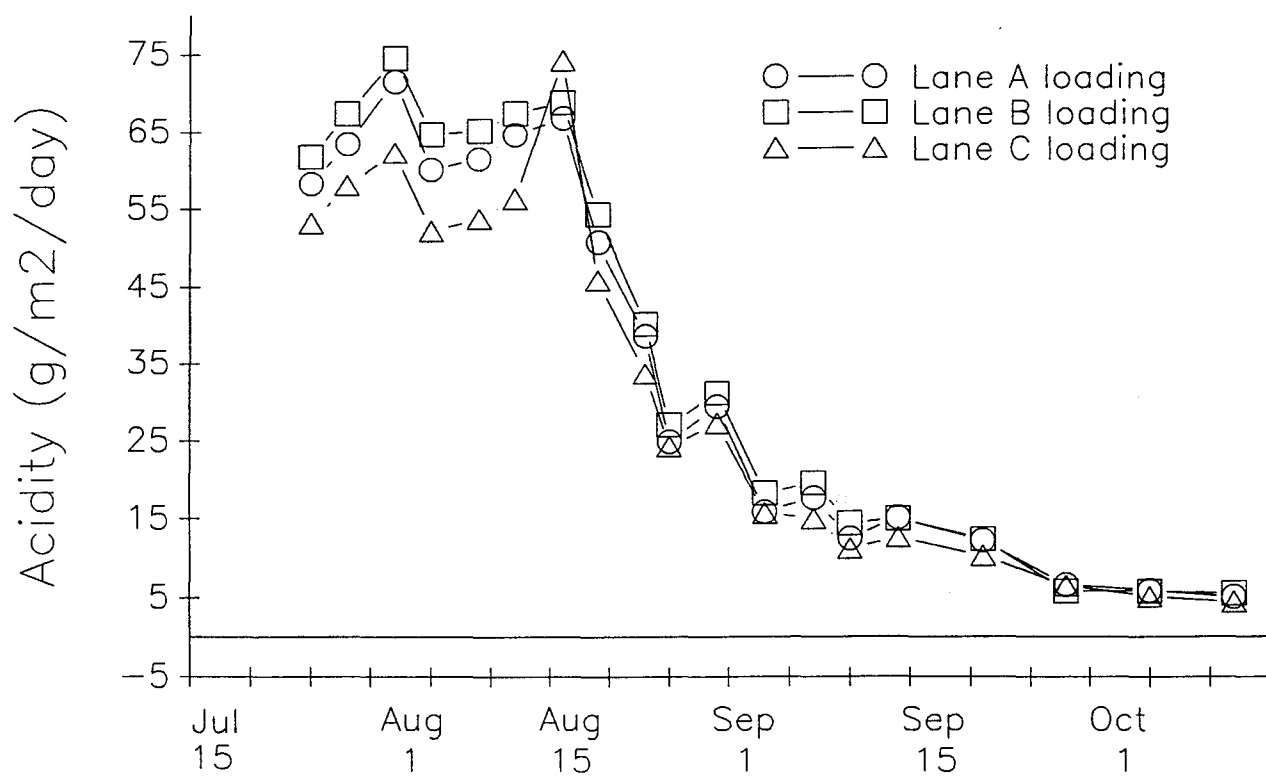


Fig. 14. Rates of acidity loading in the wetland lanes, July 24, 1990 - October 9, 1990.

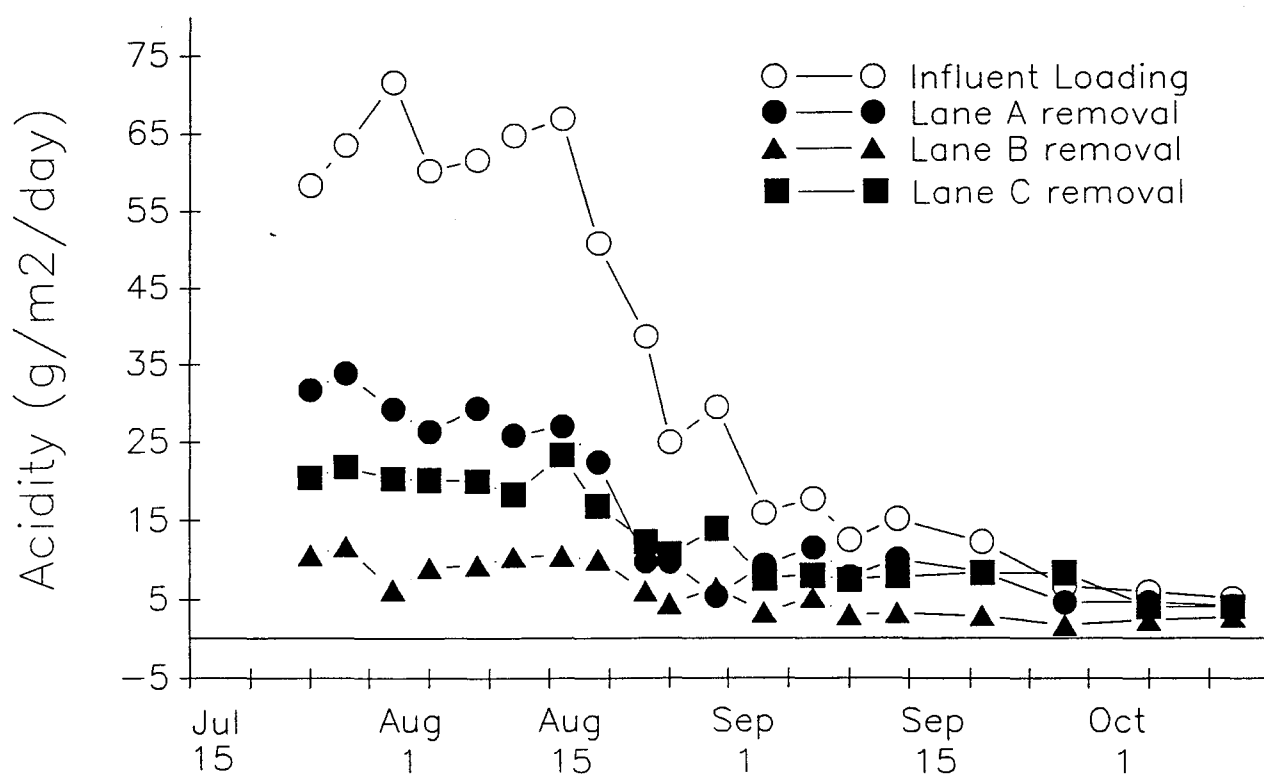


Fig. 15. Mean acidity loadings and acidity removal rates for Lanes A, B, and C, July 29, 1990 - October 9, 1990.

During the first month of this experiment, when acidity loading rates in lane B were greater than $25 \text{ g m}^{-2} \text{ day}^{-1}$, acidity removal rates averaged $9.3 \text{ g m}^{-2} \text{ day}^{-1}$. This rate was identical to the average acidity removal rate observed for lane B during the previous experiment (see table 13). Markedly higher rates of acidity removal were observed in lanes A and C. During the early stages of the experiment, removal rates of more than $20 \text{ g m}^{-2} \text{ day}^{-1}$ were observed regularly in both lanes. The average removal rates during the first month of the experiment were $26.2 \text{ g m}^{-2} \text{ day}^{-1}$ for lane A and $20.1 \text{ g m}^{-2} \text{ day}^{-1}$ for lane C.

The high rates of acidity removal by lanes A and C during the first month of this experiment were unexpected. It is unlikely that high loading rates actually stimulated alkalinity-generating processes in the wetlands. Instead, we suspect that the high removal rates were an artifact of the very low loading rates to which both lanes were exposed between May 17 and July 17. During this period, surface water in the lanes was largely alkaline. The absence of steep chemical gradients between the pools of surface water and substrate pore water likely promoted low exchange rates between the pools. Under such conditions, the products of bacterial sulfate reduction and limestone dissolution accumulate and pore water chemistry becomes highly alkaline and depleted in concentrations of metals and sulfate, compared to surface water. During low-flow, low-loading events at other constructed wetlands, we have collected pore water samples that had alkalinity concentrations of more than 1000 mg L^{-1} and sulfate concentrations that were $800\text{-}1,400 \text{ mg L}^{-1}$ lower than surface water samples (Hedin, in review).

When the flow rates into a wetland are increased suddenly, steep gradients between the chemical constituents in the overlying water and porewater can result. Under these conditions, porewater alkalinity will diffuse into the overlying water. Additionally, increased water flow over the sediment surface should increase the flux of alkalinity from the porewater to the surface water. When flow rates in cells A and C were increased from $1\text{--}2\text{ L min}^{-1}$ (their levels between May 17 and July 17) to 10 L min^{-1} , acidity loading rates increased dramatically and the pH of surface water throughout both lanes fell below 3; conditions that should be ideal for the "extraction" of accumulated, highly-alkaline pore water.

No measurements of substrate pore water chemistry were made in lanes A and C during the summer or autumn of 1990, so evaluation of the above scenario with chemical data is not possible. Calculations, however, indicate its feasibility. If $1,000\text{ mg L}^{-1}$ of accumulated "excess" alkalinity were extracted from the compost substrate over a 30 day period, an average $12\text{ g m}^{-2}\text{ day}^{-1}$ of alkalinity would be released to the surface water. This hypothetical value is large enough to explain much of the excess acidity removal observed during the first month of the experiment in lanes A and C, relative to lane B.

Thirty days into this loading experiment, acidity removal rates for lanes A and C decreased to lower levels and remained similar throughout the rest of the experiment. Removal of acidity by lane B was, however, always approximately 50% less than the removal observed for lanes A and C (fig. 15).

At this time, we cannot confidently explain the lesser acidity-removal performance of lane B. Although there are physical differences between the lanes (e.g., lane B has 50% deeper surface water), the variability that exists is typical of that found within constructed wetlands. Indeed, efforts made to standardize the physical conditions in each lane at the Friendship Hill pilot-scale wetland went far beyond any used in typical wetland construction efforts. We therefore consider the variability in acidity removal rates between the lanes to be representative of that observed in typical constructed wetlands.

Between August 21 and September 18, 1990, acidity loadings averaged $21.5 \text{ g m}^{-2} \text{ day}^{-1}$ (s.d.=9.0, n=23) and were always higher than $10 \text{ g m}^{-2} \text{ day}^{-1}$. Over this period, which excludes the atypically high acidity removal rates of the first 30 days, the average acidity removal rate for the pilot wetland was $7.6 \text{ g m}^{-2} \text{ day}^{-1}$ (s.d.=3.1, n=23).

Although we intended to subject the wetland lanes to low acidity loadings for much of the latter half of the experiment, very high influent concentrations of acidity ($850\text{-}1250 \text{ mg L}^{-1}$) kept loadings high, even when flow rates were decreased to 2 L min^{-1} . Acidity loadings

decreased below $10 \text{ g m}^{-2} \text{ day}^{-1}$ only between September 25 and October 9 when flow rates were set at 1 L min^{-1} . During this period, the average acidity loading was $5.6 \text{ g m}^{-2} \text{ day}^{-1}$ (s.d.=0.7, n=9), while the average acidity removal rate was $3.8 \text{ g m}^{-2} \text{ day}^{-1}$ (s.d.=1.4, n=9). Alkaline water was discharged from lane C on one sampling day. On all other days, the effluent of all lanes was greatly improved over influent water samples, but was still acidic.

Seasonal Variability in Acidity Removal

Between November 1, 1990 and July 3, 1991, influent flow rates to all wetland lanes were set at a constant 5 L min^{-1} . The research goal over this period of time was to determine whether rates of acidity removal decreased in winter months. A constant influent flow rate was used so that artifacts resulting from flow manipulations could be avoided. A moderately high flow rate, and hence loading rate, was selected to ensure that acidity removal would never be loading-limited.

Summary statistics for the individual lanes are shown in table 15. Acidity loadings during this period varied from $12\text{-}36 \text{ g m}^{-2} \text{ day}^{-1}$. This variation was due to natural variability in the chemistry of the influent mine water. Lanes A and C continued to remove acidity at similar rates, while removal rates for lane B were at least 50% lower.

Table 15.--Summary statistics for pilot scale wetlands, November 1, 1990 - July 15, 1991.¹

Parameter	Influent		Lane A		Lane B		Lane C	
Flow rate ²	-	-	4.7	(0.4)	4.6	(0.3)	4.7	(0.5)
Water								
Chemistry ³								
Acidity.....	837	(188)	616	(162)	731	(168)	651	(172)
Fe.....	146	(31)	124	(37)	136	(33)	121	(33)
Al.....	49	(11)	40	(11)	44	(11)	41	(11)
Ca.....	165	(42)	180	(51)	173	(48)	184	(48)
Mg.....	69	(17)	66	(20)	68	(18)	68	(19)
Sulfate.....	1493	(323)	1316	(349)	1410	(338)	1357	(346)
Acidity Loading ⁴ ...	-	-	25.1	(6.2)	26.8	(6.2)	23.1	(6.0)
Acidity Removal ⁴ ...	-	-	6.0	(2.3)	3.3	(2.8)	5.0	(2.3)

¹ All values are the average of 33 observations. Standard deviations are in parentheses.

² Flow rate data are L min⁻¹.

³ Water chemistry values are mg L⁻¹.

⁴ Loading and removal data are g m⁻² day⁻¹.

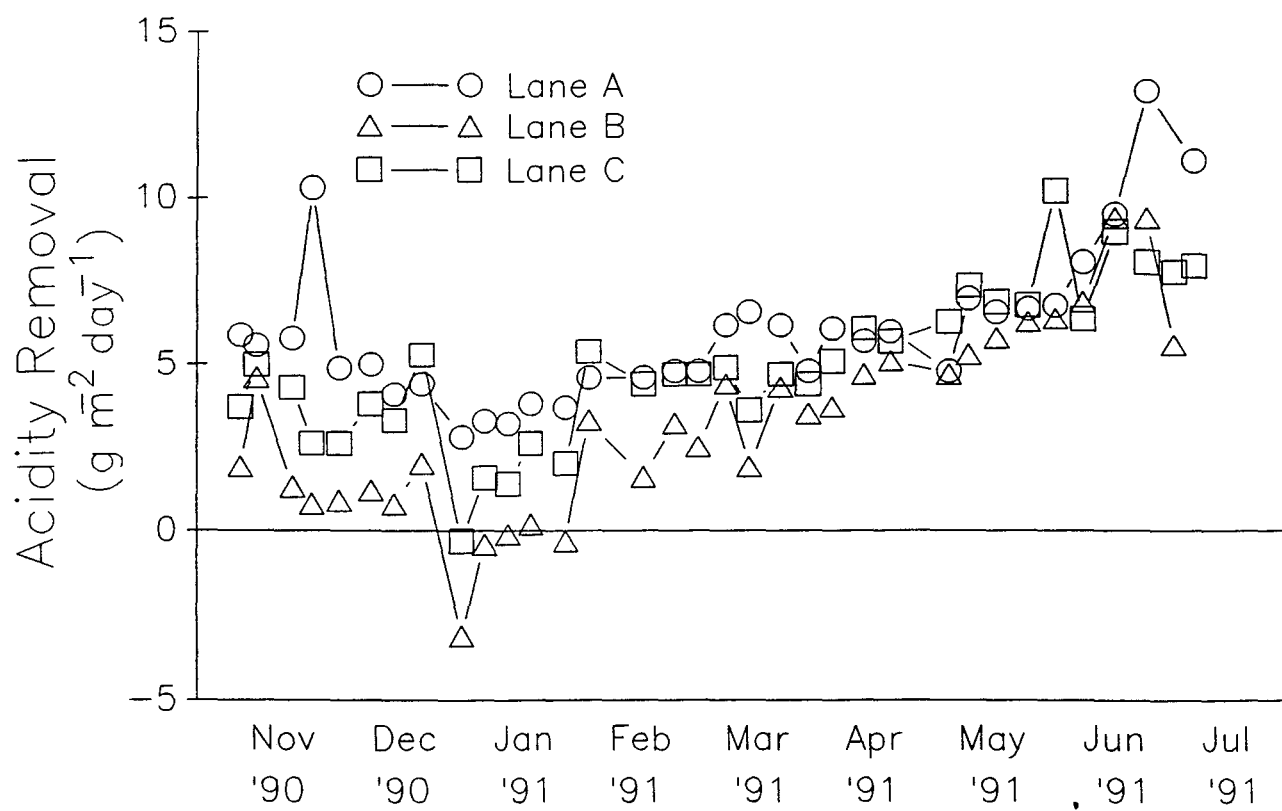


Fig. 16. Acidity removal by the wetland lanes, November 1, 1990 - March 15, 1991.

Acidity removal rates during winter months were lower than rates that had been established during experiments conducted during early summer ($9 \text{ g m}^{-2} \text{ day}^{-1}$) and autumn ($7 \text{ g m}^{-2} \text{ day}^{-1}$) 1990. Between November 2 and December 18, acidity removal rates averaged $4.4 \text{ g m}^{-2} \text{ day}^{-1}$ (s.d.=2.2, n=24). Between December 28 and January 24, acidity removal rates in all lanes decreased further, and mean acidity removal rates fell to $1.9 \text{ g m}^{-2} \text{ day}^{-1}$ (s.d.=1.9, n=15). During this period of decreased wetland performance, the wetland was partially frozen and water temperatures were less than 5°C . In February and March, acidity removal rates increased to $4\text{-}6 \text{ g m}^{-2} \text{ day}^{-1}$. The weather during this period was typified by warm days interspersed with cold, sub-freezing days. Water temperatures during this period were generally around 10°C . During spring and early summer months, acidity removal rates increased to $6\text{-}10 \text{ g m}^{-2} \text{ day}^{-1}$; rates similar to those observed during loading experiments 12 months previous.

Table 16 summarizes mean monthly acidity removal data for the pilot wetland between June 1990 and July 1991. Data from periods when acidity removal rates were underestimated due to loading-limitations and overestimated due to artifacts associated with manipulations of flow rates were deleted. Mean monthly removal of acidity varied from a high of $9.9 \text{ g m}^{-2} \text{ day}^{-1}$ in June 1990 to a low of $2.8 \text{ g m}^{-2} \text{ day}^{-1}$ in January. Removal rates decreased between June and January 1990, and then

increased between February and July 1991. Rates were similar during summer months (t-tests comparing mean rates for June, July, August and September all indicated no significant differences). The average warm weather acidity removal rate for the pilot wetland was $8.5 \text{ g m}^{-2} \text{ day}^{-1}$.

Table 16.--Mean monthly acidity removal rates for the pilot wetland.

Month	n	Average Load	(sd)	Average Removal	(sd)
Jun 1990.....	6	15.0	(7.9)	9.9	(2.1) ¹
Jul 1990.....	6	17.3	(9.3)	8.3	(1.8) ¹
Aug 1990.....	12	27.7	(8.0)	8.2	(3.2)
Sep 1990.....	12	14.3	(2.9)	7.0	(2.8)
Oct 1990.....	6	56.0	(10.6)	6.0	(1.8) ²
Nov 1990.....	15	29.5	(4.3)	4.7	(2.5)
Dec 1990.....	12	24.9	(6.2)	3.0	(2.4)
Jan 1991.....	15	21.4	(5.0)	2.8	(1.8)
Feb 1991.....	9	20.1	(4.3)	4.4	(1.1)
Mar 1991.....	12	18.1	(2.8)	4.6	(1.3)
Apr 1991.....	9	20.2	(2.9)	5.3	(0.8)
May 1991.....	15	27.8	(3.7)	6.5	(1.3)
Jun 1991.....	11	32.7	(4.3)	8.5	(2.0)
Jul 1991.....	2	31.9	(3.8)	9.5	(2.3)

Loading and removal rates are $\text{g m}^{-2} \text{ day}^{-1}$ of acidity.

¹Only removal by lanes B and C are included because lane A was underloaded during these periods.

²Only removal by lane B is included because lanes A and C had high removal rates that were considered atypical.

Rates were statistically lower in winter months, and December, January and February clumped together as a group. The average cold weather acidity removal rate for these months was $3.7 \text{ g m}^{-2} \text{ day}^{-1}$.

Sources of Alkalinity in the Pilot-Scale Wetland

It was stated earlier that alkalinity is generated in compost wetlands by limestone dissolution and bacterial sulfate reduction. Each process has an analytical "signature" that allows estimation of its rate of production. Limestone dissolution results in increased concentrations of soluble calcium, while sulfate reduction results in decreased concentrations of sulfate. Because the stoichiometry of both processes is well-known (reactions 2 and 3), the amount of alkalinity generated per gram of calcium solubilized and per gram of sulfate removed is easily calculated. Estimates of the amount of alkalinity associated with increased concentrations of calcium and decreased concentrations of sulfate correlated closely with measured acidity removal (fig. 17). On average, between July 24, 1990 and July 15, 1991, the wetlands removed $7.2 \text{ g m}^{-2} \text{ day}^{-1}$ of acidity ($n = 178$, $\text{sd.} = 5.4$). Sulfate reduction and limestone dissolution resulted in the generation of $6.8 \text{ g m}^{-2} \text{ day}$ of alkalinity ($n = 178$, $\text{sd.} = 5.5$). Thus, 94% of the acidity removal at the constructed wetland could be accounted for by these two processes.

Bacterial sulfate reduction, as indicated from removal of dissolved sulfate, was the dominant source of alkalinity in the wetland lanes (table 17). On average, the alkalinity generated by sulfate reduction accounted for 60% of the observed acidity removal. Generation of alkalinity through sulfate reduction, however, was more variable than its generation through limestone dissolution (fig. 18). Alkalinity

generated by sulfate reduction was especially variable during the winter of 1990/91 when rates of alkalinity generation attributable to it ranged from $-3 \text{ g m}^{-2} \text{ day}^{-1}$ to $10 \text{ g m}^{-2} \text{ day}^{-1}$. Over this same period, alkalinity generated from limestone dissolution only ranged from -1 to $+2 \text{ g m}^{-2} \text{ day}^{-1}$.

Table 17.--Alkalinity generation attributable to sulfate reduction and CaCO_3 dissolution in lanes A, B, and C, July 24, 1990 - July 3, 1991.

Lane	n	Source of Alkalinity			
		Sulfate Reduction		CaCO_3 Dissolution	
		mean	(sd)	mean	(sd)
A.....	59	4.3	(2.7)	3.6	(3.5)
B.....	59	2.4	(2.4)	1.3	(1.1)
C.....	60	4.8	(3.0)	2.6	(2.0)
Wetland.....	178	4.3	(3.4)	2.5	(2.5)

All rates are $\text{g m}^{-2} \text{ day}^{-1}$ of CaCO_3 equivalent.

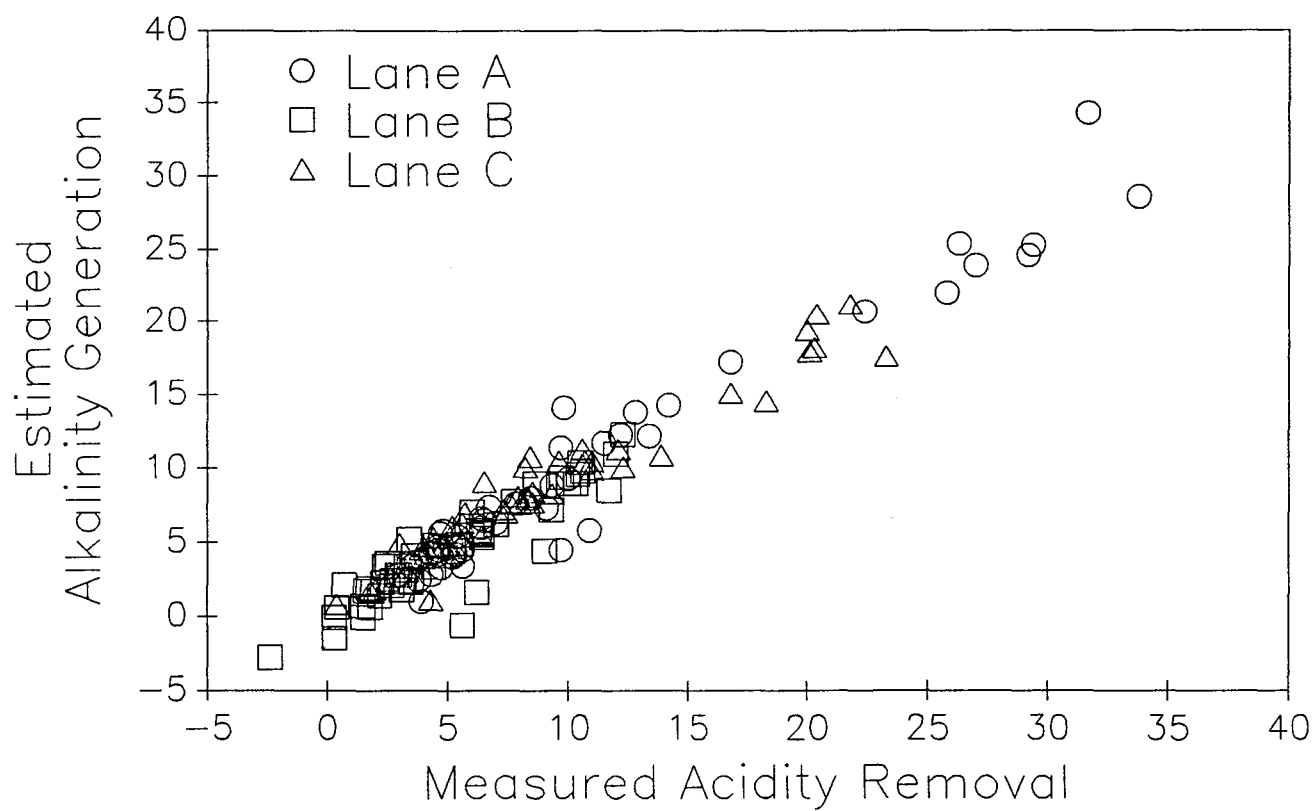


Fig. 17. Relationship between estimated rate of alkalinity generation and measures rates of acidity removal.

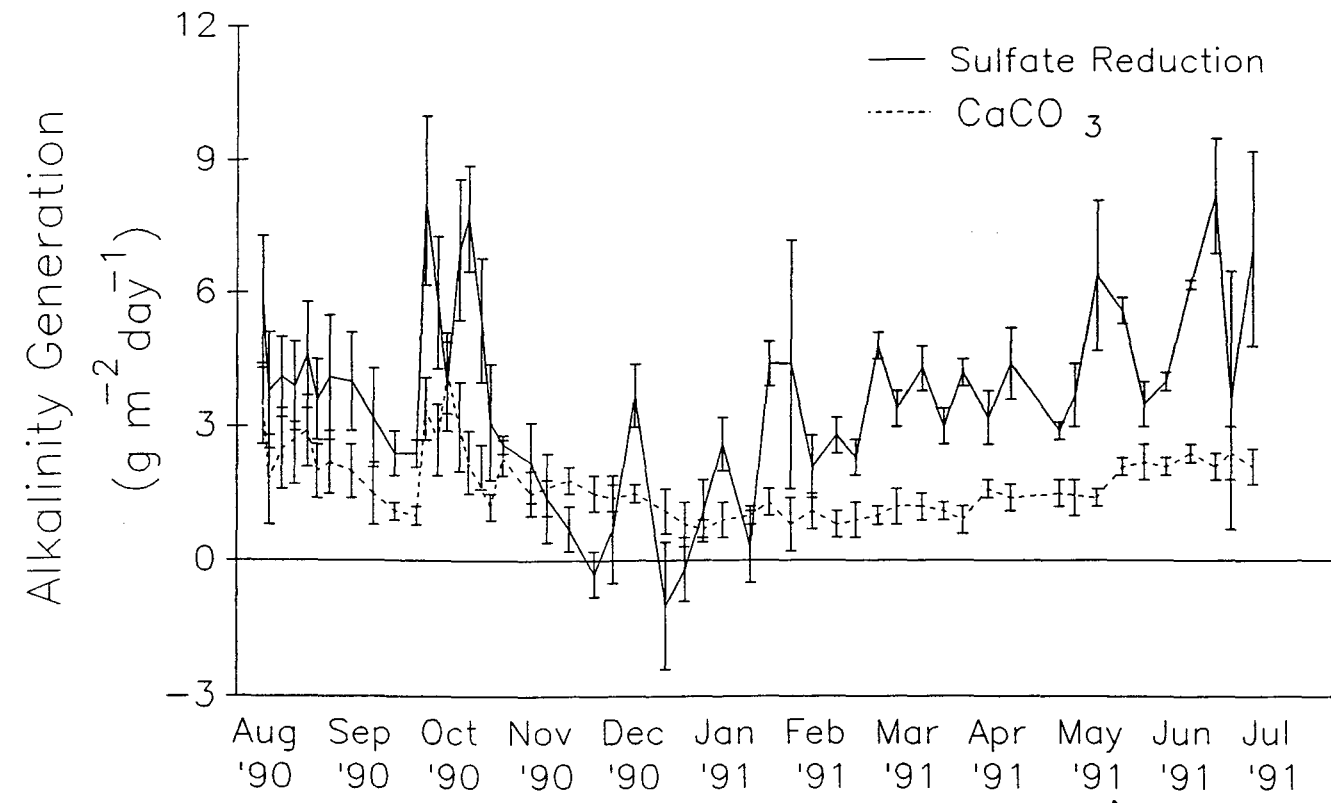


Fig. 18. Rates of alkalinity generation attributable to sulfate reduction and limestone generation.

CONCLUSIONS AND RECOMMENDATIONS

Research done during the course of this study has established that the processes occurring in constructed wetlands can be used to treat severely polluted acid mine drainage. Calculations given in this section show that the polluted water of Ice Pond Run can be treated using a wetland alone, but that this is a relatively expensive treatment alternative that will require considerable land area. In addition to wetland systems, a number of other alternative treatments could be considered for the treatment of Ice Pond Run. These potential solutions are presented in the following section, so that the relative options and costs can be compared with each other. The potential solutions to the Friendship Hill acid mine drainage problem presented here are followed by short summaries of concerns raised by National Park Service reviewers regarding each proposed solution. It should be noted that none of the proposed treatment options are perfect: some may be too expensive, some may create temporary environmental side effects unrelated to the original problem, some may alter the appearance of the landscape significantly, and some may not meet state or federal environmental requirements. Each of these problems must be investigated more fully before any of the potential solutions presented here can be implemented at the field site. The actual treatment of choice will be highly dependent upon the finances available for the construction and maintenance of a treatment system and the ultimate goals of the National Park Service.

POTENTIAL SOLUTIONS FOR THE FRIENDSHIP HILL ACID MINE DRAINAGE PROBLEM

1. No treatment. Currently, acid mine drainage flows through the park, unimproved by any NPS activities. The "no treatment" status is a legal NPS option because the drainage flows from a mine abandoned previous to the enactment of state and federal water quality standards that currently regulate the mining industry. Under current laws, the owners of lands where such unpermitted discharges occur are not legally responsible for their treatment. The simplest and cheapest option for the park is to continue to allow the discharges to flow unmitigated into Ice Pond Run.

2. Surface Mine the Abandoned Deep Mine. The most cost-effective and permanent method for decreasing the mine drainage problem at Friendship Hill is to surface mine the remaining coal. During the mining process, highly-pyritic materials that currently contaminate the mine drainage would be handled in a manner that would minimize further oxidation. Proper reclamation procedures would likely eliminate or greatly decrease the mine drainage problem. To successfully execute this option, the entire abandoned mine would probably require mining. Thus, private landowners in the area would need to be involved. Mining of the park's coal would produce income that could be used to treat any residual contaminated mine drainage that persisted.

We are aware of recent attempts by a private mining company to obtain a surface mining permit for part of the abandoned deep mine. We have not investigated the current status of this plan, or whether the park was ever involved in the permitting review process. Were the park to be contacted about such a mining project, we would recommend that the prospect not be rejected out of hand. Although the thought of surface mining part of the park property would certainly be disturbing to many parties, the possibility that Ice Pond Run could be transformed from a park detriment to a park asset should weigh heavily in any mining decisions.

Potential Problems (NPS comments):

Removal of coal from federal land alone would not solve the problem: removal of the coal from adjacent non-federal lands would have to be addressed. Would it be economically feasible to mine the coal? Hydrology studies would be required to determine the effect of mining on the subsequent drainage of water from the mine site; if AMD were to flow onto non-federal lands, would the NPS be responsible for treatment of that AMD? Existing NPS policies/regulations and other federal regulations may conflict with this recommendation.

3. Dilution of Ice Pond Run. Data collected during our investigations at Friendship Hill indicated that inputs of freshwater to Ice Pond Run occasionally resulted in significant dilution of contaminant concentrations. During several periods of 1990, dilution between the deep mine and the constructed wetland was sufficient to lower

contaminant concentrations by 60-75% (fig. 4). Flow through the rest of the watershed on these days likely decreased contaminant concentrations by at least another 75% between the wetland and the Monongahela River.

The occurrence of periods of significant dilution prompted calculations that evaluated the legitimacy of a "dilution solution." The calculations were based upon the average combined iron chemistry and flow rates of the primary and secondary mine discharges. Only iron was considered in the calculations because it is the contaminant present in the highest concentrations. The target post-dilution iron concentration was 3 mg L^{-1} , the current regulatory standard for most active coal mines in the United States.

The results of the calculations indicate that dilution is not a feasible option. To dilute the average mine discharge iron concentration of 276 mg L^{-1} to 3 mg L^{-1} would require 91 L of freshwater for each liter of contaminated water. The average mine discharge flow rate is 253 L min^{-1} , so $23,276 \text{ L min}^{-1}$ of freshwater would be necessary. On an annual basis, this is approximately 12.2 billion liters of freshwater. Rainfall in southwestern Pennsylvania averages about 100 cm/yr or 10 million L/ha/yr. The total rainfall of 1220 ha (3013 acres) would be required. Most likely, only 10-20% of the total rainfall could be captured and utilized, so approximately 20,000 ha would be necessary. This is approximately 75 square miles.

4. Pipe the Mine Discharge to the Monongahela River. Water quality data collected from Ice Pond Run during our investigations indicated that dilution was the dominant process affecting the chemistry of Ice Pond Run as it flowed to the Monongahela River (tables 3 and 4). Thus, one option is to divert the mine drainage out of Ice Pond Run for most of the stream's flow through the park. Because most of the contaminated mine drainage entering Ice Pond Run does so from two distinct points, it is technically feasible that all the contaminated water could be collected and piped to a point just above the confluence of Ice Pond Run with the Monongahela River. Combining the unpolluted Ice Pond Run with the mine discharge at this point would have the same limited detrimental effect on the Monongahela River that currently exists.

Approximately 3 km of pipe would be necessary to reach from the deep mine to the Monongahela River. For aesthetic reasons, the pipe would probably need to be buried. This job could be accomplished by park personnel with existing park equipment.

Diversion of mine drainage from Ice Pond Run would have significant impacts on both the stream's chemistry and flow. Upstream of the pipe discharge, Ice Pond Run would be unpolluted. However, because the deep mine appears to supply most of the base flow to the upper reaches of Ice Pond Run, part of it would likely become an intermittent seasonal stream. During the summer of 1990, little dilution was observed between the deep mine and the wetland on many water sampling occasions (fig. 4). This portion of the stream would likely be dry during summer months.

Perennial freshwater seeps occur several hundred meters downstream of the pilot wetland. Thus, about half of Ice Pond Run might be expected to be a year-round stream.

Potential Problems (NPS comments):

Legal and regulatory questions must be answered. What responsibilities does the NPS now have to improve water quality under the non-point source provisions of the Clean Water Act? Would piping the discharge to the Monongahela River constitute a point source discharge that would come under the regulation of the Clean Water Act? It is suggested that a meeting be held with state officials to discuss relevant regulatory issues. The discussions should include any programs the state may have, such as through Section 319 of the Clean Water Act, for mitigating acid mine drainage.

5. Chemical Treatment of Ice Pond Run. If the existing acid mine drainage problem at Friendship Hill were to occur at an active mining site, the mine operator would have little recourse but to treat the water chemically. Chemical treatment is a well-developed technology that is used widely in the mining industry and is accepted by regulatory agencies as the best available technology. We present the chemical alternative, not because it is expected to be considered by the NPS, but because it provides a backdrop against which other treatment options can be evaluated.

Costs were estimated for a sodium hydroxide (NaOH) treatment system (table 18). The components of the system include a large tank of liquid NaOH that is metered into the mine drainage and several settling ponds in which metals precipitate as "sludge." Costs associated with the

system include the construction of the ponds, the regular purchase of NaOH, the periodic cleaning of the settling ponds, the disposal of potentially toxic sludge, and the manpower necessary to monitor and maintain the system. Sodium hydroxide systems have high annual costs that persist as long as the mine drainage continues to flow. The estimated total annual costs of the chemical system would be approximately \$190,000.

Table 18.--Estimated cost of treating 450,000 grams day⁻¹ of acidity with a NaOH chemical treatment system.

Component	Approximate Cost
Construction of ponds.....	\$5,000 (one time)
350 gal/day of 20% NaOH @ \$0.70/gal.....	\$90,000/year
Settling pond maintenance and sludge disposal	\$90,000/year
Labor (0.25 man years).....	\$10,000/year

6. Passive Biological and Chemical Treatment Systems for Ice Pond Run.

Passive biological treatment options are those that operate through natural geochemical and biological processes, and, being generally self-sustaining, require little maintenance. This report identified two processes that neutralize mine water acidity: the dissolution of limestone and the bacterial reduction of sulfate. Limestone is treated separately from NaOH because it is natural (we know of no natural pools of NaOH) and its dissolution is strongly affected by biological and chemical factors. If these environmental factors can be properly maintained, a system can be built that may generate limestone-derived

alkalinity for years with little maintenance. Bacterial sulfate reduction is similar. If the proper environmental conditions are created, the generation of alkalinity for years might be expected.

Two passive treatment options are discussed. One is the construction of a wetland, similar in design to the pilot scale wetland. The second option is a containerized system. Recent work at the Bureau has established that limestone dissolution and bacterial sulfate reduction occur readily in tanks filled with substrate and subjected to flows of acid mine drainage. Because this design ensures the existence of anaerobic conditions, and maximizes the contact between the substrate and the water, we suspect that it has utility in the treatment of acid mine drainage at some locations.

6a. Construction of a Compost Wetland. Determination of the size of a wetland needed to treat the mine drainage contaminating Ice Pond Run requires information on contaminant production rates by the deep mine (grams day⁻¹) and area-adjusted contaminant removal rates by the wetland (grams day m⁻²). Division of the acidity production rate by the area-adjusted acidity removal rate results in an estimate of the size of wetland (m²) needed to treat the contaminated drainage.

The task is complicated by the observation that both the contaminant production rates of the deep mine and the contaminant removal rates of the pilot wetland displayed seasonal variability. Production of mine water and acidity by the deep mine over an 18-month period between June

1989 and November 1990 is shown in figure 19. Seasonal variability in the production of acidity resulted primarily from flow variation. Concentrations of acidity generally ranged between $1,000 \text{ mg L}^{-1}$ and $1,300 \text{ mg L}^{-1}$ during all seasons. Flows during summer and autumn months generally ranged between 100 L min^{-1} and 200 L min^{-1} . However, during winter and spring of 1990, flow rates were consistently 200 L min^{-1} to 350 L min^{-1} , and ranged on three occasions higher than 450 L min^{-1} . During these winter and spring months, production of acidity by the deep mine was 2-5 times higher than in summer and autumn.

Results of this study indicated that removal of acidity by the pilot wetland varied seasonally; rates were high in summer and low in winter. Contaminant removal rates used in calculations of wetland size estimates are shown in table 19. These data represent a smoothed version of experimental results presented in table 17.

Estimates of the wetland size needed to treat the mine drainage were made for each sampling date using the loadings shown in Figure 19c and the removal rates shown in table 19. The results of these calculations are shown in figure 20. The required wetland size varied from a minimum of $22,191 \text{ m}^2$ (5.5 acre) to a maximum of $390,591 \text{ m}^2$ (96.5 acre). During summer and autumn months, when acidity production was low and acidity removal was high, a wetland of approximately $50,000 \text{ m}^2$ (12.4 acre) was indicated. During winter and spring months, a wetland of $150,000 \text{ m}^2$

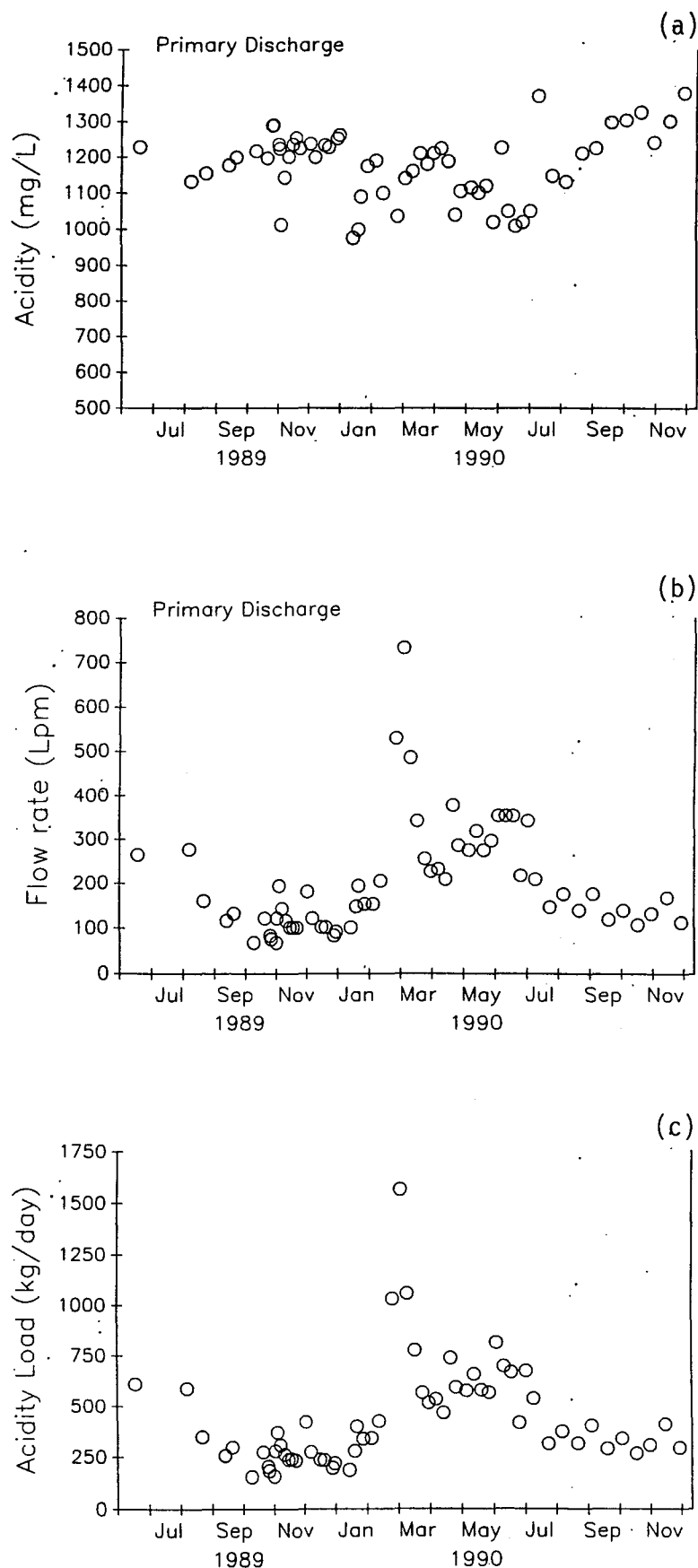


Fig. 19. (a) Concentrations of acidity at the primary deep mine discharge, (b) Flow rates at the primary deep mine discharge, and (c) Acidity loads produced by the deep mine discharges. Loadings represent the primary discharge plus 30% to account for the secondary discharge (see text, table 2).

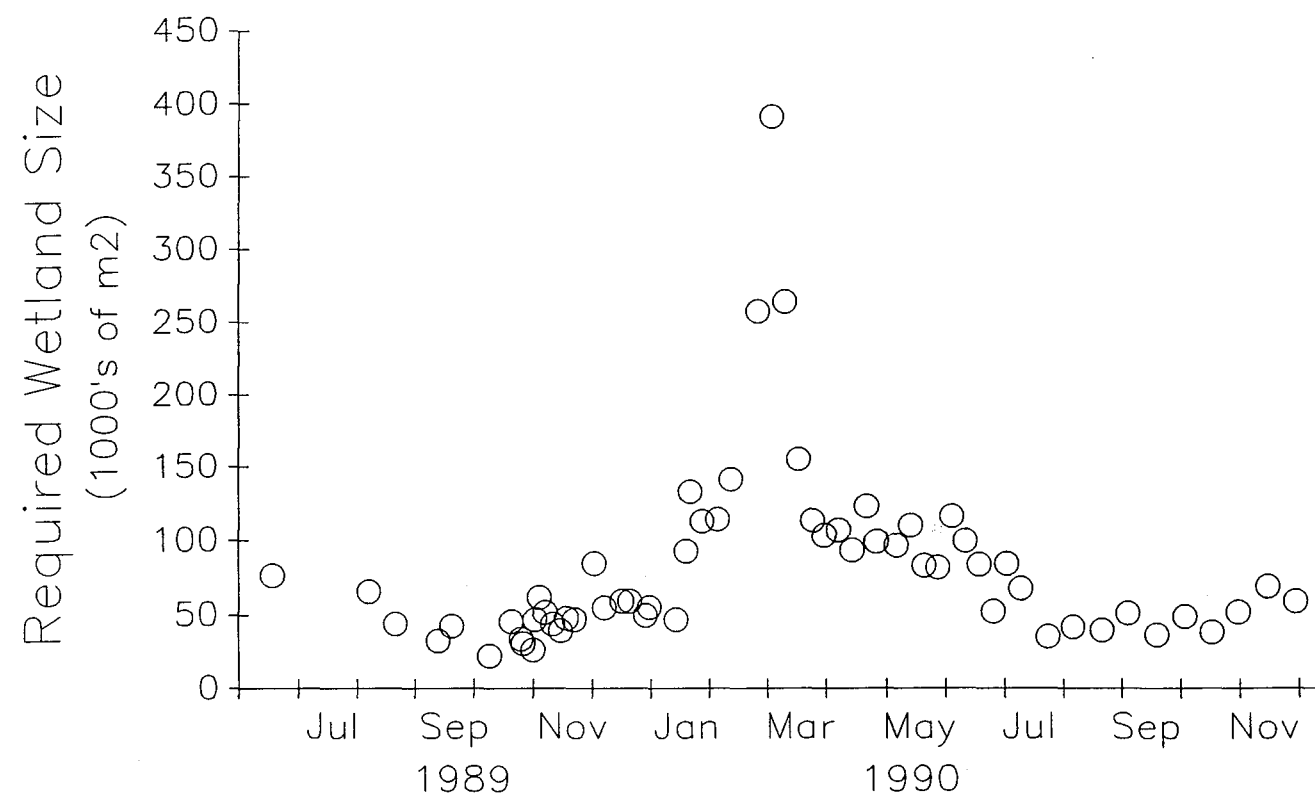


Fig. 20. Size of wetland estimated to be required for the treatment of deep mine discharges into Ice Pond Run.

Table 19.--Acidity removal rates used in wetland sizing calculations.

Month	Acidity Removal $\text{g m}^{-2} \text{ day}^{-1}$
Jan.....	3.0
Feb.....	4.0
Mar.....	5.0
Apr.....	6.0
May.....	7.0
Jun.....	8.0
Jul.....	9.0
Aug.....	8.0
Sep.....	7.0
Oct.....	6.0
Nov.....	5.0
Dec.....	4.0

(37.1 acre) was necessary on most days. On three days when unusually high flow rates were measured at the primary mine discharge point, the required wetland size increased to approximately 250,000 m^2 - 400,000 m^2 (61.8 - 96.5 acre).

The cost of constructing compost wetlands, as reported to us by mining and engineering companies that build them regularly, is about \$10 per m^2 . If the NPS were to contract for the construction of a compost wetland, its cost would likely range from \$250,000 to \$4,000,000, depending on the treatment goals. The cost of a wetland that is estimated to be capable of treating the mine discharge on all but the highest flow days is \$1,500,000.

The costs cited above are for a wetland system whose construction was contracted to a private company. We estimate that approximately half of the cost results from design, excavation, construction, and planting, while the remaining half results from the purchase and trucking of spent mushroom compost. Clearly, cost estimates decrease if park personnel do a significant part of the excavation and construction. If a local source of compost could be found, or if the park could make its own compost using local materials, the cost of the wetland would decrease substantially. If the park were to undertake as much of the construction as possible, and find an alternative source of the compost, the cost of building the wetland could decrease by as much as 50%.

Because the generation of alkalinity in a constructed wetland consumes carbon and limestone, and compost contains a limited quantity of both, an effective lifetime for the systems can be determined. We know of no compost wetlands that have ceased to generate alkalinity with increasing age. However, the oldest compost wetlands that have been studied are only 5-7 years old. Table 20 shows the results of calculations that estimate the maximum longevity of a constructed wetland that functions as the Friendship Hill pilot scale wetland did during this study. The calculations assume that the compost is 45 cm deep, that all available organic carbon is degraded through sulfate reduction processes (and thus is oxidized to bicarbonate), and that all limestone is dissolved. Because the limestone used in mushroom farming is of very high quality (>95% CaCO_3 content), the assumption about total limestone dissolution is probably reasonable. The carbon oxidation

Table 20.--Theoretical maximum alkalinity-generating capacities of 1 m² of spent mushroom compost wetland.

Source of Alkalinity	Mass (kg m ²)	Alkalinity Equivalent (g)	Wetland Removal Rate (g m ⁻² day ⁻¹)	Estimated Exhaustion (years)
Organic Carbon	52	216,666	4.7	126
Limestone.....	15	14,500	2.7	15

The calculations assume the compost depth is 45 cm. Compost described is from Moonlight Mushroom Farm, Worthington, PA.

assumption is certainly too high. Studies of carbon cycling in natural *Spartina* wetlands on Cape Cod indicate that about 75% of carbon fixed annually is eventually mineralized via sulfate reduction processes.

A more serious concern is the possibility that sulfate reduction is linked, in a dependent manner, to limestone dissolution. Sulfate-reducing bacteria are inactive at pH less than 5. Their activity in a wetland receiving lower pH water may depend, in part, on the presence of buffering supplied by limestone dissolution. Thus, limestone dissolution may create the alkaline zones in which bacterial sulfate reduction can proceed and produce further alkalinity. If this scenario is true, then a wetland constructed with spent mushroom compost might be expected to fail to generate alkalinity after about 15 years. However, it would be easy to supplement the compost with more limestone and increase the expected longevity of the substrate. We estimate that doubling the limestone content of compost used in the wetland would only increase costs by about \$0.10 per m².

Potential Problems (NPS comments):

While treatment of Ice Pond Run with a constructed wetland system appears to be feasible, this alternative is both expensive and involves converting a considerable amount of land area within the park from upland to wetland. Also, while this type of treatment system is designed to be relatively maintenance free, a question arises as to what the character of the mushroom compost is if it has to be removed after a prolonged period of treatment: would materials removed from a wetlands treatment complex, when disposed of, be regulated as a hazardous waste? If so, the maintenance costs associated with waste disposal would rise sharply.

6b. Containerized Passive Treatment. Recently, we have explored the alkalinity-generating capabilities of spent mushroom compost contained in sealed, anoxic barrels (Dvorak et al. 1991). Fifty-five gallon plastic barrels were filled with 0.21 m^3 spent mushroom compost and exposed to acid mine drainage. The barrels were set up in an underground mine where temperatures were a constant 13°C . The system removed acidity at a rate of approximately $300 \text{ g m}^3 \text{ day}^{-1}$. This rate is approximately 20 times higher than the average observed rate at the pilot scale wetland. Currently, the difference is attributed to better maintenance of anaerobic conditions in the barrels, constant water and air temperature, and maximum contact between contaminated water and spent mushroom compost.

At a removal rate of $300 \text{ g m}^{-3} \text{ day}^{-1}$, treatment of the average Friendship Hill deep mine discharge ($450,000 \text{ g day}^{-1}$) would require $1,500 \text{ m}^3$ of compost. A variety of scenarios describing the containment of this volume of compost are possible. If contained in 50 gallon

barrels, this volume of compost would require 7212 barrels. The plumbing of this number of barrels would be difficult. If 10,000 gallon tanks were utilized, 40 of these would be necessary to contain the compost. Alternatively, pits could be dug, lined with plastic, and plumbed for mine water injection.

Because the containerized approach extracts alkalinity from the compost much more quickly than the wetland approach, the compost will be exhausted much more quickly. Calculations similar to those in table 21 suggest that the substrate would need to be replenished every year. The purchase and transportation costs of this volume of compost are about \$20,000 year, and would vary, depending on the barrel size used. If the park could develop its own source of compost, this cost would obviously decrease. Methods still need to be developed for cheaply containing this volume of compost, properly plumbing the system, and disposing of the waste compost after its treatment value is exhausted.

Potential Problems (NPS comments):

Again, questions concerning proper disposal of the waste, as well as the area required for the containers, are raised.

7. Combination of Treatment Systems. A final approach to the Ice Pond Run treatment problem involves the possibility of combining different treatment methods to treat various portions of the total water flow, or to use them as backup systems during periods of time when specific systems are minimally effective or fail. In many ways, decisions

regarding the many potential combinations of treatment alternatives used could be based strictly on the basis of economics. However, we would like to point out that there would be scientific and educational value in setting up a multiple treatment system for Ice Pond Run water. The biological systems discussed in this section, including wetlands, have never been scaled-up to treat such large volumes of severely polluted acid mine drainage. Any attempt to treat Ice Pond Run using these systems would mark a pioneering effort in the treatment of acid mine drainage, the results of which would be of considerable interest to the mining industry and the scientific community. The constructed wetland at Friendship Hill already serves as an educational display demonstrating current attempts to treat acid mine drainage using natural biological processes. A multiple treatment system for Ice Pond Run could be used as the cornerstone of a large educational display to demonstrate the harmful effects of acid mine drainage, the nature of ongoing research methods being used to treat it, and the final improvements in stream ecology and the environment when such treatment systems are employed. This final option carries the problem of Ice Pond Run treatment one step further by incorporating public education as one of its essential goals, but this alternative may be more in line with the objectives of the National Park Service.

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APPENDIX A. Chronology of Research Done at Friendship Hill

The following is a brief chronology of the Bureau's research efforts to design a constructed wetland system to treat acid mine drainage (AMD) at the Friendship Hill National Historic Site.

- March 1985: An Interagency Agreement was established between the Bureau of Mines and the National Park Service to evaluate alternative methods to mitigate AMD that flows in Ice Pond Run.
- June 1985: A report "Alternative Methods to Reduce AMD Pollution in a Stream at Friendship Hill National Historic Site" was prepared that analyzed the AMD problem and presented several alternatives to treat AMD. These alternatives included mine sealing, infiltration control, daylighting, oxidation inhibitors, conventional water treatment, and wetlands.
- August 1985 - January 1986: Preliminary experiments treating Ice Pond Run AMD using an on-site wetland simulator (Portabog) were performed to test the feasibility of a wetland treatment process. Baseline flow data and the water quality of Ice Pond Run with time were determined.

- March -
June 1986: The designs for the first pilot-scale wetland were developed, reviewed, and prepared for execution.
- June 1986: A Project Status Report was prepared that described the general soil conditions of the proposed site for the pilot-scale wetland, the tolerance of various wetland vegetation to AMD, the results of the Portabog experiments, and the proposed design for the first wetland.
- Summer 1986: The first pilot-scale wetland was constructed and planted with cattails and other assorted wetland plants tolerant of AMD.
- Sep. 1986: Water began to flow through the pilot-scale wetland.
- Nov. 1986: Forty thousand pounds of live *Sphagnum* moss was planted in the upper portion of the wetland.
- June 1987: The first pilot-scale wetland ceased to be effective in the treatment of AMD.
- August 1987: Operation of the first pilot-scale wetland was terminated.

- May 1988: A Project Status Report was prepared that described the performance of the first pilot-scale wetland in considerable detail. Also prepared was a proposal for the second pilot-scale wetland based on the results of the first one, as a summary of what the Bureau had learned concerning AMD mitigation from its research at other wetlands constructed to treat AMD. The design of the second pilot-scale wetland incorporated a novel feature to promote bacterial sulfate reduction using induced subsurface flow.
- May -
July 1988: Designs for the second pilot-scale wetland were developed, reviewed, and prepared for execution.
- July -
Oct. 1988: The second pilot-scale wetland was constructed on the site of the first one. Planting of cattails was in early October.
- Nov. 1988: The second pilot-scale wetland was put into full operation during the first week of November. The full operation included the use of the novel subsurface flow capability.
- Feb. 1989: A Project Status Report was prepared that described the construction and start-up of the second pilot-scale wetland with preliminary observations on its performance.

- August 1989: Cattail growth was well-established in the pilot-scale wetland. Engineering revisions were made to overcome operation and maintenance problems with the original subsurface flow system. A Project Status Report was prepared that detailed the performance of the second pilot-scale wetland and presented the results of intensive monitoring efforts.
- Sep. 1989 -
June 1990: Sulfate reduction experiments were carried out and minor design modifications were made to the wetland.
- July 1990 -
March 1991: Contaminant loading and removal studies were carried out.
- May 1991: Draft final report submitted to National Park Service.
- Oct. 1991: Final report submitted to National Park Service

APPENDIX B. Data tables

Key

Stat = station

Flow = set and actual

pH = standard units

Alkalinity/Acidity = $\text{mg L}^{-1} \text{CaCO}_2$ equivalent

All other ions are reported in mg L^{-1}

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
10-Nov-88	1			2.8	0	1404	28	228	243	97	82	13	5	2300
10-Nov-88	A2	7.6		2.9	0	1230	36	229	287	105	79	13	9	2300
10-Nov-88	B2	7.6		2.9	0	1311	29	243	273	105	81	13	6	2300
10-Nov-88	C2	7.6		2.9	0	1276	51	237	283	104	78	13	8	2300
15-Nov-88	1			2.8	0	1225	11	194	222	87	77	12	5	2000
15-Nov-88	A2	5.7		2.8	0	1246	22	224	278	104	80	13	8	2300
15-Nov-88	B2	5.2		2.8	0	1255	17	226	278	103	80	13	7	2200
15-Nov-88	C2	6.7		2.9	0	1222	23	218	273	101	79	13	8	2200
29-Nov-88	1			2.7	0	1119	na	223	211	83	68	11	5	1900
29-Nov-88	A2	9.1		2.8	0	1055	na	210	226	85	66	12	6	1900
29-Nov-88	A3	9.1		2.9	0	952	na	185	241	84	63	11	7	1900
29-Nov-88	B2	2.8		2.8	0	945	na	180	248	87	61	11	8	1925
29-Nov-88	C2	4.7		2.8	0	963	na	179	240	83	62	11	8	1925
16-Dec-88	1			2.9	0	1405	na	214	246	100	82	13	5	2237
16-Dec-88	A2	2.8		2.9	0	1540	na	254	301	122	98	15	7	2600
16-Dec-88	A3	2.8	3.1	3.0	0	1364	na	219	348	127	89	15	9	2575
16-Dec-88	B2	2.6		2.9	0	1504	na	243	281	113	92	14	6	2475
16-Dec-88	B3	2.6	2.0	3.0	0	1357	na	224	305	115	87	14	8	2475
16-Dec-88	C2	4.3		2.9	0	1526	na	247	286	116	95	15	6	2600
16-Dec-88	C3	4.3	4.7	2.9	0	1490	na	240	304	121	95	15	11	2575
27-Dec-88	1			2.8	0	906	76	158	157	61	50	9	4	1375
27-Dec-88	A2	8.5		2.8	0	1033	83	199	196	75	62	10	6	1600
27-Dec-88	A3	8.5	8.7	2.8	0	1005	77	201	203	80	63	11	6	1775
27-Dec-88	B2	7.1		2.8	0	1165	96	226	218	85	70	12	5	1900
27-Dec-88	B3	7.1	6.2	2.8	0	1172	94	233	229	88	72	12	6	1950
27-Dec-88	C2	8.1		2.8	0	1013	91	210	197	78	64	11	5	1825
27-Dec-88	C3	8.1	7.6	2.8	0	998	84	204	209	80	63	11	6	1850
03-Jan-89	1			2.8	0	655	31	79	98	36	30	5	6	1175
09-Jan-89	1			3.0	0	431	2	63	91	34	29	5	7	800
09-Jan-89	A2	7.6		3.0	0	615	23	114	143	55	42	8	7	1175
09-Jan-89	A3	7.6	10.9	3.0	0	560	22	101	146	53	39	7	7	1175
09-Jan-89	B2	7.6		2.8	0	795	38	146	175	67	50	9	7	1500
09-Jan-89	B3	7.6	6.7	2.8	0	778	38	140	184	68	49	9	7	1525
09-Jan-89	C2	7.1		2.8	0	729	31	135	173	64	48	9	7	1425
09-Jan-89	C3	7.1	6.6	2.9	0	708	30	126	178	64	46	9	7	1425
17-Jan-89	1			2.8	0	588	42	109	104	40	34	5	6	1050
17-Jan-89	A2	7.1		2.8	0	516	33	97	112	41	33	6	7	975
17-Jan-89	A3	7.1	8.8	2.8	0	489	29	88	121	42	33	6	7	975
17-Jan-89	B2	7.6		2.8	0	648	45	128	137	52	41	7	7	1200
17-Jan-89	B3	7.6	7.1	2.7	0	664	45	134	153	56	43	8	7	1275
17-Jan-89	C2	6.5		2.7	0	620	38	124	139	52	39	7	7	975
17-Jan-89	C3	6.5	6.1	2.8	0	619	39	117	155	55	40	7	7	1225
24-Jan-89	1			2.7	0	787	20	142	144	56	50	8	6	1375
24-Jan-89	A2	7.1		2.7	0	890	19	165	169	66	57	9	6	1575
24-Jan-89	A3	7.1	7.6	2.8	0	790	23	147	160	61	61	9	5	1425
24-Jan-89	B2	7.6		2.7	0	961	24	187	185	73	61	9	5	1650
24-Jan-89	B3	7.6	6.5	2.8	0	907	28	173	189	72	58	9	6	1675
24-Jan-89	C2	7.0		2.7	0	963	27	182	185	73	61	9	6	1725
24-Jan-89	C3	7.0	31.6	2.8	0	915	29	175	188	71	58	9	6	1525
07-Feb-89	1			2.8	0	765	23	154	143	57	49	7	5	1350

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
07-Feb-89	A2	8.8		2.9	0	697	18	136	135	54	44	7	6	1275
07-Feb-89	A3	8.8	9.5	2.9	0	651	18	124	136	52	42	7	6	1200
07-Feb-89	B2	8.1		2.8	0	817	24	166	162	65	53	8	5	1525
07-Feb-89	B3	8.1	7.3	2.9	0	816	24	157	163	63	52	8	6	1550
07-Feb-89	C2	8.5		2.8	0	835	21	162	158	62	53	8	6	1525
07-Feb-89	C3	8.5	7.6	2.9	0	772	21	149	162	62	49	8	6	1450
22-Feb-89	1			3.0	0	673	17	135	108	42	41	6	4	1100
22-Feb-89	A2	7.2		2.9	0	595	10	106	105	39	37	5	5	1025
22-Feb-89	A3	7.2	11.4	4.9	0	139	na	33	281	54	12	5	10	1178
22-Feb-89	B2	7.6		2.9	0	817	16	162	134	52	48	7	4	1400
22-Feb-89	B3	7.6	8.5	6.3	152	0	na	25	465	76	7	8	10	1510
22-Feb-89	C2	6.6		3.0	0	652	6	128	116	43	39	6	4	1150
22-Feb-89	C3	6.6	7.6	6.6	254	0	na	13	466	69	1	5	11	1300
08-Mar-89	1			2.9	0	829	23	157	121	50	43	6	4	1325
08-Mar-89	A2	7.6		2.9	0	689	11	129	113	46	40	6	5	1150
08-Mar-89	A3	7.6	10.4	6.4	118	0	24	24	377	66	4	6	10	1475
08-Mar-89	B2	7.6		2.9	0	917	15	182	146	60	51	7	4	1475
08-Mar-89	B3	7.6	8.1	6.0	94	0	21	33	456	78	12	9	8	1475
08-Mar-89	C2	7.0		2.9	0	860	16	171	137	56	49	7	4	1450
08-Mar-89	C3	7.0	6.6	6.5	183	0	11	16	467	68	1	6	6	1325
21-Mar-89	1			2.8	0	862	20	168	131	56	49	7	5	1525
21-Mar-89	A2	7.1		3.0	0	749	11	149	125	51	45	6	5	1270
21-Mar-89	A3	7.1	12.1	3.4	0	325	22	73	217	49	21	6	6	1040
21-Mar-89	B2	7.6		2.9	0	916	12	189	156	64	54	7	6	1580
21-Mar-89	B3	7.6	7.6	3.3	0	462	25	105	266	63	30	7	6	1360
21-Mar-89	C2	8.1		2.8	0	862	14	178	148	60	51	7	5	1490
21-Mar-89	C3	8.1	8.5	3.2	0	408	18	94	245	56	28	6	6	1235
05-Apr-89	1			2.6	0	763	28	149	116	49	41	6	4	1200
05-Apr-89	A2	5.2		2.8	0	595	14	110	121	46	35	5	6	1050
05-Apr-89	A3	5.2	11.4	3.7	0	157	17	37	254	49	14	5	8	1025
05-Apr-89	B2	5.7		2.8	0	675	14	127	119	47	38	5	4	1100
05-Apr-89	B3	5.7	4.8	3.2	0	305	13	62	263	54	19	5	7	1150
05-Apr-89	C2	6.6		2.6	0	689	15	129	127	50	38	6	5	1150
05-Apr-89	C3	6.6	5.7	6.4	115	0	16	26	408	61	4	6	8	1200
18-Apr-89	1			2.6	0	982	18	162	146	61	52	7	1	1675
18-Apr-89	A2	7.2		2.7	0	867	12	159	161	65	53	7	2	1575
18-Apr-89	A3	7.2	9.5	3.2	0	355	21	60	297	69	27	8	3	1450
18-Apr-89	B2	7.4		2.7	0	948	14	176	170	70	56	8	1	1675
18-Apr-89	B3	7.4	6.2	3.4	0	260	24	61	378	76	21	8	3	1525
18-Apr-89	C2	7.5		2.7	0	901	14	163	174	68	55	7	1	1650
18-Apr-89	C3	7.5	6.9	3.2	0	419	37	89	314	74	31	9	2	1525
02-May-89	1			2.8	0	664	32	114	99	41	31	5	4	925
02-May-89	A2	8.1		2.8	0	505	39	98	98	37	28	4	5	875
02-May-89	A3	8.1	11.4	3.1	0	313	28	63	155	40	18	5	5	850
02-May-89	B2	7.1		2.8	0	673	21	126	129	51	36	6	4	1175
02-May-89	B3	7.1	5.5	3.3	0	281	24	58	261	57	16	6	5	1150
02-May-89	C2	3.3		2.9	0	471	13	78	104	37	25	4	4	875
02-May-89	C3	3.3	3.6	3.2	0	322	28	62	181	46	21	5	5	1100
16-May-89	1			2.8	0	543	46	108	87	36	27	4	3	850
16-May-89	A2			2.9	0	410	12	68	84	32	22	4	5	700

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
16-May-89	A3		9.9	3.1	0	264	16	47	129	34	16	4	6	675
16-May-89	B2			2.8	0	473	25	67	87	34	24	4	4	825
16-May-89	B3		6.4	3.1	0	280	24	54	170	40	16	5	4	750
16-May-89	C2			2.9	0	317	27	40	105	34	21	4	5	725
16-May-89	C3		0.9	5.1	0	56	17	17	222	42	5	5	5	775
23-May-89	1			2.6	0	710	35	119	111	47	35	5	4	1200
23-May-89	A2	7.1		2.8	0	494	15	81	116	41	29	5	5	975
23-May-89	A3	7.1	11.4	3.0	0	300	4	42	164	44	21	5	6	900
23-May-89	B2	6.6		2.7	0	559	3	94	125	47	33	5	4	1050
23-May-89	B3	6.6	9.0	3.1	0	313	6	47	180	47	22	5	5	975
23-May-89	C2	7.6		2.8	0	540	6	95	127	48	32	5	5	1050
23-May-89	C3	7.6	10.0	2.9	0	410	6	68	153	48	27	5	5	975
06-Jun-89	1			2.8	0	874	118	182	149	64	45	7	4	1500
06-Jun-89	A2	6.6		3.2	0	493	69	104	247	68	29	7	6	1375
06-Jun-89	A3	6.6	5.9	3.3	0	252	20	49	282	65	16	7	7	1250
06-Jun-89	B2	6.6		3.2	0	607	92	130	227	67	36	7	5	1425
06-Jun-89	B3	6.6	6.4	3.4	0	375	53	73	278	67	26	7	5	1350
06-Jun-89	C2	5.9		3.3	0	419	73	101	270	72	27	7	8	1400
06-Jun-89	C3	5.9	6.4	3.5	0	171	12	33	324	72	13	7	8	1300
21-Jun-89	1			3.0	0	312	22	42	189	49	19	6	5	950
21-Jun-89	1			2.7	0	538	43	85	95	40	28	5	3	900
21-Jun-89	A2			2.9	0	428	25	64	131	43	23	5	5	900
21-Jun-89	A3			3.0	0	390	38	63	149	45	22	5	4	900
21-Jun-89	B2			2.9	0	394	18	62	178	51	22	5	4	1000
21-Jun-89	B3			3.1	0	288	19	39	228	56	19	6	4	1075
21-Jun-89	C2			2.9	0	380	22	56	185	52	21	5	5	975
21-Jun-89	C3			3.1	0	260	14	31	216	55	17	6	5	975
06-Jul-89	1			2.9	0	502	57	82	89	37	27	4	3	1075
06-Jul-89	A2			3.2	0	168	14	29	158	39	6	4	7	700
06-Jul-89	A3			3.2	0	105	5	16	167	37	2	4	8	675
06-Jul-89	B2			3.0	0	349	15	52	134	42	18	5	4	800
06-Jul-89	B3			6.7	189	30	9	14	314	46	0	3	7	800
06-Jul-89	C2			3.3	0	147	7	20	180	44	7	4	7	750
06-Jul-89	C3			3.9	0	73	41	41	176	41	0	3	9	625
25-Jul-89	1			2.8	0	488	71	82	83	32	23	4	4	800
25-Jul-89	A2	3.8		3.3	0	106	17	21	157	37	2	4	9	625
25-Jul-89	A3	3.8	0.3	3.6	0	50	3	8	145	34	0	3	7	550
25-Jul-89	B2	3.8		3.2	0	137	22	25	171	41	6	4	6	650
25-Jul-89	B3	3.8	2.7	7.4	108	0	8	10	208	41	0	2	5	450
25-Jul-89	C2	3.8		3.1	0	173	13	30	152	40	8	4	7	725
25-Jul-89	C3	3.8	3.0	3.6	0	58	6	9	165	40	1	4	7	625
08-Aug-89	1			2.8	0	665	120	139	122	51	41	6	5	1125
08-Aug-89	A2	3.8		3.1	0	212	8	21	180	49	14	5	8	800
08-Aug-89	A3	3.8	6.9	3.9	0	38	2	10	153	38	0	3	9	575
08-Aug-89	B2	3.1		3.4	0	205	12	20	189	51	19	5	7	875
08-Aug-89	B3	3.1	5.0	7.3	150	0	7	9	233	45	0	3	7	575
08-Aug-89	C2	1.5		3.5	0	190	26	32	191	52	15	5	9	850
08-Aug-89	C3	1.5	1.1	3.5	0	98	1	5	191	50	7	5	8	725
23-Aug-89	1			2.6	0	960	7	144	188	80	61	9	4	1700
23-Aug-89	A2			3.0	0	536	13	57	230	76	52	8	6	1350

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
23-Aug-89	A3			3.4	0	190	9	21	229	64	22	6	6	1275
23-Aug-89	B2			3.1	0	596	31	69	252	82	57	9	5	1475
23-Aug-89	B3			7.3	145	0	7	11	288	65	0	5	7	825
23-Aug-89	C2			3.0	0	713	56	102	235	84	65	9	6	1600
23-Aug-89	C3			3.2	0	395	25	42	262	78	43	8	6	1300
06-Sep-89	1			2.6	0	1184	22	195	241	103	75	11	5	2150
06-Sep-89	A2	3.7		3.3	0	496	49	68	393	109	48	12	11	1925
06-Sep-89	A3	3.7	3.0	5.9	40	0	30	45	439	87	0	9	10	1525
06-Sep-89	B2	3.8		3.1	0	652	67	101	366	106	57	12	8	2000
06-Sep-89	B3	3.8	2.9	3.6	0	233	3	10	403	101	28	11	7	1675
06-Sep-89	C2	4.0		3.2	0	545	61	81	400	109	47	11	12	2000
06-Sep-89	C3	4.0	2.7	3.4	0	365	28	44	402	109	37	11	13	1875
19-Sep-89	1			2.6	0	1068	7	176	211	89	64	10	4	1875
19-Sep-89	A2	3.8		3.0	0	755	56	126	289	97	61	10	7	1825
19-Sep-89	A3	3.8	3.1	6.0	0	10	95	103	498	107	0	10	10	1700
19-Sep-89	B2	3.8		2.9	0	881	50	165	283	100	61	11	6	1950
19-Sep-89	B3	3.8	3.8	3.2	0	492	28	66	345	100	45	11	6	1750
19-Sep-89	C2	3.8		3.0	0	723	54	111	297	96	62	10	7	1800
19-Sep-89	C3	3.8	3.3	3.1	0	551	24	69	305	93	53	10	7	1700
04-Oct-89	1			2.7	0	920	9	146	175	74	55	9	4	1600
04-Oct-89	A3	3.5	6.4	3.1	0	459	15	55	276	83	38	9	7	1450
04-Oct-89	B3	3.8	2.8	3.2	0	497	24	62	295	85	42	10	5	1600
04-Oct-89	C1	3.8	3.8	2.7	0	980	13	158	182	76	56	9	4	1750
04-Oct-89	C3	3.8	2.7	3.1	0	527	21	61	181	84	46	9	7	1650
17-Oct-89	1			2.7	0	567	2	82	109	43	34	5	3	1025
17-Oct-89	A2	3.8		2.8	0	550	5	84	137	50	37	6	4	1050
17-Oct-89	A3	3.8	10.7	3.0	0	480	14	71	190	60	39	7	5	1175
17-Oct-89	B2	3.5		2.9	0	593	7	95	162	57	42	7	4	1225
17-Oct-89	B3	3.5	9.8	3.0	0	538	24	82	221	68	44	8	4	1325
17-Oct-89	C2	3.8		2.8	0	553	14	91	162	56	38	6	4	1175
17-Oct-89	C3	3.8	10.5	3.0	0	490	22	75	195	61	39	7	5	1200
14-Nov-89	1			2.7	0	798	7	133	150	61	48	8	4	1425
14-Nov-89	A2	3.8		2.8	0	805	5	131	186	71	57	8	5	1550
14-Nov-89	A3	3.8	0.9	3.0	0	610	5	89	215	72	50	9	5	1500
14-Nov-89	B2	3.8		2.7	0	798	7	146	193	75	59	9	5	1725
14-Nov-89	B3	3.8	3.8	3.1	0	572	22	84	250	78	49	9	5	1550
14-Nov-89	C2	3.8		2.8	0	816	12	133	192	73	56	9	5	1600
14-Nov-89	C3	3.8	3.8	3.0	0	668	15	103	229	76	56	9	5	1500
21-Nov-89	1			2.8	0	733	3	130	148	59	44	7	4	1300
21-Nov-89	A2	1.4		3.0	0	490	3	78	145	50	36	6	6	950
21-Nov-89	A3	1.4	1.7	6.4	146	0	100	108	311	71	5	8	7	950
21-Nov-89	B2	1.9		5.8	79	0	31	76	317	84	29	7	25	1200
21-Nov-89	B3	1.9	1.7	6.6	145	0	40	42	389	87	4	8	14	1250
21-Nov-89	C2	1.9		6.0	116	0	34	34	386	97	2	4	41	1500
21-Nov-89	C3	1.9	1.2	6.6	303	0	62	62	442	87	1	7	26	1300
28-Nov-89	1			2.8	0	762	3	135	148	60	47	7	5	1425
28-Nov-89	A2			6.2	269	0	24	41	362	100	22	6	48	1388
28-Nov-89	A3		1.8	6.1	77.5	0	53	54	327	85	1	8	25	1375
28-Nov-89	B2			5.9	83.2	0	36	49	374	93	14	6	24	1450
28-Nov-89	B3		1.6	6.6	157	0	36	38	410	86	1	7	14	1375

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
28-Nov-89	C2			6.9	569	0	11	12	478	109	0	2	45	1475
28-Nov-89	C3		1.6	6.6	316	0	35	35	456	99	0	5	38	1425
13-Dec-89	1			2.8	0	1009	5	183	194	81	61	10	5	1800
13-Dec-89	A2	3.8		3.1	0	667	12	146	253	86	48	8	11	1720
13-Dec-89	A3	3.8	3.9	6.5	118	0	91	92	414	95	0	10	18	1580
13-Dec-89	B2	3.8		3.2	0	612	25	136	310	94	47	10	11	1820
13-Dec-89	B3	3.8	3.4	6.9	115	0	76	76	469	98	2	10	14	1670
13-Dec-89	C2	3.8		6.9	297	0	13	21	579	115	0	6	18	1780
13-Dec-89	C3	3.8	3.3	6.8	334	0	17	19	560	114	0	5	20	1710
27-Dec-89	1			2.7	0	1080	9	183	221	95	73	11	5	1975
27-Dec-89	A2	3.8		6.6	221	0	33	33	523	119	1	5	21	1850
27-Dec-89	A3	3.8	3.8	6.4	428	0	78	78	516	125	1	9	45	1875
27-Dec-89	B2	3.8		6.6	341	0	16	16	620	135	1	3	19	1925
27-Dec-89	B3	3.8	3.8	6.4	359	0	84	84	584	122	1	11	28	1900
27-Dec-89	C2	3.8		6.7	300	0	49	49	620	120	1	10	16	1950
27-Dec-89	C3	3.8	3.8	6.7	459	0	26	27	647	120	1	7	21	1825
03-Jan-90	A2	3.8		3.1	0	436	23	88	208	64	31	6	8	1175
03-Jan-90	A3	3.8	5.7	3.6	0	290	36	81	273	76	23	7	13	1350
03-Jan-90	B2	3.8		6.5	193	0	20	20	493	103	1	6	10	1650
03-Jan-90	B3	3.8	3.3	6.3	186	0	52	52	463	103	0	9	16	1700
03-Jan-90	C1	4.5	4.5	2.8	0	640	6	109	126	52	41	6	5	1200
03-Jan-90	C2	4.5		5.8	56	0	50	63	399	89	12	9	10	1575
03-Jan-90	C3	4.5	3.8	6.1	94	0	44	46	424	92	3	9	11	1550
10-Jan-90	1			3.0	0	275	3	21	28	9	7	1	2	450
10-Jan-90	A2	3.8		3.2	0	440	20	89	166	51	29	5	6	1100
10-Jan-90	A3	3.8	5.7	3.4	0	310	26	71	207	58	24	6	8	1100
10-Jan-90	B2	3.8		3.0	0	590	23	114	156	54	37	6	4	1200
10-Jan-90	B3	3.8	3.8	3.6	0	260	77	77	252	63	19	7	6	1225
10-Jan-90	C1	3.8	3.8	2.8	0	830	13	150	152	61	48	7	4	1425
10-Jan-90	C2	3.8		3.6	0	325	57	81	260	66	26	7	7	1325
10-Jan-90	C3	3.8	7.3	4.8	0	160	47	49	289	67	16	6	8	1250
17-Jan-90	1			2.9	0	365	6	83	89	35	28	5	5	670
17-Jan-90	A2	3.8		3.0	0	510	19	104	179	58	33	6	7	1225
17-Jan-90	A3	3.8	5.0	3.3	0	320	35	78	230	65	24	6	10	1250
17-Jan-90	B2	3.6		2.8	0	690	11	132	151	60	44	7	5	1350
17-Jan-90	B3	3.6	3.2	3.3	0	370	50	91	239	66	29	7	6	1275
17-Jan-90	C2	3.6		4.4	0	250	63	87	344	79	21	8	10	1475
17-Jan-90	C3	3.6	3.6	4.5	0	190	57	58	347	79	20	8	10	1450
23-Jan-90	A2	2.8		3.3	0	305	17	62	138	42	20	4	8	825
23-Jan-90	A3	2.8	5.2	3.4	0	230	26	50	178	50	16	4	9	925
23-Jan-90	B2	3.8		2.9	0	595	10	108	128	51	36	6	8	1150
23-Jan-90	B3	3.8	3.8	3.2	0	400	43	86	195	54	25	6	7	1125
23-Jan-90	C2	2.8		3.2	0	420	73	108	212	58	26	6	7	1225
23-Jan-90	C3	2.8	2.7	3.8	0	260	59	79	257	62	19	6	9	1225
30-Jan-90	A2	3.8		4.5	0	95	11	27	120	30	9	2	8	540
30-Jan-90	A3	3.8	7.1	5.8	5	34	20	22	132	41	5	2	10	720
30-Jan-90	B2	3.3		3.0	0	313	13	61	85	28	18	3	4	660
30-Jan-90	B3	3.3	3.3	3.2	0	290	36	71	147	41	18	5	5	880
30-Jan-90	C1	3.8	3.8	3.0	0	292	6	55	62	25	18	3	5	560
30-Jan-90	C2	3.8		3.2	0	269	39	69	148	39	16	4	5	850

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
30-Jan-90	C3	3.8	3.8	4.0	0	153	35	52	191	44	12	4	7	880
13-Feb-90	A2	3.3		3.4	0	230	13	60	148	40	19	4	7	750
13-Feb-90	A3	3.3	6.3	5.4	0	40	23	32	179	42	8	4	8	725
13-Feb-90	B2	3.8		2.9	0	630	9	124	141	52	37	6	4	1150
13-Feb-90	B3	3.8	4.4	3.2	0	410	27	89	176	52	27	6	5	1075
13-Feb-90	C1	3.8	3.8	2.8	0	790	11	156	129	53	45	7	4	1275
13-Feb-90	C2	3.8		3.1	0	490	27	104	174	54	31	6	5	1150
13-Feb-90	C3	3.8	3.8	3.2	0	320	20	76	193	51	24	5	6	1025
27-Feb-90	1			2.6	0	907	4	156	141	60	48	7	3	1575
27-Feb-90	A2	3.8		2.8	0	550	15	118	171	56	34	6	6	1200
27-Feb-90	A3	3.8	15.1	3.2	0	260	27	73	203	51	16	5	8	975
27-Feb-90	B2	3.8		2.7	0	860	16	173	185	72	51	8	4	1625
27-Feb-90	B3	3.8	9.5	2.8	0	710	29	148	206	69	42	8	5	1550
27-Feb-90	C2	3.8		2.8	0	730	37	150	223	76	49	8	7	1675
27-Feb-90	C3	3.8	15.1	2.9	0	590	38	171	253	74	39	8	6	1550
13-Mar-90	A2	3.8		3.1	0	490	22	97	227	63	30	6	6	1330
13-Mar-90	A3	3.8	3.8	3.5	0	209	42	64	274	66	18	6	6	1270
13-Mar-90	B2	3.8		2.9	0	826	25	166	224	78	50	8	5	1750
13-Mar-90	B3	3.8	2.8	3.1	0	588	50	134	280	83	37	9	6	1710
13-Mar-90	C1	3.8	3.8	2.7	0	756	6	181	172	76	57	8	4	1750
13-Mar-90	C2	3.8		2.9	0	868	19	161	208	78	54	8	5	1725
13-Mar-90	C3	3.8	2.8	3.1	0	576	27	117	263	79	41	7	6	1625
29-Mar-90	A2	3.8		3.2	0	460	15	90	191	55	28	6	6	1200
29-Mar-90	A3	3.8	5.0	3.5	0	270	30	66	235	59	20	6	6	1150
29-Mar-90	B2	3.8		2.9	0	760	9	141	171	64	43	7	5	1450
29-Mar-90	B3	3.8	3.3	3.1	0	585	28	122	223	70	36	8	6	1450
29-Mar-90	C1	3.3	3.3	2.8	0	890	9	162	157	65	50	7	4	1550
29-Mar-90	C2	3.3		3.3	0	360	20	73	271	76	31	7	11	1450
29-Mar-90	C3	3.3	2.8	4.5	0	150	20	36	331	80	20	7	11	1425
12-Apr-90	A2	3.8	4.7	3.2	0	281	14	62	151	41	19	5	6	850
12-Apr-90	A3	3.8	4.7	3.7	0	172	30	49	195	47	13	5	6	890
12-Apr-90	B2	3.8	3.3	2.8	0	572	6	107	123	47	33	5	5	1080
12-Apr-90	B3	3.8	3.8	3.0	0	494	29	104	172	54	29	6	5	1160
12-Apr-90	C1	2.8	2.8	2.7	0	665	3	118	116	48	37	6	4	1150
12-Apr-90	C2	2.8	2.8	3.0	0	513	30	104	155	51	32	6	4	1110
12-Apr-90	C3	2.8	1.9	3.3	0	283	23	66	234	59	21	6	6	1160
25-Apr-90	A2	3.3		3.2	0	371	25	80	195	55	24	6	6	1100
25-Apr-90	A3	3.3	2.2	3.6	0	204	41	60	226	55	15	6	7	975
25-Apr-90	B2	3.8		2.8	0	739	10	137	171	65	41	7	6	1425
25-Apr-90	B3	3.8	3.6	3.0	0	573	42	122	211	68	33	7	6	1350
25-Apr-90	C1	3.8	3.8	2.7	0	880	10	160	159	69	49	7	4	1500
25-Apr-90	C2	3.8		2.8	0	703	6	115	161	63	43	7	5	1300
25-Apr-90	C3	3.8	2.0	3.4	0	277	29	69	269	68	21	7	6	1175
01-May-90	A2	3.3	4.1	3.1	0	480	34	109	234	65	31	7	6	1300
01-May-90	A3	3.3	3.8	4.4	0	185	53	66	268	61	14	7	6	1075
01-May-90	B2	3.3	2.8	2.8	0	895	49	163	210	77	51	8	5	1700
01-May-90	B3	3.3	3.1	3.0	0	635	71	138	250	77	37	8	5	1575
01-May-90	C1	3.3	3.3	2.6	0	1035	6	176	181	75	57	8	4	1775
01-May-90	C3	3.3	2.8	3.9	0	155	24	41	344	78	15	7	10	1375
07-May-90	A2	1.9		5.9	40.1	0	21	25	270	51	4	5	8	875

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
07-May-90	A3	1.9	2.8	5.3	0	0	32	33	272	55	1	6	7	925
07-May-90	B2	1.0		2.9	0	557	9	92	143	51	33	6	4	1100
07-May-90	B3	1.0	2.8	3.0	0	421	23	77	169	52	26	6	4	1025
07-May-90	C2	1.0		3.1	0	279	14	42	278	69	18	7	7	1290
07-May-90	C3	1.0	0.5	6.5	125	0	22	22	375	73	2	7	9	1230
17-May-90	A2	1.0		3.5	0	80	27	31	134	29	6	3	5	575
17-May-90	A3	1.0	4.7	3.6	0	50	33	36	177	37	3	4	5	675
17-May-90	B2	2.8		2.8	0	550	27	99	160	52	32	6	4	1200
17-May-90	B3	2.8	3.8	3.1	0	420	85	105	209	57	25	7	4	1200
17-May-90	C1	1.4	1.4	2.8	0	480	4	84	93	37	26	4	4	875
17-May-90	C2	1.4		3.1	0	220	61	68	235	56	7	5	5	1100
17-May-90	C3	1.4	2.8	4.8	0	10	37	37	289	60	2	6	6	1075
23-May-90	A2	1.1	0.5	5.7	33.7	0	15	20	227	46	5	5	8	775
23-May-90	A3	1.1	1.3	6.0	40	0	24	27	219	45	1	5	6	725
23-May-90	B2	2.8	3.5	2.9	0	591	23	89	237	76	43	8	6	1450
23-May-90	B3	2.8	3.0	3.1	0	411	27	64	257	72	32	8	5	1325
23-May-90	C1	1.3	1.5	2.6	0	990	10	178	178	77	54	8	4	1700
23-May-90	C2	1.3	1.5	3.5	0	125	15	23	318	76	5	10	9	1275
23-May-90	C3	1.3	0.5	6.6	231	0	24	24	357	69	1	6	8	1025
06-Jun-90	A2	0.3	0.8	3.5	0	148	14	24	159	41	12	4	6	720
06-Jun-90	A3	0.3	1.4	6.2	62.4	0	32	40	176	37	0	4	6	500
06-Jun-90	B2	3.4	2.8	3.0	0	610	21	96	233	76	46	8	5	1425
06-Jun-90	B3	3.4	3.0	3.2	0	428	47	79	270	77	34	8	6	1375
06-Jun-90	C1	1.8	2.1	2.7	0	977	12	178	172	74	54	8	5	1625
06-Jun-90	C2	1.8	1.5	3.3	0	170	17	26	289	72	12	7	6	1195
06-Jun-90	C3	1.8	0.3	6.6	253	0	26	26	334	65	0	5	7	875
20-Jun-90	A2	0.7	1.6	3.3	0	185	32	45	176	45	8	5	5	815
20-Jun-90	A3	0.7	0.7	6.3	99.4	0	49	63	159	35	1	3	5	460
20-Jun-90	B2	3.6	3.1	3.0	0	641	45	113	268	85	45	9	7	1620
20-Jun-90	B3	3.6	3.4	3.2	0	520	79	112	280	81	36	9	6	1540
20-Jun-90	C1	2.1	2.1	2.7	0	1050	8	183	195	82	58	9	4	1800
20-Jun-90	C2	2.1	1.5	3.1	0	342	52	92	314	81	15	8	6	1460
20-Jun-90	C3	2.1	1.2	6.5	165	0	32	36	328	67	1	6	6	970
03-Jul-90	A2	1.0	0.9	3.2	0	254	45	57	215	56	14	7	6	975
03-Jul-90	A3	1.0	0.7	6.6	119	0	27	34	164	39	0	3	7	450
03-Jul-90	B2	3.5	2.9	2.9	0	840	67	161	268	92	56	10	6	1800
03-Jul-90	B3	3.5	3.1	3.1	0	660	87	130	294	89	48	9	6	1750
03-Jul-90	C1	1.9	1.9	2.6	0	1083	15	185	210	86	62	9	6	1890
03-Jul-90	C2	1.9	1.0	3.0	0	553	35	99	286	86	36	9	5	1600
03-Jul-90	C3	1.9	0.7	5.9	29.2	0	25	31	348	78	10	7	6	1220
10-Jul-90	A2	0.9	0.8	3.1	0	372	61	86	222	65	20	7	6	1200
10-Jul-90	A3	0.9	1.1	6.3	182	0	42	54	179	43	1	4	6	525
10-Jul-90	B2	3.8	3.5	2.7	0	960	49	182	227	88	56	9	6	1800
10-Jul-90	B3	3.8	3.9	2.9	0	783	75	161	257	89	49	9	6	1725
10-Jul-90	C1	1.8	1.8	2.6	0	1127	10	187	218	92	63	10	5	1925
10-Jul-90	C2	1.8	2.5	3.0	0	718	110	187	252	89	34	9	6	1625
10-Jul-90	C3	1.8	3.2	3.2	0	306	59	91	296	82	22	8	6	1350
17-Jul-90	A2	0.7	0.6	3.0	0	339	45	73	158	50	17	5	5	925
17-Jul-90	A3	0.7	0.5	6.5	201	0	32	39	171	38	1	4	5	400
17-Jul-90	B2	3.4	3.1	2.8	0	668	29	126	176	66	39	7	5	1325

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
17-Jul-90	B3	3.4	3.1	2.9	0	578	64	124	195	67	36	7	5	1325
17-Jul-90	C1	1.5	1.5	2.7	0	909	32	168	182	76	52	8	5	1350
17-Jul-90	C2	1.5	1.0	2.9	0	489	53	107	208	69	23	7	6	1250
17-Jul-90	C3	1.5	0.6	6.6	256	0	25	28	313	66	4	5	6	890
24-Jul-90	A2	9.9	9.8	2.7	0	785	40	137	188	75	48	8	5	1513
24-Jul-90	A3	9.9	9.8	3.1	0	402	57	110	244	71	27	7	5	1225
24-Jul-90	B2	9.1	8.9	2.6	0	854	28	153	193	78	52	8	5	1625
24-Jul-90	B3	9.1	9.0	2.7	0	800	79	148	209	79	52	8	5	1600
24-Jul-90	C1	9.5	9.5	2.7	0	786	9	130	153	65	43	7	4	1375
24-Jul-90	C2	9.5	9.1	2.8	0	706	29	125	209	77	45	8	6	1500
24-Jul-90	C3	9.5	8.9	2.9	0	588	30	114	227	78	40	8	6	1425
27-Jul-90	A2	10.0	9.8	2.6	0	854	59	148	207	81	54	9	5	1650
27-Jul-90	A3	10.0	9.4	3.0	0	448	64	113	262	78	32	8	5	1450
27-Jul-90	B2	9.8	9.4	2.6	0	891	56	161	208	83	58	9	5	1760
27-Jul-90	B3	9.8	9.4	2.7	0	808	81	146	211	80	54	8	5	1650
27-Jul-90	C1	9.5	9.5	2.6	0	1046	13	173	201	83	59	9	5	1650
27-Jul-90	C2	9.5	9.0	2.8	0	782	53	135	237	86	51	8	6	1675
27-Jul-90	C3	9.5	8.8	2.9	0	654	38	119	245	86	45	8	6	1575
31-Jul-90	A2	9.8	9.6	2.6	0	1090	54	198	230	93	66	10	5	1975
31-Jul-90	A3	9.8	9.9	3.0	0	651	80	154	299	91	39	10	5	1775
31-Jul-90	B2	9.5	9.4	2.6	0	1135	60	203	227	92	67	10	5	2025
31-Jul-90	B3	9.5	9.5	2.7	0	1018	100	194	234	92	63	10	5	1975
31-Jul-90	C1	9.5	9.5	2.5	0	1171	7	198	223	94	66	10	5	2025
31-Jul-90	C2	9.5	9.3	2.7	0	903	70	173	264	93	55	9	6	1925
31-Jul-90	C3	9.5	9.1	2.9	0	755	54	152	278	93	49	9	6	1800
03-Aug-90	A2	7.8	7.4	2.6	0	1065	43	176	237	93	65	10	5	1940
03-Aug-90	A3	7.8	7.3	3.0	0	650	84	165	312	97	42	11	5	1775
03-Aug-90	B2	7.8	7.4	2.6	0	1120	33	198	240	98	71	10	5	2125
03-Aug-90	B3	7.8	7.6	2.7	0	1010	59	190	254	98	67	10	5	2050
03-Aug-90	C1	7.8	7.8	2.5	0	1190	7	196	230	96	70	10	5	2150
03-Aug-90	C2	7.8	7.3	2.7	0	913	39	159	279	98	58	10	6	1960
03-Aug-90	C3	7.8	7.1	2.9	0	707	33	136	298	96	50	9	6	1820
07-Aug-90	A2	7.7	7.2	2.6	0	1050	72	199	259	99	65	12	6	2075
07-Aug-90	A3	7.7	7.2	3.0	0	634	103	165	338	102	37	10	5	1900
07-Aug-90	B2	7.6	7.4	2.6	0	1130	61	225	248	101	69	11	5	2100
07-Aug-90	B3	7.6	7.3	2.7	0	1040	94	218	265	102	67	10	5	2075
07-Aug-90	C1	7.7	7.7	2.5	0	1195	9	208	234	100	70	10	5	2150
07-Aug-90	C2	7.7	5.6	2.7	0	986	57	192	272	102	66	11	5	2000
07-Aug-90	C3	7.7	5.5	2.9	0	748	40	154	301	100	53	10	6	1850
10-Aug-90	A2	7.7	7.4	2.6	0	1120	50	197	270	107	71	11	5	2140
10-Aug-90	A3	7.7	8.2	3.0	0	761	103	176	334	107	50	12	5	2025
10-Aug-90	B2	7.6	7.5	2.6	0	1168	42	212	256	107	73	11	5	2200
10-Aug-90	B3	7.6	7.6	2.7	0	1070	74	207	276	107	71	11	3	2125
10-Aug-90	C1	7.7	7.7	2.5	0	1230	8	205	246	105	72	11	5	2225
10-Aug-90	C2	7.7	7.5	2.7	0	1000	40	183	299	109	66	10	6	2175
10-Aug-90	C3	7.7	7.4	2.8	0	840	30	157	313	105	57	10	1	2050
14-Aug-90	A2	7.6	7.4	2.6	0	1157	49	202	241	111	73	11	6	2125
14-Aug-90	A3	7.6	7.6	3.0	0	785	109	186	353	112	51	13	6	2100
14-Aug-90	B2	7.5	7.3	2.6	0	1197	52	221	272	111	76	11	6	2300
14-Aug-90	B3	7.5	7.3	2.8	0	1108	83	215	291	111	72	11	6	2200

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
14-Aug-90	C1	9.6	9.6	2.6	0	1261	6	216	265	113	78	12	5	2325
14-Aug-90	C2	9.6	9.3	2.7	0	1070	33	194	304	114	76	11	6	2250
14-Aug-90	C3	9.6	9.0	2.8	0	911	43	176	327	113	61	11	6	2200
17-Aug-90	A2	5.5	5.3	2.7	0	1146	63	211	303	117	74	12	6	2300
17-Aug-90	A3	5.5	5.5	3.0	0	770	130	184	377	118	49	13	6	2150
17-Aug-90	B2	5.6	5.3	2.6	0	1236	46	222	283	116	79	12	6	2325
17-Aug-90	B3	5.6	5.4	2.7	0	1127	79	214	306	118	75	12	6	2300
17-Aug-90	C1	5.7	5.7	2.6	0	1318	6	223	269	117	79	12	5	2375
17-Aug-90	C2	5.7	5.3	2.8	0	1063	46	186	334	116	69	12	6	2325
17-Aug-90	C3	5.7	5.2	2.9	0	875	43	165	354	118	62	11	6	2200
21-Aug-90	A2	5.6	9.7	2.7	0	1146	32	164	220	86	55	9	5	1725
21-Aug-90	A3	5.6	20.7	3.0	0	770	65	144	252	85	43	9	5	1575
21-Aug-90	B2	5.6	8.8	2.6	0	1067	39	201	232	95	64	10	5	1925
21-Aug-90	B3	5.6	13.8	2.8	0	868	52	167	216	84	51	9	5	1688
21-Aug-90	C1	5.5	5.5	2.6	0	1224	5	205	246	104	73	11	5	2175
21-Aug-90	C2	5.5	10.8	2.9	0	750	33	136	233	84	45	8	5	1625
21-Aug-90	C3	5.5	23.6	3.2	0	672	36	137	256	87	46	9	5	1675
23-Aug-90	A2	3.8	4.5	2.8	0	848	19	138	276	88	37	10	5	1650
23-Aug-90	A3	3.8	6.1	3.1	0	603	70	143	206	81	51	8	5	1600
23-Aug-90	B2	3.8	4.3	2.7	0	1017	20	179	214	89	59	9	5	1825
23-Aug-90	B3	3.8	5.2	2.7	0	852	42	164	209	84	52	9	5	1700
23-Aug-90	C1	3.9	3.9	2.6	0	1109	7	185	222	96	66	10	5	1988
23-Aug-90	C2	3.9	4.3	2.8	0	814	46	153	251	91	50	9	5	1775
23-Aug-90	C3	3.9	5.4	3.0	0	600	36	121	276	89	39	8	5	1600
27-Aug-90	A2	3.6	3.2	2.7	0	1028	41	200	273	105	65	11	6	2100
27-Aug-90	A3	3.6	3.4	2.7	0	1005	50	203	271	104	62	11	6	2025
27-Aug-90	B2	3.6	3.2	2.7	0	1141	22	214	255	105	68	11	6	2100
27-Aug-90	B3	3.6	3.5	2.8	0	976	50	200	270	104	62	11	6	2025
27-Aug-90	C1	3.7	3.7	2.6	0	1218	6	213	252	108	73	12	5	2200
27-Aug-90	C2	3.7	3.0	2.7	0	967	46	182	288	107	64	11	6	2100
27-Aug-90	C3	3.7	3.0	2.9	0	618	37	144	332	107	52	11	6	1950
31-Aug-90	A2	1.9	3.0	2.8	0	1038	59	196	279	104	62	11	6	2050
31-Aug-90	A3	1.9	3.0	3.2	0	523	122	157	357	106	29	12	6	1800
31-Aug-90	B2	2.2	2.7	2.8	0	1139	26	207	248	102	67	11	5	2075
31-Aug-90	B3	2.2	3.0	2.9	0	982	47	197	266	101	61	11	6	1975
31-Aug-90	C1	2.2	2.2	2.6	0	1211	9	206	246	105	71	11	5	2125
31-Aug-90	C2	2.2	2.4	2.8	0	980	56	189	286	107	64	11	6	2050
31-Aug-90	C3	2.2	2.3	3.0	0	643	40	142	330	105	49	10	6	1825
04-Sep-90	A2	2.0	1.6	2.7	0	943	77	180	314	110	64	12	6	2150
04-Sep-90	A3	2.0	1.4	3.0	0	463	151	166	397	112	22	14	6	1825
04-Sep-90	B2	2.2	1.6	2.6	0	1096	45	205	276	110	74	12	6	2200
04-Sep-90	B3	2.2	1.7	2.8	0	943	79	194	296	109	64	11	6	2075
04-Sep-90	C1	1.9	1.9	2.5	0	1256	11	218	266	113	78	12	5	2325
04-Sep-90	C2	1.9	1.5	2.7	0	992	51	183	307	111	68	11	6	2150
04-Sep-90	C3	1.9	1.3	2.9	0	625	53	136	371	115	52	12	6	1975
07-Sep-90	A2	1.7	3.5	2.8	0	668	31	119	183	70	43	7	4	1350
07-Sep-90	A3	1.7	2.2	3.2	0	405	120	140	306	90	25	11	5	1500
07-Sep-90	B2	2.0	2.7	2.8	0	885	23	161	196	84	55	9	5	1650
07-Sep-90	B3	2.0	2.7	2.9	0	808	67	167	218	84	50	9	5	1650
07-Sep-90	C1	1.9	1.9	2.6	0	1142	10	195	239	102	70	11	5	2050

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
07-Sep-90	C2	1.9	4.7	2.9	0	795	96	166	229	85	49	8	5	1700
07-Sep-90	C3	1.9	1.9	3.2	0	339	58	91	286	82	28	8	5	1375
11-Sep-90	A2	1.9	1.4	2.8	0	874	26	164	256	92	53	10	6	1825
11-Sep-90	A3	1.9	1.4	3.1	0	402	67	117	339	100	26	12	6	1650
11-Sep-90	B2	2.0	1.5	2.7	0	1002	14	195	226	92	61	10	6	1875
11-Sep-90	B3	2.0	1.6	2.8	0	842	17	166	231	89	52	9	5	1775
11-Sep-90	C1	1.9	1.9	2.6	0	1094	10	198	225	94	65	10	5	1925
11-Sep-90	C2	1.9	1.1	2.8	0	845	34	124	258	95	56	10	5	1825
11-Sep-90	C3	1.9	1.4	3.0	0	430	28	98	321	96	36	9	6	1550
18-Sep-90	A2	1.7	1.4	2.8	0	747	116	133	212	78	44	9	5	1537
18-Sep-90	A3	1.7	1.3	3.2	0	347	89	119	310	91	22	11	6	1475
18-Sep-90	B2	1.8	1.2	2.8	0	855	9	159	198	76	48	9	6	1625
18-Sep-90	B3	1.8	1.3	2.9	0	732	21	144	207	78	45	8	5	1525
18-Sep-90	C1	1.7	1.7	2.7	0	868	8	150	175	73	50	9	5	1550
18-Sep-90	C2	1.7	1.1	2.9	0	726	23	133	215	78	47	9	5	1575
18-Sep-90	C3	1.7	1.0	3.5	0	204	38	77	317	88	27	8	6	1350
25-Sep-90	A2	1.0	0.6	2.8	0	639	11	104	202	71	39	8	5	1375
25-Sep-90	A3	1.0	0.6	3.2	0	309	62	88	290	85	18	11	5	1350
25-Sep-90	B2	0.9		2.8	0	716	7	128	168	67	43	8	5	1375
25-Sep-90	B3	0.9	0.6	2.9	0	623	13	115	198	71	38	8	5	1350
25-Sep-90	C1	0.9	0.9	2.7	0	869	5	155	171	72	51	9	5	1550
25-Sep-90	C2	0.9	0.9	2.9	0	641	27	109	206	72	43	8	5	1400
25-Sep-90	C3	0.9	0.7	6.8	332	0	44	40	436	100	4	9	7	1150
02-Oct-90	A2	0.9	0.6	2.8	0	649	10	111	240	83	46	9	6	1538
02-Oct-90	A3	0.9	0.7	3.2	0	224	53	75	301	86	15	12	6	1275
02-Oct-90	B2	0.8		2.8	0	752	14	134	206	79	52	9	6	1550
02-Oct-90	B3	0.8	0.6	2.9	0	581	20	130	232	79	38	9	6	1450
02-Oct-90	C1	0.9	0.9	2.6	0	1096	7	199	229	95	70	11	5	1975
02-Oct-90	C2	0.9	0.5	2.9	0	687	51	132	239	83	51	9	6	1550
02-Oct-90	C3	0.9	0.2	3.2	0	230	50	73	297	84	15	11	5	1290
09-Oct-90	A2	0.8	0.7	2.8	0	657	25	99	225	79	45	9	6	1525
09-Oct-90	A3	0.8	0.6	3.2	0	190	26	42	279	80	13	10	6	1200
09-Oct-90	B2	0.8	0.4	2.8	0	765	5	127	200	80	58	9	6	1600
09-Oct-90	B3	0.8	0.7	2.9	0	504	9	83	229	80	34	8	6	1400
09-Oct-90	C1	0.8	0.8	2.6	0	988	6	176	203	86	61	10	5	1825
09-Oct-90	C2	0.8	0.5	2.9	0	609	7	95	225	80	48	9	6	1475
09-Oct-90	C3	0.8	0.2	4.3	0	68	31	37	283	75	12	7	6	1075
12-Oct-90	A2	10.4	15.3	2.7	0	662	10	117	151	59	43	7	3	1250
12-Oct-90	A3	10.4	25.1	2.9	0	492	23	98	163	57	32	7	4	1100
12-Oct-90	B2	10.4	13.0	2.6	0	806	9	140	169	69	50	8	4	1450
12-Oct-90	B3	10.4	18.3	2.7	0	720	16	130	172	66	47	8	4	1375
12-Oct-90	C1	11.4	11.4	2.6	0	870	12	147	165	71	53	9	4	1550
12-Oct-90	C2	11.4	16.7	2.7	0	623	17	113	147	56	40	7	4	1150
12-Oct-90	C3	11.4	28.5	2.8	0	581	12	104	154	57	39	7	4	1175
16-Oct-90	A2	9.9	9.8	2.8	0	784	5	135	164	67	47	8	5	1400
16-Oct-90	A3	9.9	9.8	3.0	0	637	22	119	184	67	41	8	5	1350
16-Oct-90	B2	10.2	9.9	2.8	0	787	5	138	159	65	47	8	5	1400
16-Oct-90	B3	10.2	9.9	2.8	0	740	6	125	158	63	44	8	4	1350
16-Oct-90	C1	9.6	9.6	2.8	0	835	8	143	161	66	49	8	4	1450
16-Oct-90	C2	9.6	9.1	2.8	0	779	6	133	164	65	47	8	4	1425

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
16-Oct-90	C3	9.6	8.9	2.9	0	677	8	118	174	65	43	8	5	1300
19-Oct-90	A2	10.2	10.1	2.6	0	805	5	136	159	63	49	8	4	1400
19-Oct-90	A3	10.2	10.2	2.6	0	688	26	128	200	69	46	9	4	1425
19-Oct-90	B2	10.2	9.7	2.6	0	860	4	151	177	71	54	9	4	1575
19-Oct-90	B3	10.2	9.8	2.7	0	801	13	141	187	72	54	9	5	1525
19-Oct-90	C1	8.8	8.8	2.7	0	811	7	141	172	68	51	8	4	1475
19-Oct-90	C2	8.8	8.7	2.6	0	804	8	139	174	67	51	8	4	1500
19-Oct-90	C3	8.8	9.0	2.8	0	716	11	128	197	70	50	8	5	1450
23-Oct-90	A2	10.6	13.7	2.8	0	582	8	103	128	50	37	7	4	1100
23-Oct-90	A3	10.6	15.3	2.9	0	509	21	99	158	54	33	7	4	1100
23-Oct-90	B2	9.2	11.0	2.7	0	644	5	114	133	53	40	8	4	1150
23-Oct-90	B3	9.2	12.3	2.7	0	648	11	118	146	58	42	7	4	1225
23-Oct-90	C1	10.1	10.1	2.7	0	566	6	101	116	47	35	6	4	1025
23-Oct-90	C2	10.1	13.1	2.8	0	565	11	99	128	49	36	6	4	1050
23-Oct-90	C3	10.1	14.6	2.8	0	511	8	94	144	52	35	6	4	1050
26-Oct-90	A2	9.8	9.8	2.8	0	689	4	125	150	61	44	8	5	1275
26-Oct-90	A3	9.8	10.1	2.9	0	581	18	113	167	61	39	8	5	1200
26-Oct-90	B2	7.7	7.4	2.8	0	653	3	116	136	56	40	7	4	1175
26-Oct-90	B3	7.7	7.6	2.9	0	602	5	106	139	54	39	7	4	1125
26-Oct-90	C1	9.2	9.2	2.8	0	761	11	139	152	62	45	8	4	1350
26-Oct-90	C2	9.2	8.9	2.8	0	657	4	115	143	57	42	7	4	1175
26-Oct-90	C3	9.2	8.7	2.9	0	582	6	104	149	57	38	7	4	1125
30-Oct-90	A2	9.6	9.5	2.6	0	931	5	170	186	77	57	9	5	1650
30-Oct-90	A3	9.6	9.6	2.7	0	791	19	155	200	76	52	9	5	1525
30-Oct-90	B2	10.2	9.9	2.6	0	920	3	168	184	76	57	9	5	1625
30-Oct-90	B3	10.0	9.9	2.6	0	867	4	161	183	74	55	9	5	1550
30-Oct-90	C1	9.0	9.0	2.6	0	963	7	179	189	79	60	10	5	1675
30-Oct-90	C2	9.0	8.8	2.6	0	899	4	167	190	78	59	9	5	1625
30-Oct-90	C3	9.0	8.5	2.8	0	822	6	155	196	77	55	9	5	1525
02-Nov-90	A2	5.0	4.9	2.7	0	970	4	174	194	81	61	10	5	1725
02-Nov-90	A3	5.0	4.9	2.9	0	790	24	147	212	81	57	10	5	1575
02-Nov-90	B2	5.0	4.7	2.7	0	959	4	172	189	81	61	10	5	1675
02-Nov-90	B3	5.0	4.9	2.7	0	872	6	155	191	77	56	9	5	1625
02-Nov-90	C1	5.0	5.0	2.6	0	1081	7	190	203	86	65	10	5	1850
02-Nov-90	C2	5.0	4.8	2.7	0	921	7	162	195	79	61	9	5	1700
02-Nov-90	C3	5.0	4.4	2.8	0	824	8	150	204	79	56	9	5	1575
06-Nov-90	A2	5.0	5.0	2.7	0	1005	15	180	220	88	65	10	5	1825
06-Nov-90	A3	5.0	5.2	2.8	0	825	35	151	230	83	59	10	5	1675
06-Nov-90	B2	5.0	4.5	2.7	0	1023	18	182	213	86	67	10	5	1825
06-Nov-90	B3	5.0	4.9	2.7	0	902	23	164	225	88	64	10	5	1775
06-Nov-90	C1	5.0	5.1	2.5	0	1130	4	201	216	90	69	11	5	1925
06-Nov-90	C2	5.0	4.8	2.7	0	983	15	172	219	86	65	10	5	1825
06-Nov-90	C3	5.0	4.7	2.8	0	831	14	146	231	84	59	10	5	1700
15-Nov-90	A2	5.0	4.4	2.7	0	931	4	161	188	77	58	8	6	1663
15-Nov-90	A3	5.0	4.6	2.9	0	726	26	137	211	76	51	9	5	1525
15-Nov-90	B2	5.0	4.2	2.6	0	897	6	152	177	72	56	9	5	1725
15-Nov-90	B3	5.0	4.3	2.7	0	798	5	137	174	68	51	8	5	1475
15-Nov-90	C1	5.0	4.5	2.6	0	961	6	162	182	76	59	9	5	1675
15-Nov-90	C2	5.0	4.2	2.7	0	829	4	140	172	68	53	8	5	1525
15-Nov-90	C3	5.0	3.8	2.8	0	677	7	127	182	68	46	8	5	1375

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
20-Nov-90	A2	5.0	4.1	2.6	0	965	4	172	191	78	58	9	5	1737
20-Nov-90	A3	5.0	4.1	2.9	0	593	28	151	221	80	51	10	4	1600
20-Nov-90	B2	5.0	3.7	2.7	0	974	4	173	187	77	60	10	5	1725
20-Nov-90	B3	5.0	3.8	2.6	0	919	6	169	196	79	58	10	5	1700
20-Nov-90	C1	5.0	4.0	2.6	0	1018	6	186	190	70	62	10	6	1750
20-Nov-90	C2	5.0	3.6	2.7	0	943	6	167	191	77	59	9	5	1675
20-Nov-90	C3	5.0	3.3	2.7	0	824	9	151	208	78	55	9	5	1600
27-Nov-90	A2	5.0	4.9	2.7	0	939	5	162	194	77	58	10	5	1725
27-Nov-90	A3	5.0	4.9	2.7	0	805	19	151	217	80	53	10	5	1650
27-Nov-90	B2	5.0	4.2	2.6	0	990	3	173	195	80	61	10	5	1750
27-Nov-90	B3	5.0	4.5	2.6	0	925	7	161	204	80	58	10	5	1700
27-Nov-90	C1	5.0	4.7	2.6	0	992	8	175	188	79	59	10	5	1675
27-Nov-90	C2	5.0	4.5	2.6	0	948	6	183	200	80	60	10	5	1800
27-Nov-90	C3	5.0	4.3	2.7	0	861	8	144	214	80	55	0	5	1675
05-Dec-90	A2	5.0	4.9	2.7	0	840	3	145	171	68	51	8	5	1550
05-Dec-90	A3	5.0	5.0	2.9	0	730	23	138	200	73	47	9	4	1550
05-Dec-90	B2	5.0	4.2	2.7	0	880	3	159	178	73	56	9	4	1675
05-Dec-90	B3	5.0	4.1	2.7	0	855	7	153	183	74	53	9	5	1600
05-Dec-90	C1	5.0	4.6	2.7	0	836	7	145	162	68	51	8	4	1550
05-Dec-90	C2	5.0	4.2	2.7	0	832	4	147	174	70	52	9	5	1575
05-Dec-90	C3	5.0	3.9	2.8	0	727	10	132	195	71	47	8	5	1575
11-Dec-90	A2	5.0	4.4	2.8	0	895	2	161	174	74	51	9	5	1600
11-Dec-90	A3	5.0	4.4	2.9	0	772	18	146	202	75	48	9	5	1575
11-Dec-90	B2	5.0	4.6	2.8	0	888	12	164	172	72	52	9	5	1575
11-Dec-90	B3	5.0	4.7	2.8	0	869	4	158	185	74	52	9	5	1625
11-Dec-90	C1	5.0	4.4	2.8	0	906	4	166	173	72	52	9	4	1600
11-Dec-90	C2	5.0	4.1	2.8	0	862	2	154	180	71	51	9	5	1550
11-Dec-90	C3	5.0	3.7	2.9	0	774	6	147	197	75	49	9	5	1500
18-Dec-90	A2	5.0	12.5	3.0	0	366	2	65	98	34	23	4	3	725
18-Dec-90	A3	5.0	14.0	3.0	0	343	5	60	100	34	22	4	2	700
18-Dec-90	B2	5.0	8.2	2.8	0	660	4	117	140	54	40	7	3	1200
18-Dec-90	B3	5.0	13.7	2.8	0	578	5	97	131	49	34	6	3	1050
18-Dec-90	C1	5.0	5.6	2.7	0	870	3	151	170	68	51	8	4	1500
18-Dec-90	C2	5.0	12.1	2.9	0	415	6	66	106	37	24	4	2	800
18-Dec-90	C3	5.0	22.1	3.0	0	350	4	58	111	36	21	4	3	750
28-Dec-90	A2	5.0	6.8	2.7	0	896	2	169	146	62	49	8	3	1500
28-Dec-90	A3	5.0	7.9	2.8	0	721	28	155	175	65	43	8	4	1375
28-Dec-90	B2	5.0	5.9	2.7	0	988	1	190	157	68	56	8	3	1600
28-Dec-90	B3	5.0	6.2	2.7	0	923	8	186	164	69	53	8	4	1575
28-Dec-90	C1	5.0	6.4	2.7	0	993	2	185	159	69	56	8	4	1575
28-Dec-90	C2	5.0	7.1	2.7	0	930	7	178	157	67	54	8	3	1525
28-Dec-90	C3	5.0	7.2	2.8	0	829	2	165	172	67	49	8	3	1475
03-Jan-91	A2	5.0	5.4	2.7	0	834	2	162	144	61	49	8	4	1425
03-Jan-91	A3	5.0	5.4	2.9	0	625	17	123	154	57	41	8	4	1250
03-Jan-91	B2	5.0	5.0	2.7	0	901	1	184	147	63	54	8	4	1500
03-Jan-91	B3	5.0	5.1	2.8	0	792	4	162	148	63	49	8	4	1425
03-Jan-91	C1	5.0	4.8	2.6	0	1024	2	196	157	69	58	9	3	1675
03-Jan-91	C2	5.0	4.6	2.7	0	851	2	168	154	64	51	8	4	1450
03-Jan-91	C3	5.0	4.4	2.8	0	720	5	146	162	62	45	8	4	1350
09-Jan-91	A2	5.0	6.4	2.7	0	687	2	128	125	52	40	6	4	1175

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
09-Jan-91	A3	5.0	7.3	2.8	0	560	14	111	133	50	35	6	4	1075
09-Jan-91	B2	5.0	5.1	2.7	0	787	2	145	131	56	45	7	4	1275
09-Jan-91	B3	5.0	5.7	2.7	0	703	6	134	134	55	41	6	4	1225
09-Jan-91	C1	5.0	4.8	2.6	0	845	2	156	138	60	47	7	4	1400
09-Jan-91	C2	5.0	5.4	2.7	0	740	4	136	138	57	43	6	4	1250
09-Jan-91	C3	5.0	5.5	2.8	0	659	5	125	146	56	39	6	4	1225
15-Jan-91	A2	5.0	5.2	2.7	0	778	3	144	134	58	45	7	4	1300
15-Jan-91	A3	5.0	5.4	2.8	0	593	20	118	150	56	37	7	4	1170
15-Jan-91	B2	5.0	4.4	2.6	0	828	2	156	137	60	48	7	4	1325
15-Jan-91	B3	5.0	4.8	2.7	0	744	5	142	144	60	44	7	4	1275
15-Jan-91	C1	5.0	4.6	2.6	0	923	3	172	146	65	52	7	4	1475
15-Jan-91	C2	5.0	4.5	2.7	0	776	4	144	144	60	46	7	4	1325
15-Jan-91	C3	5.0	4.2	2.8	0	644	7	123	156	59	39	7	4	1175
24-Jan-91	A2	5.0	5.0	2.6	0	877	3	164	154	66	51	8	4	1525
24-Jan-91	A3	5.0	5.0	2.8	0	712	30	152	175	67	44	8	4	1425
24-Jan-91	B2	5.0	4.4	2.6	0	952	2	172	157	69	54	8	4	1575
24-Jan-91	B3	5.0	4.6	2.6	0	877	9	162	178	71	50	8	4	1575
24-Jan-91	C1	5.0	4.5	2.5	0	960	3	174	178	71	54	8	4	1550
24-Jan-91	C2	5.0	4.3	2.6	0	916	3	163	157	68	52	8	4	1500
24-Jan-91	C3	5.0	4.1	2.7	0	766	10	145	178	69	46	8	4	1450
30-Jan-91	A2	5.0	5.6	2.9	0	341	5	60	76	29	20	4	4	625
30-Jan-91	A3	5.0	5.3	3.0	0	354	20	70	104	35	20	5	4	725
30-Jan-91	B2	5.0	4.5	2.8	0	371	2	62	71	29	21	4	4	600
30-Jan-91	B3	5.0	4.6	2.8	0	392	14	72	94	35	23	4	4	750
30-Jan-91	C1	5.0	4.6	2.7	0	484	3	85	90	39	28	4	5	800
30-Jan-91	C2	5.0	4.5	2.8	0	445	6	77	95	37	26	4	5	775
30-Jan-91	C3	5.0	4.4	3.0	0	340	11	66	121	39	21	5	4	750
06-Feb-91	A2	15.0	15.9	2.7	0	640	4	121	125	53	38	6	4	1163
06-Feb-91	A3	15.0	17.9	2.7	0	605	12	121	134	53	38	7	4	1150
06-Feb-91	B2	15.0	15.8	2.7	0	696	2	132	127	55	41	7	4	1225
06-Feb-91	B3	15.0	16.4	2.7	0	655	5	127	128	54	40	6	4	1225
06-Feb-91	C1	15.0	14.6	2.7	0	666	3	124	120	52	38	6	4	1175
06-Feb-91	C2	15.0	15.8	2.7	0	626	6	121	126	53	38	6	4	1100
06-Feb-91	C3	15.0	15.6	2.7	0	599	6	117	136	54	38	6	3	1125
13-Feb-91	A2	5.0	4.5	2.8	0	760	2	137	138	59	43	7	4	1375
13-Feb-91	A3	5.0	6.7	3.0	0	600	21	123	162	60	39	7	4	1225
13-Feb-91	B2	5.0	4.3	2.8	0	818	6	152	150	64	48	7	4	1475
13-Feb-91	B3	5.0	4.5	2.9	0	768	9	151	162	66	46	8	4	1425
13-Feb-91	C1	5.0	4.8	2.7	0	824	2	152	148	64	47	7	4	1475
13-Feb-91	C2	5.0	4.6	2.9	0	739	3	138	159	65	45	7	4	1375
13-Feb-91	C3	5.0	4.5	2.9	0	637	6	128	173	64	41	7	4	1325
21-Feb-91	A2	5.0	5.1	2.9	0	427	3	77	93	38	26	5	4	800
21-Feb-91	A3	5.0	5.4	3.0	0	382	16	73	112	39	24	5	4	850
21-Feb-91	B2	5.0	4.3	2.8	0	482	3	89	96	41	28	5	4	900
21-Feb-91	B3	5.0	4.3	2.9	0	467	5	89	104	42	28	5	4	925
21-Feb-91	C1	5.0	4.6	2.8	0	530	3	99	104	45	31	5	4	975
21-Feb-91	C2	5.0	4.5	2.9	0	468	4	87	106	43	29	5	4	925
21-Feb-91	C3	5.0	4.3	3.0	0	402	6	76	118	43	25	5	4	875
27-Feb-91	A2	5.0	4.1	2.7	0	709	2	133	145	61	42	7	4	1325
27-Feb-91	A3	5.0	3.6	2.9	0	584	14	118	158	59	39	7	4	1225

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
27-Feb-91	B2	5.0	3.8	2.7	0	764	2	144	153	65	46	7	4	1400
27-Feb-91	B3	5.0	3.5	2.8	0	722	5	142	155	65	44	7	4	1375
27-Feb-91	C1	5.0	4.5	2.7	0	768	2	144	149	64	45	7	4	1400
27-Feb-91	C2	5.0	3.9	2.8	0	689	4	130	156	64	44	7	4	1350
27-Feb-91	C3	5.0	3.5	2.9	0	612	6	117	173	64	40	7	4	1300
06-Mar-91	A2	5.0	8.3	3.0	0	410	4	71	100	38	25	4	4	800
06-Mar-91	A3	5.0	11.7	3.1	0	316	9	60	105	37	21	4	4	725
06-Mar-91	B2	5.0	5.9	3.0	0	432	4	80	96	40	26	5	5	800
06-Mar-91	B3	5.0	7.6	3.0	0	372	5	68	94	36	23	4	4	750
06-Mar-91	C1	5.0	4.3	2.9	0	501	4	94	104	44	30	5	4	900
06-Mar-91	C2	5.0	7.2	3.0	0	443	4	83	108	42	28	4	4	850
06-Mar-91	C3	5.0	8.7	3.1	0	349	6	67	113	39	23	5	4	750
12-Mar-91	A2	5.0	4.5	2.7	0	629	3	118	146	57	37	7	5	1200
12-Mar-91	A3	5.0	4.7	3.0	0	496	20	105	160	56	31	7	4	1125
12-Mar-91	B2	5.0	4.0	2.7	0	744	3	133	142	59	42	7	4	1275
12-Mar-91	B3	5.0	4.2	2.8	0	695	6	131	150	61	40	7	4	1250
12-Mar-91	C1	5.0	4.7	2.7	0	766	3	136	141	60	42	7	4	1300
12-Mar-91	C2	5.0	4.4	2.7	0	699	3	125	146	60	41	7	4	1250
12-Mar-91	C3	5.0	4.2	2.8	0	604	7	113	156	58	36	7	4	1175
12-Mar-91	A2	5	4.5	2.7		629	3	118	146	57	37	7	5	1200
12-Mar-91	A3	5	4.7	3.0		496	20	105	160	56	31	7	4	1125
12-Mar-91	B2	5	4.0	2.7		744	3	133	142	59	42	7	4	1275
12-Mar-91	B3	5	4.2	2.8		695	6	131	150	61	40	7	4	1250
12-Mar-91	C1	5	4.7	2.7		766	3	136	141	60	42	7	4	1300
12-Mar-91	C2	5	4.4	2.7		699	3	125	146	60	41	7	4	1250
12-Mar-91	C3	5	4.2	2.8		604	7	113	156	58	36	7	4	1175
20-Mar-91	A2	5	5.5	2.9		358	4	58	95	35	21	4	4	750
20-Mar-91	A3	5	5.1	3.0		331	7	53	112	37	21	5	4	750
20-Mar-91	B2	5	4.0	2.9		436	3	75	96	39	25	4	4	825
20-Mar-91	B3	5	4.3	2.9		417	4	70	105	40	24	5	4	850
20-Mar-91	C1	5	4.5	2.8		526	4	90	108	45	30	5	4	975
20-Mar-91	C2	5	3.7	2.9		413	4	71	98	38	25	4	4	825
20-Mar-91	C3	5	3.7	3.0		363	5	63	112	39	23	5	4	775
27-Mar-91	A2	5	4.9	2.8		560	4	96	123	49	32	6	4	1075
27-Mar-91	A3	5	5.1	3.0		443	11	77	127	45	27	6	4	925
27-Mar-91	B2	5	4.0	2.8		609	3	102	118	49	34	6	4	1125
27-Mar-91	B3	5	4.1	2.9		512	8	89	120	46	29	5	4	1000
27-Mar-91	C1	5	4.9	2.7		690	3	114	127	53	38	6	4	1225
27-Mar-91	C2	5	3.6	2.8		556	4	90	125	49	33	6	4	1075
27-Mar-91	C3	5	3.6	2.9		473	6	81	131	47	29	6	4	1000
02-Apr-91	A2	5	4.6	2.7		650	3	116	148	59	38	7	4	1225
02-Apr-91	A3	5	4.8	2.9		511	13	101	158	58	33	7	4	1125
02-Apr-91	B2	5	3.8	2.7		703	2	129	145	61	41	7	4	1275
02-Apr-91	B3	5	3.9	2.8		655	5	128	150	61	39	7	4	1250
02-Apr-91	C1	5	4.4	2.7		747	3	132	150	64	43	7	4	1350
02-Apr-91	C2	5	4.0	2.8		658	3	117	152	62	41	7	4	1250
02-Apr-91	C3	5	3.8	2.9		576	5	110	161	62	38	7	4	1200
10-Apr-91	A2	5	6.0	2.7		581	10	103	141	55	33	6	4	1187
10-Apr-91	A3	5	4.4	2.9		512	27	105	156	55	30	7	4	1125
10-Apr-91	B2	5	3.2	2.7		679	12	123	147	60	39	7	4	1300

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set	act											
		Lpm	Lpm											
10-Apr-91	B3	5	3.8	2.8		608	27	119	160	61	36	7	4	1275
10-Apr-91	C1	5	4.4	2.7		645	9	112	133	56	37	6	4	1225
10-Apr-91	C2	5		2.8		600	21	108	156	58	35	6	4	1250
10-Apr-91	C3	5		2.9		516	14	99	171	60	33	7	4	1175
17-Apr-91	A2	5	5.5	2.8		487	4	84	119	46	29	5	4	989
17-Apr-91	A3	5	3.1	3.0		408	14	80	138	47	25	6	4	925
17-Apr-91	B2	5	5.7	2.8		534	3	93	115	48	32	5	4	1000
17-Apr-91	B3	5	3.3	2.8		506	7	94	135	52	31	6	4	1000
17-Apr-91	C1	5	4.1	2.7		444	7	97	105	44	32	5	3	1000
17-Apr-91	C2	5	3.9	2.8		480	7	84	135	49	29	6	4	1000
17-Apr-91	C3	5	3.7	2.9		399	4	72	146	48	26	5	4	1000
02-May-91	A2	5	5.1	2.7		730	4	121	163	66	41	7	4	1350
02-May-91	A3	5	4.9	2.8		621	12	104	173	63	36	7	4	1300
02-May-91	B2	5	2.9	2.7		746	4	127	157	66	42	7	4	1425
02-May-91	B3	5	2.8	2.8		661	6	117	167	65	39	7	4	1350
02-May-91	C1	5	5.1	2.6		828	5	133	165	70	45	7	4	1425
02-May-91	C2	5	4.3	2.7		675	5	113	180	68	40	7	4	1400
02-May-91	C3	5	4.1	2.8		601	8	102	184	66	36	7	4	1325
07-May-91	A2	5	5.4	2.7		720	7	129	170	70	42	7	4	1400
07-May-91	A3	5	5.4	2.8		648	18	126	186	70	39	8	4	1375
07-May-91	B2	5	3.7	2.7		782	7	148	177	75	46	8	4	1525
07-May-91	B3	5	3.6	2.8		721	11	140	184	74	42	8	4	1475
07-May-91	C1	5	5.1	2.6		782	4	133	163	71	44	8	4	1475
07-May-91	C2	5	4.5	2.7		701	10	129	177	71	42	8	4	1450
07-May-91	C3	5	4.2	2.8		619	8	116	196	71	38	8	4	1450
14-May-91	A2	5	8.6	2.7		777	14	133	189	77	45	8	4	1550
14-May-91	A3	5	10.8	2.8		655	31	124	189	71	39	8	4	1400
14-May-91	B2	5	7.9	2.7		809	13	141	190	78	47	8	4	1500
14-May-91	B3	5	10.0	2.7		709	18	127	184	73	42	8	4	1285
14-May-91	C1	5	4.9	2.6		776	6	127	177	73	44	8	4	1500
14-May-91	C2	5	9.5	2.7		706	17	117	192	74	41	8	4	1322
14-May-91	C3	5	12.2	2.8		630	16	105	193	71	38	8	4	1375
22-May-91	A2	5	4.6	2.8		894	15	152	221	88	54	9	4	1700
22-May-91	A3	5	4.4	2.9		772	58	148	235	85	50	9	4	1625
22-May-91	B2	5	3.6	2.8		923	17	157	219	88	55	9	5	1725
22-May-91	B3	5	3.6	2.9		832	48	151	231	88	50	9	5	1675
22-May-91	C1	5	4.5	2.7		996	5	156	218	92	58	9	4	1800
22-May-91	C2	5	4.1	2.8		858	24	146	229	89	53	9	4	1650
22-May-91	C3	5	3.6	2.9		780	29	129	242	88	49	9	4	1625
29-May-91	A2	5	6.0	2.8		949	24	165	240	97	56	6	6	1912
29-May-91	A3	5	5.9	2.9		829	68	168	261	95	51	10	5	1825
29-May-91	B2	5	4.3	2.8		988	20	177	238	100	59	10	5	1925
29-May-91	B3	5	4.3	2.9		878	54	175	253	97	53	10	5	1875
29-May-91	C1	5	5.1	2.7		1019	6	162	230	98	62	10	5	1950
29-May-91	C2	5	4.7	2.8		910	33	163	248	97	56	10	5	1900
29-May-91	C3	5	4.3	2.9		832	39	153	261	97	51	10	5	1950
05-Jun-91	A2	5	4.8	2.7		874	32	152	221	89	51	9	5	1750
05-Jun-91	A3	5	4.2	29.0		738	95	158	239	86	44	9	5	1675
05-Jun-91	B2	5	4.0	2.7		907	13	155	213	87	53	9	5	1750
05-Jun-91	B3	5	4.0	2.8		782	53	143	225	85	46	9	5	1675

Date	Stat	Flow		pH	alk	acid	Fe2+	Fetot	Ca	Mg	Al	Mn	Na	SO4
		set Lpm	act Lpm											
05-Jun-91	C1	5	4.6	2.6		987	6	148	210	90	57	10	5	1850
05-Jun-91	C2	5	4.1	2.7		843	29	147	223	88	51	9	5	1700
05-Jun-91	C3	5	3.6	2.8		752	38	131	230	85	46	9	5	1650
13-Jun-91	A2	5	4.5	2.7		904	45	165	246	96	56	10	5	1860
13-Jun-91	A3	5	4.3	2.9		784	101	168	260	94	50	10	5	1780
13-Jun-91	B2	5	3.7	2.7		964	40	174	239	99	60	10	5	1900
13-Jun-91	B3	5	3.7	2.8		823	101	162	254	96	54	10	5	1820
13-Jun-91	C1	5	4.5	2.6		976	8	155	227	94	60	10	5	1910
13-Jun-91	C2	5	3.9	2.7		850	47	158	248	95	54	10	5	1900
13-Jun-91	C3	5	3.4	2.8		774	62	148	261	96	52	10	5	1760
21-Jun-91	A2	5	4.8	2.7		977	45	191	272	108	61	11	5	1978
21-Jun-91	A3	5	4.6	3.0		837	124	205	290	109	56	12	5	1925
21-Jun-91	B2	5	4.1	2.7		1036	21	191	258	107	63	11	5	2000
21-Jun-91	B3	5	4.1	2.9		918	82	185	269	104	55	11	6	1975
21-Jun-91	C1	5	4.6	2.6		1080	4	167	257	110	67	11	5	2050
21-Jun-91	C2	5	4.1	2.8		965	45	185	274	108	60	11	5	1950
21-Jun-91	C3	5	3.6	2.9		933	78	174	277	107	57	11	5	1925
26-Jun-91	A2	5	4.7	2.7		966	34	178	248	102	57	11	6	1963
26-Jun-91	B2	5	4.0	2.7		1014	20	178	247	104	63	11	6	2025
26-Jun-91	B3	5	3.9	2.8		928	62	166	260	94	56	10	5	1950
26-Jun-91	C2	5	4.0	2.7		992	34	166	259	99	57	10	4	1950
26-Jun-91	C3	5	3.4	2.8		895	55	169	270	103	53	11	6	1900
03-Jul-91	A2	5	4.7	2.7		837	29	151	223	89	51	9	5	1725
03-Jul-91	A3	5	4.5	2.9		732	93	170	247	92	42	10	5	1650
03-Jul-91	B2	5	4.4	2.7		844	17	146	216	88	52	9	5	1725
03-Jul-91	C1	5	4.9	2.6		912	8	145	216	91	57	10	5	1800
03-Jul-91	C2	5	4.6	2.8		860	59	172	232	92	52	10	5	1750
03-Jul-91	C3	5	4.0	2.9		739	80	151	226	86	45	9	5	1650

APPENDIX C. U.S. Bureau of Mines Biotechnology Group
Publications and Presentations Including
Friendship Hill Wetland Research.

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