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CHEMICAL AND BIOLOGICAL MONITORING OF A CONSTRUCTED WETLAND ON JONES BRANCH TREATING ACID MINE DRAINAGE

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ABSTRACT

Acid mine drainage (AMD) from an abandoned underground coal mine in the Jones Branch watershed in McCreary County, KY, substantially reduced water quality in Jones Branch. Downstream from the mine seeps, the pH was routinely below 4.5 and concentrations of most heavy metals, especially iron, were elevated. A cattail wetland (1,022 m^2) was constructed on Jones Branch in 1988-1989 to obviate the effects of the AMD. Monthly chemical monitoring was performed on the water from above, from below, from the inlet and outlet of the wetland, and from the 25 cells within the wetland. Based on chemical monitoring, the wetland initially improved water quality, increasing the pH and removing substantial amounts of heavy metals. Beginning in the winter of 1991, water quality at the wetland outlet began to decline, but was above levels reported for most contaminants prior to construction. To augment the chemical monitoring, a biomonitoring study was initiated in the spring of 1990. Acute 48-hr static tests were conducted with newly hatched fathead minnows (*Pimephales promelas*). Water samples were obtained from the seep inlet, four cells within the wetland, and from Jones Branch above and below the wetland site. Median lethal concentration (LC_{50}) values determined monthly reflect the decline in water quality at the outlet over time. However, within the wetland there was gradual improvement in survivability from inlet to outlet, providing evidence that the wetland was responsible for a modest improvement in water quality. Although there was modest overall improvement in the water quality of Jones Branch due to wetland treatment, additional remediation will be required before the stream can support vertebrate organisms.

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INTRODUCTION

OBJECTIVES

Acid mine drainage is a persistent problem in the watershed of White Oak Creek in McCreary County, Kentucky. Seeps from collapsed mine portals of an abandoned underground coal mine are polluting Jones Branch, a tributary of White Oak Creek, with two isolated seeps on Jones Branch reducing the pH of the stream below the mine seeps to a mean of 2.90. Little or no life was found in Jones Branch below the entry of these seeps into the stream. The pollution problems associated with this abandoned mine, as with similar mines on lands acquired by the Forest Service, will be dealt with in cooperation with other federal, state, and local agencies so as to abate watershed damages and restore and sustain a level of water quality necessary to provide for suitable future uses of these resources.

Traditional approaches to the treatment of acid mine drainage include neutralization by addition of a base, oxidation by aeration, and precipitation in a settling basin or pond. These approaches are expensive, and a more economical way of treating acid mine drainage is needed, especially on abandoned lands. Studies have shown that constructed wetlands have the ability to remove many toxic metals and substantially improve water quality (1-8). Through a Cooperative Agreement with the Kentucky Division of Abandoned Lands, the Daniel Boone National Forest was funded to construct a wetland designed to treat the acid mine drainage affecting Jones Branch. The construction of the wetland was completed in the spring of 1989. The U.S. Forest Service's Northeastern Forest Experiment Station at Berea, Kentucky, participated in the design and was responsible for subsequent monitoring of the system. Chemical monitoring was performed on water from the wetland in an attempt to identify the component(s) which contributed to the overall effectiveness of the structure as a biofilter, and to estimate the functional longevity of the system. The current study was undertaken to augment the water chemical analyses with data on the ability of the wetland to support life by conducting a series of biomonitoring tests. The biological monitoring portion of this study was based on accepted techniques for monitoring effluents from both point- and nonpoint-sources (9-11). The technique used was the 48-hr acute bioassay utilizing fathead minnow (*Pimephales promelas*) larvae as test organisms. This test was selected because of its demonstrated ability to estimate the acute toxicity of a variety of aquatic pollutants, especially heavy metals. Acute toxicity tests were conducted on water obtained from various sites within the wetland and on water from above and below the seeps. The original objectives of the project were fulfilled, with the exception of estimating the chronic toxicity of the water by conducting 8-day embryo-larval toxicity tests with fathead minnows. The extreme acute toxicity of the water precluded the necessity of establishing chronic toxicity.

BACKGROUND

The contamination of Appalachian rivers and streams by acid mine drainage is an extensive problem (12). Much of the acid mine drainage is produced by mine sites in the region that are on abandoned lands. The mine on Jones Branch is such a site. The Surface Mining Control and Reclamation Act of 1977, with its amendments, mandates that mine drainage meet minimum water quality standards for several parameters, including pH, iron, manganese, and total dissolved solids. Although mines the age of those contaminating Jones Branch are exempt from the specifications of this law, the provisions of the Clean Water Act necessitate remediation of the Jones Branch site. Traditional technologies to improve water quality have proven to be expensive and complex. Therefore, new approaches to improving the quality of mine drainage waters are needed.

Wetlands, both natural and artificial, have been shown to treat effectively or supplement the treatment of urban stormwater runoff and municipal wastewaters by removing selected pollutants (13-19). Over the past 10-15 years, both laboratory and field studies have investigated the effectiveness of wetlands to treat acid mine drainage, and over 400 wetland systems have been put in place. Their effectiveness has been variable and it has become evident that site specific conditions contribute to the success of the wetland as a remediation technique (1, 5, 6, 20-25). As outlined by Wildeman, *et al.* (6) and others (26-28), the mechanisms involved in the improvement of pH and removal of heavy metals from acid mine drainage can include:

"1) Exchange of metals by an organic-rich substrate, which is usually peat in natural wetlands.

2) Sulfate reduction with precipitation of iron and other sulfides.

3) Precipitation of ferric and manganese hydroxides.

4) Adsorption of metals by ferric hydroxides.

5) Metal uptake by living plants.

6) Filtering suspended and colloidal material from water.

7) Neutralization and precipitation through the generation of NH_3 and HCO_3^- by bacterial decay of biologic matter.

8) Adsorption or exchange of metals onto algal materials."

The importance of each of these actions in the remediation process is dependent upon the design of the wetland, including pretreatment of the acid mine waters and the extent of subsurface, anaerobic flow through the wetland.

Long-term studies on wetland effectiveness are not common, but they are helpful in evaluating the various design approaches and technologies available for acid mine drainage problems. The U.S. Environmental Protection Agency funded the construction of a pilot constructed wetland at Big Five

Tunnel, a non-coal mining acid mine drainage site in Idaho Springs, Colorado. The resulting report (6) discussed the design principles, metal removal, and mechanisms at work in improving the water quality over a three-year period. A similar 2-year study evaluating the effectiveness of five different wetland substrates on the treatment of coal acid mine drainage in western Kentucky also addressed questions of design and mechanisms of metal and sulfate removal (7). Overall, it is becoming clear that not only the plants in a constructed wetland are important in establishing an environment for removal of heavy metals from contaminated waters, but also pattern of flow (*i.e.*, surface or subsurface flow) and the bacterial, algal, and fungal populations play a significant role (6, 29).

The capacity of a wetland to treat acid mine drainage has been examined by several investigators and standards have changed as more information has become available. Initial guidelines for sizing constructed wetlands were based on acid mine drainage with low flow and moderate contamination (30). Hedin and Nairn (4) proposed a different strategy for sizing and evaluating the performance of constructed wetlands. Their approach involved the calculation of an area-adjusted loading and removal factor based upon flow rate, iron concentrations, and the area of the wetland. The factor is expressed as gdm (g/day/m^2). Hedin suggested that a wetland treating acid mine drainage with a pH less than 3 should be able to remove iron at the rate of 4 gdm, while waters with a pH of 4 or greater could remove 10 gdm. This approach to calculating the wetland size has been applied to several wetland sites and has received mixed success as a sizing technique (6). As will be seen in the Discussion, the design used for the Jones Branch wetland was not adequate to treat fully the acid mine flows present, but the design was based on guidelines current to the period of time the project was initiated.

RESEARCH PROCEDURES

The protocol followed in this study involved three approaches. A brief description of each of these strategies is given below, followed by more detailed procedures.

1. The first question to be addressed by the proposed study was where within the wetland would the water quality be improved enough to support aquatic life. This objective was approached by conducting toxicity tests on water collected from various sites within the wetland.
2. The second objective was to evaluate the length of time the wetland would be functional in obviating the effects of acid mine drainage on aquatic life. This was accomplished by conducting monthly toxicity tests over a period of two years, and by evaluating the effectiveness of the wetland over time.
3. The third objective was to evaluate the component cells of the wetland to determine if any particular site within the wetland was especially important in removing/reducing contaminants. This objective was addressed by extensive sampling and chemical analysis of cells throughout the wetland.

STUDY SITE

Jones Branch, a tributary of White Oak Creek, is located in McCreary County, Kentucky. The stream is impacted by acid mine drainage (AMD) from two collapsed mine portals (Seeps 1 and 2) located approximately 1.4 stream miles above the confluence of Jones Branch with White Oak Creek. Other mines that occur on Jones Branch and neighboring watersheds of Rock Creek are also contributing to similar water quality problems. The Daniel Boone National Forest designed, contracted, and supervised the construction of a wetland and the access road to the project. Construction was completed during the spring of 1989 and the flow of acid mine water through the wetland was initiated in June of 1989.

WETLAND DESIGN

The wetland designed at the Jones Branch site consisted of a total area of 11,000 sq. ft. (1022 m^2) comprised of two fields. A schematic representation of the constructed wetland is presented in Figure 1. Field No. 1 consisted of 16 cells, approximately 425 sq. ft. per cell, with cell 0 containing no vegetation. The remaining cells were planted with cattails (Typha sp.). AMD from the two mine portals was flumed into Cell 0. Water flowed progressively through the remaining 15 cells of Field No. 1 and was then flumed into Field No. 2 at Cell 16. After flowing through the 10 cells of Field No. 2, the water was allowed to flow into Jones Branch. The wetland design projected a surface area of 200 to 600 sq. ft. per flowing gallon per minute, using an anticipated flow rate of 23 to 75 gpm (1.46 to 4.75 L/sec) based on previous, periodic flow estimates made in the field. The wetland was sized to be within this goal 80% of the time. The length of the flow path through Fields 1 and 2 was approximately 580 to 600 linear ft., providing a contact time of approximately 120 min for the water as it passed through the wetland.

Each cell of the wetland was constructed with a 9 in. limestone base overlaid with 18 in. of compost or humus material. About 1,250 cattails from a local coal preparation plant were planted on three foot centers in all cells except the two settling basins. Four cells were planted with cattails raised in the greenhouse at the U.S. Forest Service Northeastern Experiment Station, Berea, Kentucky. These plants were used to compare the survival, hardiness, and efficiency of greenhouse-grown and field-collected plants. Greenhouse-grown plants did not thrive as well as did the field-collected ones. Since the initial planting, other plants have invaded the area. After the cattails were planted, the wetland was

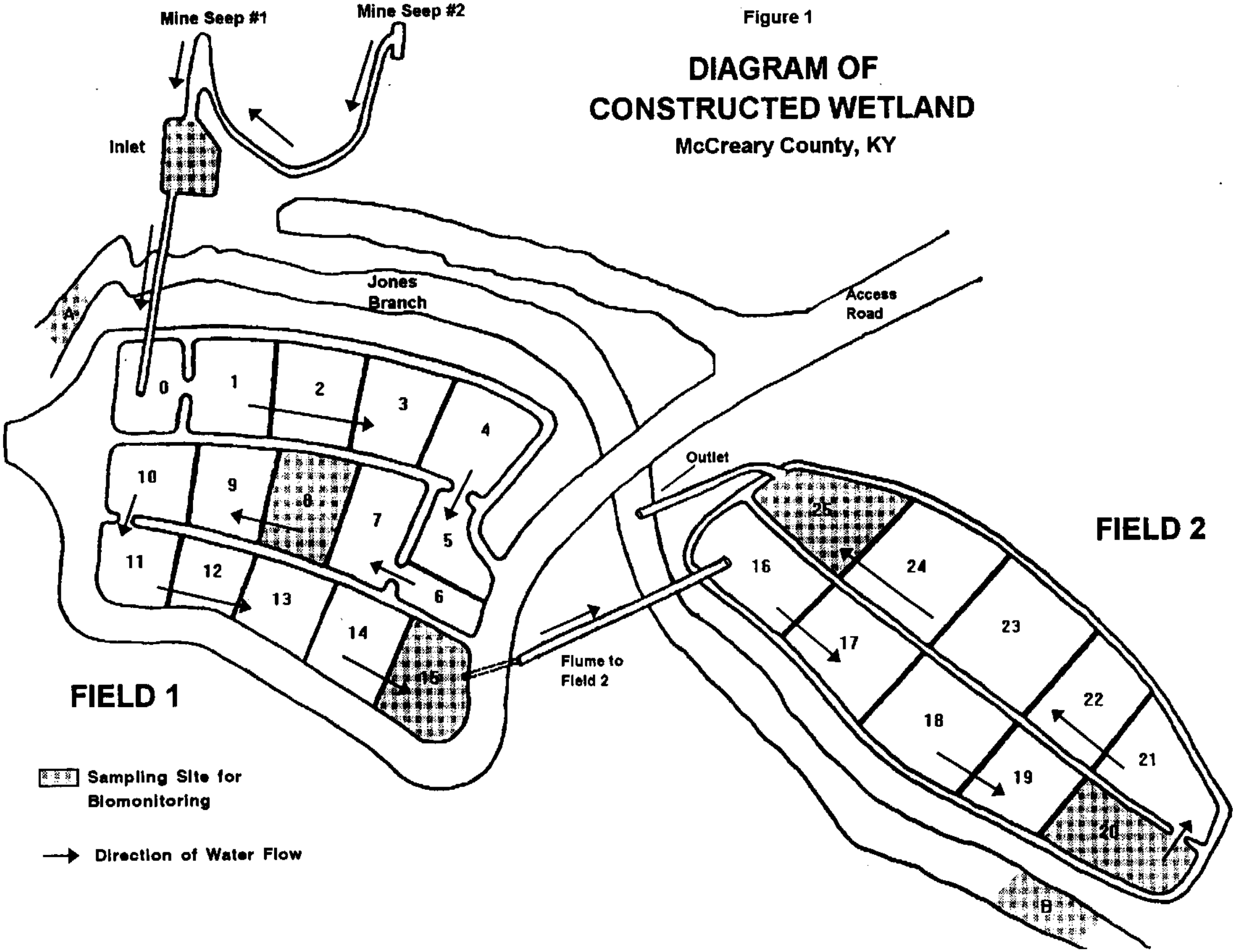

Figure 1

DIAGRAM OF CONSTRUCTED WETLAND
McCreary County, KY

topdressed with 440 lbs of hydrated lime. As part of the study, no subsequent alterations were made to the wetland system, so as to allow a full and thorough evaluation of the design parameters used.

CHEMICAL MONITORING

The U.S. Forest Service's Experiment Station at Berea, Kentucky, conducted a chemical monitoring program of the wetland with three major objectives. The first objective was to determine if wetland treatment would restore stream water quality to acceptable levels. The second objective was to evaluate the cells of the wetland to identify the portion and constituents of the wetland which were most important in removing specific components of the AMD. Finally, the long-term effectiveness of the wetland was to be determined by monitoring at regular intervals over a three-year period.

Beginning in June of 1989, water samples were collected every two weeks. After August of 1989, Forest Service personnel obtained water samples once a month from 1) the AMD entering the wetland, 2) even numbered cells within the wetland, beginning with Cell 0, and 3) the water entering Jones Branch from the wetland. In addition, water from Jones Branch above and below the wetland site was routinely sampled. Below the wetland site, Jones Branch is a perennial stream more than 90% of the time. Above the wetland Jones Branch is a third-order intermittent stream, with several months of no-flow during the year. At times of low natural flow, virtually all of the stream water below the wetland originated from the wetland outfall.

Each water sample consisted of four 8-oz/100 mL bottles of water. One bottle contained filtered water, one contained water filtered and acidified with nitric acid, and the remaining two bottles were raw, untreated water. Water samples were transported to the Forest Service Laboratory and either analyzed immediately or stored at 4°C until analyzed. The water was analyzed for a wide range of water quality parameters and for the presence of several metals. Table 1 lists the analyses performed on each sample.

TABLE 1. Water sample analyses for the wetland study.[1]

Variable	Sample Type[2]	Units	Method[3]
Sediment	Raw	ppm	Filtration
Turbidity	Raw	JTU	Colorimetric
Conductivity	Raw	μmho	Potentiometric
pH	Raw		Potentiometric
Acidity	Raw	mg/L as $CaCO_3$	Titration
Alkalinity	Raw	mg/L as $CaCO_3$	Titration
TDS	Raw		Colorimetric
SO_4	F	mg/L	IC
Ni	FA	mg/L	APS
K	FA	mg/L	APS
Cr	FA	mg/L	APS
B	FA	mg/L	APS
Si	FA	mg/L	APS
Zn	FA	mg/L	APS
P	FA	mg/L	APS
Fe	FA	mg/L	APS
Cu	FA	mg/L	APS
Mn	FA	mg/L	APS
Mg	FA	mg/L	APS
Na	FA	mg/L	APS
Co	FA	mg/L	APS
Al	FA	mg/L	APS
Ca	FA	mg/L	APS
Pb	FA	mg/L	APS
Ti	FA	mg/L	APS

[1] Analyses performed by the Forest Research Station Laboratory, Berea, KY.
[2] Sample type refers to a raw sample, a filtered (F) sample, and a filtered, acidified (FA) sample.
[3] Method refers to ion chromatography (IC) and argon plasma spectroscopy (APS).

ANALYSIS OF CHEMICAL DATA

Although numerous parameters were measured (Table 1), only data for pH, conductivity, sulfate, and selected metal concentrations are discussed. Selection of these parameters was based upon the predominance of these constituents in the acid mine drainage. Overall mean values were determined over the time span of the study reflecting the operation of the wetland. Means also were calculated and reported for the period of June, 1989, through January, 1990, and February, 1990, through May, 1992. This subdivision of the operation time was based upon the performance of the wetland in improving pH of the outlet water. The mean pH values were mathematically determined by conversion of all pH values to hydrogen ion normalities prior to averaging (31).

Loading factors at the inlet and outlet were calculated by the following formulae:

A) *Loading at inlet (mg/sec) = Inlet concentration (mg/L) X Inlet flow rate (L/sec)*

B) *Loading at outlet (mg/sec) = Outlet concentration (mg/L) X Outlet flow rate (L/sec)*

The efficiency of the wetland was analyzed by the following formula:

C) *Efficiency = Loading at outlet (mg/sec)/Loading at inlet (mg/sec)*

BIOMONITORING

Biomonitoring of the water from various cells within the wetland supplemented the chemical monitoring data to aid in evaluating the effectiveness of the wetland in obviating the effects of AMD. Toxicity tests were performed following procedures recommended by the U.S. Environmental Protection Agency (9, 10). Initially, water samples were obtained from the combined effluents of Seeps 1 and 2, from each even numbered cell in the wetland, and from the outflow to Jones Branch. These samples were collected at the same time that Forest Service personnel collect samples for chemical analyses.

After preliminary toxicity tests indicated that there was little difference in response between successive cells along the continuum, it was decided to test water from the wetland inlet, cells 8, 15, 20, 25 (outlet), and from Jones Branch above and below the wetland (Figure 1). These sample sites provided data from the beginning, middle, and end of each of the two fields. Monthly samples were collected as grab samples in clean 1 gal "milk" jugs, placed on ice, and returned to the laboratory at Eastern Kentucky University. Samples were used immediately or refrigerated at 4°C for no more than 72 hr. For all sites, toxicity tests were conducted using the sampled water at full strength (100%) and at four dilutions. All wetland cell sites were tested at dilutions of 12.5%, 6.25%, 3.1%, and 1.5% of the sample. Water samples from Jones Branch above the wetland were diluted to 50%, 25%, 12.5% and 3.1%, while water from below the site was diluted to 25%, 12.5%, 6.25%, and 3.1%.

Acute toxicity tests were conducted with newly hatched (1-3 day old) fathead minnows (*Pimephales promelas*). This particular test was selected after consultation with Q.H. Pickering of the Aquatic Biology Section, U.S. Environmental Protection Agency (EPA), Newtown, Ohio (personal communication). Fathead minnow larvae were obtained from the U.S. EPA in Newtown, Ohio. Ten larvae were placed in 1 L Pyrex beakers containing 0.75 L of test solution. Tests were conducted for 48 hr in replicate at 22 ± 2°C with no renewal. Initially, water in Jones Branch upstream of the mine seeps was evaluated for its ability to serve as a source of control and dilution water. It proved to be unsuitable, both in quality and supply, and a synthetic fresh water of moderate hardness (9) served as the dilution water for all toxicity tests. Test and control water were evaluated for standard water quality parameters at the beginning and end of the test. Temperature, dissolved oxygen, conductivity, and pH were determined using a Fisher LCD thermometer, YSI oxygen meter (model 54), a Markson conductivity meter (model 10), and a Fisher pH meter (model 735), respectively. Test organisms were monitored daily and dead specimens were removed. At the beginning of selected tests, the chemical stability of the water samples, having been stored for up to 3 days, was evaluated. Full-strength samples of each test water were preserved and sent to the Forest Service Laboratory for analysis of the full range of metals. The complete analysis is reported in the Appendix (Table A-1).

TEST RESPONSES AND ANALYSIS OF DATA

The test response in the 48 hr static acute test was mortality, which was determined by the failure of the larva to move when prodded. Median lethal concentrations (LC_{50}) were calculated using the Trimmed Spearman-Karber method (32).

DATA AND RESULTS

WATER QUALITY IN JONES BRANCH

Water quality in Jones Branch was monitored in 1987 and 1988 to establish a database, allowing comparison of characteristics before and after construction of the artificial wetland. Several water quality parameters in Jones Branch were monitored (Table 1), and mean values prior to and after construction for sites above and below the wetland are given in Table 2. The water below the mine seeps prior to construction contained substantially higher concentrations of heavy metals and acid compared to the above sampling site (Table 2). To evaluate the significance of these levels, parameters measured were compared to criteria for warmwater aquatic habitat established by the Commonwealth of Kentucky (33). Criteria for all parameters have not been established by the state, and comparisons were made only between those metals and parameters for which both current data and a criterion were available (Table 3). In water above the mine seeps, pH, copper, and lead were not in compliance with state regulations. Prior to construction, water below the mine seeps contained levels of iron and sulfate above the criteria, and the pH of 2.90 was markedly below the standard of 6.0. After the wetland was constructed and measurements were taken from June, 1989, through January, 1990, pH improved to a mean of 5.23 but only met the criterion in August of 1989, when a pH of 6.12 was reported (Table 4). This initial improvement in pH most likely was the result of the buffering capacity of both the limestone/compost bed and the additional lime used to topdress the wetland. When armorization of the limestone in the open ditches occurred because the readily available carbonate sources present from fugitive dust generated from construction and placement of the limestone aggregate layer in the wetland and from topdressing the wetland with 440 lbs of hydrated lime were exhausted, the pH decreased and did not improve through the end of the study. During the last 28 months, pH ranged from 2.61 - 4.97 (Table 4, Figure 2). The limestone bed on the bottom of the cells planted with cattails remained clean and unarmored, although, since it is surrounded by an anaerobic environment, there was no effect on pH levels.

The improvement in pH during the first 8 months of the study also resulted in a decrease in the concentration of heavy metals in Jones Branch, and improvement in other water quality parameters (Tables 5-10, Figures 3-6). Prior to construction, mean specific conductivity in Jones Branch below was 2673 μmhos (Table 2). After construction, conductivity dropped to approximately that of the above sampling site (Figure 3). Compared to the level of conductivity of the acid mine drainage, the conductivity in Jones Branch below the wetland after construction was substantially improved (Table 5). However, this improvement was largely due to dilution from upstream flow and precipitation because the outfall from the wetland does not show comparable long-term improvement (Table 5). This pattern was especially evident in the summer of 1991, when dry conditions lowered the percent reduction in conductivity in Jones Branch to 22.8-39.0% of the inlet conductivity (Table 5).

During the first 8 months of operation, the levels of all monitored metals and other cations and anions in Jones Branch improved substantially, sometimes as much as two orders of magnitude (Table 2). During the subsequent 28 months of monitoring, this reduction in most metals continued, but not to the same degree as initially observed. Some elements (*i.e.*, boron, chromium, cobalt, phosphorus, titanium) exceeded concentrations found in the stream prior to construction. Negligible changes were noted in potassium. After construction of the wetland, both sediment levels and turbidity increased in Jones Branch (Table 2). This increase resulted from the flow of water over the wetland sediments, as well a from construction modification to the area, including a short channel change in Jones Branch to reduce potential flood damage to the wetland.

During the first 8 months of operation, iron levels in Jones Branch improved substantially and approached the criterion level, meeting it twice (Tables 3, 6). Although the mean concentration for iron in the last 28 months was 150.6 mg/L, the range, as seen in Figure 4, was extensive (i.e., 2.14 - 775 mg Fe/L). The Jones Branch water was in compliance with the criterion for iron only 4 months during this time. This reduction in iron in Jones Branch was due both to oxidation and precipitation of iron in the wetland and to dilution, as the percent removal at the wetland outlet was not as great as in the stream over most of the study (Table 6). Reduced efficiency of iron removal in Jones Branch during the summer months of 1990 and 1991 was observed (Table 6). Similar reductions in efficiency were noted for manganese (Table 7), zinc (Table 8), and sulfate (Table 9, Figure 5). The effects of low flow and rainfall in the summers of 1990 and 1991 were evident when Jones Branch manganese concentrations were elevated compared to those in the acid mine drainage (inlet). The increase was especially pronounced in September, 1991, when manganese increased by 69.2% over that found in the acid mine drainage (Table 7). Although zinc in Jones Branch never exceeded that found in the inlet water, effectiveness of removal was reduced during the summers of 1990 and 1991 (Table 8). The levels of zinc in the stream always met the state zinc criterion (Tables 3, 8). Sulfate concentrations in Jones Branch met the domestic water criterion for the first year of operation and during November, 1990, May, 1991, and January through February, 1992 (Tables 3, 9, Figure 5). Aluminum removal was very efficient, even in the summer months with low stream flow (Table 9, Figure 6).

WATER QUALITY THROUGHOUT THE WETLAND

One major objective of the study was to evaluate the effectiveness of the wetland to improve the water quality of the acid mine drainage. In addition, extensive chemical monitoring was undertaken to evaluate the various sections of the wetland to identify any component that was especially important in removing/reducing contaminants. The approach used to evaluate the results of the chemical monitoring in light of the two objectives involved 1) an analysis of absolute concentrations of contaminants as they progressed through the wetland (Figures 7-14), and 2) an analysis of loading factors for each contaminant at the inlet and outlet of the wetland (Tables 11-18, Figures 15-21).

As can be seen in Table 4, water from the mine seeps (inlet) had an average pH of 3.12 for the 3 years of the study. As the water moved through the wetland, pH improved substantially at the end of the first field of cells. At the outlet, the pH of the water was initially improved, but after 6 months, the pH dropped to 2.58 and was not substantially improved after that date (Table 4, Figure 7). In fact, the pH at the outfall was usually below that of the inlet. This increased hydrogen ion concentration may be the result of bacterial activity under aerobic conditions, successfully removing iron but lowering the pH (24). Also, the initial decline in wetland efficiency during the winter of 1989-1990 may have been exacerbated by the excessive cold and the formation of ice in the wetland in addition to depletion of the readily available carbonate source provided by the hydrated lime. Loading factors for pH were not calculated.

A similar pattern was observed for conductivity (Table 5, Figure 8) and index of metal and salt concentrations. The initial flow through the wetland improved conductivity from an inlet value of 5240 μmhos to an outlet level of 579 μmhos (Table 5). However, over the next 6 months, the conductivity gradually increased in the outlet water, showing only a 6.7% reduction in December, 1989. On five occasions in the last 28 months of monitoring, conductivity in the outlet water exceeded that found in the acid mine drainage (inlet). Conductivity never reached levels observed in water above the wetland (Figure 3). During the first 6 months of operation, Field No. 1 (cells 0 - 15) of the wetland achieved most of the reduction in conductivity, as relatively little additional reduction occurred in the second field (Table 5). After the initial improvement, reduction in the first field compared to the second was variable, with conductivity of the water actually increasing in the second field on several occasions (Table 5).

Concentrations of heavy metals and sulfates varied greatly throughout the wetland. This variation was partly due to heavy metal concentrations (*e.g.*, aluminum, iron) in the acid mine water (inlet) which fluctuated somewhat over time (Tables 6-18). The concentrations of iron were reduced dramatically during the initial wetland treatment, declining from an input level of 1061 mg/L in June, 1989, to an outlet concentration of 0.62 mg/L (Table 6). This removal of iron by the wetland continued through November, 1989. After that time, removal of iron was not as efficient, with some loading of iron in the outlet water occurring in January, 1991, due to loss of alkalinity, increasing acidity, and the decline in microbial activity. Virtually 100% of the iron was removed in the first 6 months by the first field of the wetland (Table 6, Figure 9). Initially, the pH of the water had improved to a mean of 5.23 in the wetland, thus allowing the precipitation of iron. As can be seen in Table 5, this improvement was achieved by cell 15 through September of 1989. By November, with the end of the cattail growing season, the efficiency of the first field of cells in the wetland for removing iron dropped, most likely coincident with decreased availability of the carbonate source provided by the hydrated lime topdressed over the wetland to stimulate growth and reproduction of the planted cattails. An evaluation of the loading data, based on flow rate of acid mine drainage at the inlet and of the treated water at the outlet and iron concentration, revealed that on three occasions the outlet level exceeded inlet loading (Table 12, Figure 16). On these occasions (March, 1990, February and March, 1992), the flow rate at the outlet exceeded the flow rate at the inlet (Table 12).

When analyses were made of aluminum (Tables 10, 13, Figures 10, 17), manganese (Tables 7, 14, Figures 11, 18), zinc (Tables 8, 15, Figure 19), cobalt (Table 17, Figures 12, 20), sulfate (Tables 9, 18, Figure 21), boron (Table 16), lead (Figure 13), and nickel (Figure 14), results were similar to that reported for iron. The reduction of sulfate is a bacterially-mediated process that occurs most efficiently in anaerobic systems (35). Although most of the flow in this wetland was surface flow, initially the organic matter in the wetland substrate provided some anaerobic conditions that fostered the removal of sulfate. After armorization and accumulation of precipitates on the surface of the organic substrate, water did not have ready access to the anaerobic components, thus reducing the effectiveness of the removal of sulfate. The wetland functioned well between June, 1989, and January, 1990, for all parameters analyzed. After January of 1990, the reduction in individual metals varied somewhat, but removal was not as complete as during the first 8 months of operation. The first field of the wetland appeared to remove the bulk of the contaminants, while the second field continued reduction but not to the same degree.

TOXICOLOGICAL MONITORING

The quality of water directly affects the survival of aquatic organisms. Prior to the construction of the wetland, no animal life was observed in Jones Branch. Therefore, one of the goals of this remediation project was to evaluate the success of the treatment by determining if sensitive life stages of fish could survive. This component of the study was initiated approximately 12 months after initiation of AMD through the wetland. As noted in the previous section, water quality throughout the wetland had begun to degrade by the spring of 1990, and therefore, interpretation of results from the toxicity tests should be made in light of the failure of less efficient removal of toxicants by the wetland during the period of the toxicity testing.

Newly hatched larvae of the fathead minnow were selected as test organisms for the toxicity tests. Acute 48-hour static tests were conducted monthly from July of 1990, to May, 1992. At no time did any larvae survive in the full strength water taken from any of the wetland cells or from Jones Branch above and below the wetland. Full-strength water from the wetland cells produced mortality of all test animals, usually within the first 2-4 hours of exposure. The pH of the wetland cell water was always below 4.0, and most likely caused the mortality (34). Substantial dilution of the test water was always required to allow survival of the larvae. Dose-response data for the test conducted in the month of June, 1991, are given in Table 19, and these responses are typical of those obtained throughout the 2-year study. A 50%

dilution of water from above the wetland resulted in complete survival, while water below the wetland was diluted to 12.5% of sample before complete survival was attained. Water from the inlet and cells throughout the wetland required dilution to 1.6% of sample to achieve survival, with one exception. At a dilution of 3.1%, water from the outlet allowed partial survival of the test population. Since the waters were complex mixtures of heavy metals and acid, the specific contributing components to mortality could not be determined in this study as it was designed. The highly toxic nature of the water suggests that not only pH but also high levels of some of the heavy metals contributed to its toxic nature.

In order to compare the toxicological data obtained from the various sites, median lethal concentrations (LC_{50}) were determined. Table 20 gives the LC_{50}'s, expressed as percent of sample, for each of the 21 tests. Jones Branch above the wetland was intermittent and water samples could not be collected in late summer or early fall of 1990 and 1991. Due to technical difficulties, there were not enough larvae to conduct a complete suite of tests in September or November, 1990. Therefore, LC_{50} values were available only for the outlet and Jones Branch below the wetland. Other missing data were due to problems collecting enough water to run the test.

As can be seen in both Table 20 and Figure 22, toxicity of water in Jones Branch below the wetland increased in the summer and improved substantially (*i.e.*, became less toxic) during the winter. In most tests, the Jones Branch water below the wetland also was substantially less toxic than the water coming out of the wetland (outlet). These improved LC_{50} values for water below the wetland compared to the outlet probably were due to dilution by upstream water. Both on the basis of relative toxicity between the outlet and below sites and on the seasonal toxicities noted, the data compare well with results of the chemical monitoring.

An examination of the survival responses throughout the wetland indicated that no significant improvement in survival was achieved between inlet and outlet (Table 20, Figure 22). However, this result must be evaluated in light of the fact that the toxicity tests were done during the last 24 months of the study and were not conducted at the time of optimal remediation (*i.e.*, June, 1989 - January, 1990). It can be concluded that, although there was improvement in overall water quality, contaminants were not removed at a level sufficient to support life. Both LC_{50} values and water quality characteristics of the wetland acid mine drainage water were examined to determine whether any correlations existed. Analysis of the data yielded little positive correlation.

CONCLUSIONS

The constructed wetland on Jones Branch in McCreary County, Kentucky, initially achieved dramatic improvement in water quality in the stream. However, the long-term operation of the wetland did not sustain the initial improvement. Despite the lack of sustained extensive improvement, the overall water quality at the end of the 3-year study was better for most parameters than before construction. The improvements in pH were somewhat modest, and along with iron levels, did not meet the criteria established by the state of Kentucky for warmwater habitat. The low pH and high iron levels also contributed to the toxicity of the waters to larval fish, indicating that further improvement will be necessary to support aquatic vertebrates in the stream.

The continued remediation of Jones Branch will be necessary if long-term water quality improvement is desired. Several design modification should be considered. Since increasing the size of the wetland is not feasible due to topographic limitations, these modifications include the following: (1) piping of AMD from the abandoned mine into an anaerobic lagoon to maintain and even depress the dissolved oxygen content (currently at about 0.6 percent) as it leaves the mine (the lagoon will be maintained in an anaerobic state through the use of semi-floating organic mulches); (2) conveying the mine effluent from the lagoon as subsurface flow through two elevated, limestone-filled, high density polyethylene pipes into the first two cells of the wetland to increase alkalinity, reduce iron solubility, and induce precipitation of iron sulfide forms; and (3) promoting subsurface flow throughout the wetland by installing a series of stand pipes connected with perforated pipes buried in the limestone layer on the bottom of the wetland to increase alkalinity and residence time in an anaerobic environment. Without some modifications, the only other viable alternative would be to provide supplemental treatment through addition of a base of alkaline solution at much higher cost.

Since this is a wetland that contains toxic levels of metals, it also is advised that the wetland be monitored for use by wildlife. Migratory birds could potentially be attracted to the wetland as a foraging site. Also aquatic insects and other organisms (*e.g.*, amphibians) may try to utilize this site as a breeding ground. Since high levels of contaminants are present, offspring most likely would not survive.

Table 2. Mean values for water quality parameters in Jones Branch above mine seeps and below mine seeps determined before (pre-) and after (post-) construction of a wetland to treat acid mine drainage.

Variable	**Above Pre-Construction (n = 11)**	**Above Post-Construction (n = 26)**	**Below Pre-Construction (n = 5)**	**Below Post-Construction (n = 29)**
Sediment (mg/L)	0.273	0.500	23.2	43.6
Turbidity (JTU)	4.36	4.31	70.8	150
Conductivity (μmhos)	57.8	61.2	2673	1142
pH	4.27	4.39	2.90	3.33
Acidity (mg/L as $CaCO_3$)	5.78	78.7	1093	155
Alkalinity (mg/L as $CaCO_3$)	0.091	0.000	0.000	0.276
Hardness (mg/L as $CaCO_3$)	13.3	16.2	1477	600
TDS	27.0	31.7	2819	1037
SO_4 (mg/L)	18.1	20.3	2076	743
Ni (mg/L)	0.007	0.007	0.290	0.104
K (mg/L)	0.957	1.12	7.95	6.84
Cr (mg/L)	0.001	0.004	0.022	0.033
B (mg/L)	0.001	0.006	0.246	0.230
Si (mg/L)	1.90	2.94	7.53	4.29
Zn (mg/L)	0.010	0.007	0.394	0.076
P (mg/L)	0.011	0.053	1.33	2.39
Fe (mg/L)	0.290	0.746	431	128
Cu (mg/L)	0.006	0.005	0.074	0.010
Mn (mg/L)	0.138	0.181	9.79	5.97
Mg (mg/L)	1.41	1.48	66.0	28.2
Na (mg/L)	0.887	1.14	64.7	21.2
Co (mg/L)	0.002	0.007	0.088	0.108
Al (mg/L)	0.160	0.199	11.8	1.89
Ca (mg/L)	2.33	2.93	139	93.4
Pb (mg/L)	0.013	0.013	0.826	0.311
Ti (mg/L)	0.005	0.007	0.086	0.093

Table 3. Mean values of selected water quality parameters for sites above and below the wetlands prior to and after construction compared to Kentucky criteria for warmwater aquatic habitat.[a]

Parameter	Above Pre-Const.	Criterion	Above Post-Const.	Criterion	Below Pre-Const.	Criterion	Below Post-Const. 6/89-1/90	Criterion	Below Post-Const. 2/90-5/92	Criterion
pH	4.27	6.0	4.39	6.0	2.9	6.0	5.23	6.0	3.25	6.0
Cr (mg/L)	0.001	0.333	0.004	0.393	0.022	15.75	0.004	1.109	0.039	8.58
Cu (mg/L)	0.006	0.003	0.005	0.003	0.074	0.224	0.004	0.011	0.011	0.111
Fe (mg/L)	0.29	4.0	0.416	4.0	431	4.0	7.33	4.0	150.6	4.0
Ni (mg/L)	0.007	0.257	0.007	0.304	0.29	13.84	0.015	0.893	0.122	7.38
Pb (mg/L)	0.013	0.006	0.013	0.008	0.826	2.52	0.052	0.041	0.366	0.977
Zn (mg/L)	0.01	0.021	0.007	0.025	0.394	1.15	0.009	0.074	0.088	0.611
SO_4 (mg/L)	18.1	250[b]	20.3	250[b]	2076	250[b]	56.3	250[b]	874	250[b]
Hardness (mg/L as $CaCO_3$)	13.3		16.2		1477		57.9		703	

[1] Criteria are acute criteria for warmwater habitat (30). Criteria for Cr (as Cr III), Cu, Ni, Pb, and Zn calculated using mean hardness during each sampling period.

[2] Criterion for SO_4 for warmwater habitat not available. Value given is for domestic water.

Table 4. Monthly values for pH determined in acid mine drainage (inlet), outlet of wetland, and in Jones Branch above and below the wetland site.

Sampling Date	Inlet pH	Outlet pH	Below pH	Above pH
June 28 89	3.17	7.70	-	4.41
July 13 89	2.89	7.66	-	4.38
Aug 8 89	3.01	7.70	-	4.40
Aug 31 89	2.97	7.92	6.12	4.34
Sep 21 89	3.05	7.80	-	4.31
Nov 14 89	2.92	6.72	5.85	4.54
Dec 14 89	3.33	6.10	5.37	4.54
Jan 17 90	3.12	5.33	4.76	4.56
Feb 14 90	3.08	2.58	4.21	4.72
Mar 14 90	3.61	2.74	3.36	4.68
Apr 23 90	3.23	2.74	3.44	4.48
May 9 90	3.4	2.96	4.97	4.54
June 11 90	3.34	2.61	3.86	4.44
July 10 90	3.10	2.66	3.70	-
Aug 14 90	3.08	2.58	2.61	-
Oct 15 90	3.06	2.69	2.95	4.28
Nov 14 90	2.83	2.49	4.57	4.22
Jan 14 91	3.10	2.71	4.46	4.57
Feb 26 91	3.69	2.77	3.89	4.40
Mar 25 91	2.94	2.50	4.13	4.59
Apr 22 91	3.28	2.48	3.03	4.35
May 28 91	3.24	2.64	3.53	4.20
June 24 91	3.02	2.52	3.17	4.31
July 28 91	3.22	2.50	3.20	-
Aug 25 91	2.99	2.34	3.10	-
Sep 23 91	3.25	2.48	3.46	-
Oct 28 91	2.97	2.51	-	-
Nov 18 91	2.98	2.71	2.70	-
Jan 28 92	2.99	2.83	4.07	4.26

Table 4 - continued

Sampling Date	Inlet pH	Outlet pH	Below pH	Above pH
Feb 25 92	3.26	2.82	3.45	4.22
Mar 30 92	3.85	2.79	3.14	4.36
Apr 20 92	3.49	2.74	2.87	4.35
May 18 92	3.27	2.55	3.88	4.23
Mean pH June/89 - May/92	3.12	2.74	3.32	4.39
Mean pH June/89 - Jan/90	3.04	6.14	5.23	4.43
Mean pH Feb/90 - May/92	3.15	2.61	3.25	4.37

Table 5. Effectiveness of a constructed wetland to reduce conductivity. Percent reduction was calculated by the formula (inlet conductivity - cell 15 or outlet or below conductivity)/inlet conductivity.

Sampling Date	Inlet (μmhos)	Cell 15 (μmhos)	Outlet (μmhos)	Below (μmhos)	% Reduction at Cell 15	% Reduction at Outlet	% Reduction Below
June 28 89	5240	1250	579	ND*	76.1	89.0	-
July 13 89	5870	1050	947	ND	82.1	83.9	-
Aug 8 89	5560	2490	2450	ND	55.2	55.9	-
Aug 31 89	5390	2430	1501	311	54.9	72.2	94.2
Sep 21 89	5460	2340	ND	ND	57.1	-	-
Nov 14 89	4380	2570	2230	79	41.3	49.1	98.2
Dec 14 89	4620	3250	4310	89	29.7	6.7	98.1
Jan 17 90	4180	3590	3000	213	14.1	28.2	94.9
Feb 14 90	3250	2700	2720	87	16.9	16.3	97.3
Mar 14 90	4690	4860	4750	504	-3.6	-1.3	89.3
Apr 23 90	4420	4540	4650	455	-2.7	-5.2	89.7
May 9 90	4620	2620	ND	101	43.3	-	97.8
June 11 90	5560	3760	ND	655	32.4	-	88.2
July 10 90	4950	5090	5260	3100	-2.8	-6.3	37.4
Aug 14 90	4870	4530	4310	3700	7.0	11.5	24.0
Oct 15 90	5300	4430	4310	1440	16.4	18.7	72.8
Nov 14 90	5500	4010	3690	215	27.1	32.9	96.1
Jan 14 91	2520	3330	3990	101	-32.1	-58.3	96.0
Feb 26 91	4260	3580	2740	153	16.0	35.7	96.4
Mar 25 91	4290	3000	3600	84	30.1	16.1	98.0
Apr 22 91	4260	4210	3620	489	1.2	15.0	88.5
May 28 91	4180	3110	3760	333	25.6	10.0	92.0
June 24 91	5250	4560	4700	1437	13.1	10.5	72.6
July 28 91	4770	3610	3900	2910	24.3	18.2	39.0
Aug 25 91	5240	ND	ND	3490	-	-	33.4
Sep 23 91	5130	4930	ND	3960	3.9	-	22.8
Oct 28 91	5140	ND	3110	ND	-	39.5	-
Nov 18 91	5200	5200	5050	4900	0.0	2.9	5.8

Table 5 -
continued

Sampling Date	Inlet (μmhos)	Cell 15 (μmhos)	Outlet (μmhos)	Below (μmhos)	% Reduction at Cell 15	% Reduction at Outlet	% Reduction Below
Jan 28 92	4790	3270	ND	160	31.7	-	96.7
Feb 25 92	4800	4800	4800	420	0.0	0.0	91.3
Mar 30 92	4490	4120	3820	692	8.2	14.9	84.6
Apr 20 92	4840	4950	4990	1760	-2.3	-3.1	63.6
May 18 92	4960	ND	ND	647	-	-	87.0
Overall Mean	4787	3606	3569	1160			
SD	674	1107	1258	1437			
Mean Conductivity June/89 - Jan/90	5088	2371	2145	173			
SD	613	872	1279	110			
Mean Conductivity June/89 - Jan/90	4691	4055	4093	1325			
SD	676	804	758	1492			

*ND = Not determined

Table 6. Effectiveness of a constructed wetland to remove iron. Percent removal was calculated by the formula (inlet iron concentration - cell 15 or outlet or below iron concentration/inlet iron concentration.

Sampling Date	Inlet Fe (mg/L)	Cell 15 Fe (mg/L)	Outlet Fe (mg/L)	Below Fe (mg/L)	% Removal at Cell 15	% Removal at Outlet	% Removal Below
June 28 89	1060.802	1.049	0.617	ND*	99.9	99.9	-
July 13 89	1349.328	0.302	2.008	ND	100.0	99.9	-
Aug 8 89	1304.781	0.159	0.455	ND	100.0	100.0	-
Aug 31 89	1413.075	0.178	0.208	14.948	100.0	100.0	98.9
Sep 21 89	1242.656	0.162	ND	ND	100.0	-	-
Nov 14 89	960.338	113.242	0.181	2.020	88.2	100.0	99.8
Dec 14 89	1296.575	501.000	231.347	3.516	61.4	82.2	99.7
Jan 17 90	560.053	376.485	168.716	8.822	32.8	69.9	98.4
Feb 14 90	627.711	375.287	272.212	2.244	40.2	56.6	99.6
Mar 14 90	988.161	847.073	767.763	38.191	14.3	22.3	96.1
Apr 23 90	928.144	785.090	755.486	29.240	15.4	18.6	96.8
May 9 90	1022.387	210.800	ND	3.167	79.4	-	99.7
June 11 90	1109.963	310.627	ND	35.083	72	-	96.8
July 10 90	941.436	483.339	145.071	268.116	48.7	84.6	71.5
Aug 14 90	895.506	637.833	476.051	373.203	28.8	46.8	58.3
Oct 15 90	1075.750	795.065	584.183	113.830	26.1	45.7	89.4
Nov 14 90	1218.159	647.255	444.699	11.220	46.9	63.5	99.1
Jan 14 91	475.616	614.240	676.830	3.383	-29.1	-42.3	99.3
Feb 26 91	639.118	510.778	254.478	5.397	20.1	60.2	99.2
Mar 25 91	747.866	156.429	258.738	2.140	79.1	65.4	99.7
Apr 22 91	1036.353	654.167	412.397	24.842	36.9	60.2	97.6
May 28 91	933.090	514.841	523.231	17.794	44.8	43.9	98.1
June 24 91	1168.180	830.092	662.765	117.985	28.9	43.3	89.9
July 28 91	1226.767	522.259	335.197	363.509	57.4	72.7	70.4
Aug 25 91	1090.859	ND	ND	380.326	-	-	65.1
Sep 23 91	1322.160	873.140	ND	649.800	34.0	-	50.9
Oct 28 91	1302.025	ND	223.190	ND	-	82.9	-
Nov 18 91	1240.018	1149.489	856.054	775.338	7.3	31.0	37.5
Jan 28 92	1403.714	529.808	ND	11.193	62.3	-	99.2

Table 6 -
continued

Sampling Date	**Inlet Fe (mg/L)**	**Cell 15 Fe (mg/L)**	**Outlet Fe (mg/L)**	**Below Fe (mg/L)**	**% Removal at Cell 15**	**% Removal at Outlet**	**% Removal Below**
Feb 25 92	1150.037	946.727	904.995	34.880	17.7	21.3	97.0
Mar 30 92	1056.405	749.578	558.233	46.381	29.0	47.2	95.6
Apr 20 92	1240.300	1047.760	1038.150	239.800	15.5	16.3	80.7
May 18 92	1439.623	ND	ND	69.324	-	-	95.2
Overall Mean	1074.756	506.142	405.894	130.203			
SD	251.609	335.548	309.567	204.968			
Mean Fe June/89 - Jan/90	1148.451	124.072	57.649	7.327			
SD	281.555	200.861	98.935	5.860			
Mean Fe Feb/90 - May/92	1051.174	645.076	534.196	150.683			
SD	242.690	257.301	255.536	215.059			

*ND = Not determined.

Table 7. Effectiveness of a constructed wetland to remove manganese. Percent removal was calculated by the formula (inlet manganese concentration - cell 15 or outlet or below manganese concentration/inlet manganese concentration.

Sampling Date	**Inlet Mn (mg/L)**	**Cell 15 Mn (mg/L)**	**Outlet Mn (mg/L)**	**Below Mn (mg/L)**	**% Removal at Cell 15**	**% Removal at Outlet**	**% Removal Below**
June 28 89	15.773	0.517	0.293	ND*	96.7	98.1	-
July 13 89	21.662	0.343	0.582	ND	98.4	97.3	-
Aug 8 89	20.810	2.948	0.826	ND	85.8	96.0	-
Aug 31 89	21.327	6.641	0.684	1.439	68.9	96.8	93.3
Sep 21 89	37.326	3.230	ND	ND	91.3	-	-
Nov 14 89	15.759	10.498	9.083	0.259	33.4	42.4	98.4
Dec 14 89	18.700	11.726	13.673	0.293	37.3	26.9	98.4
Jan 17 90	15.217	12.068	8.484	0.443	20.7	44.2	97.1
Feb 14 90	10.354	7.752	7.686	0.181	25.1	25.8	98.3
Mar 14 90	15.672	15.417	14.627	0.872	1.6	6.7	94.4
Apr 23 90	15.755	15.038	16.083	0.849	4.6	-2.1	94.6
May 9 90	17.456	7.521	ND	0.289	56.9	-	98.3
June 11 90	18.744	12.361	ND	2.876	34.1	-	84.7
July 10 90	18.618	18.898	20.333	25.823	-1.5	-9.2	-38.7
Aug 14 90	17.038	14.994	15.070	17.175	12.0	11.6	-0.8
Oct 15 90	21.580	16.578	17.048	5.910	23.2	21.0	72.6
Nov 14 90	22.829	15.139	15.479	1.069	33.7	32.2	95.3
Jan 14 91	8.531	11.416	14.121	0.176	-33.8	-65.5	97.9
Feb 26 91	13.887	10.913	7.761	0.264	21.4	44.1	98.1
Mar 25 91	13.878	7.078	10.791	0.117	49.0	22.2	99.2
Apr 22 91	15.066	13.800	12.007	0.740	8.4	20.3	95.1
May 28 91	47.049	32.539	38.814	2.116	30.8	17.5	95.5
June 24 91	17.399	15.780	16.559	5.670	9.3	4.8	67.4
July 28 91	19.381	14.028	15.441	20.490	27.6	20.3	-5.7
Aug 25 91	19.907	ND	ND	23.040	-	-	-15.7
Sep 23 91	18.085	18.442	ND	30.596	-2.0	-	-69.2
Oct 28 91	19.353	ND	9.637	ND	-	50.2	-
Nov 18 91	17.452	17.832	17.330	20.871	-2.2	0.7	-19.6
Jan 28 92	20.249	10.923	ND	0.473	46.1	-	97.7

Table 7 - continued

Sampling Date	Inlet Mn (mg/L)	Cell 15 Mn (mg/L)	Outlet Mn (mg/L)	Below Mn (mg/L)	% Removal at Cell 15	% Removal at Outlet	% Removal Below
Feb 25 92	17.472	16.304	17.767	0.934	6.7	-1.7	94.7
Mar 30 92	17.396	14.066	13.103	1.200	19.1	24.7	93.1
Apr 20 92	16.250	16.020	16.310	3.960	1.4	-0.4	75.6
May 18 92	19.819	ND	ND	2.515	-	-	87.3
Overall Mean	18.963	12.360	12.677	6.094			
SD	6.839	6.393	7.882	9.338			
Mean Mn June/89 - Jan/90	20.822	5.996	4.804	0.609			
SD	7.175	4.918	5.500	0.559			
Mean Mn Feb/90 - May/92	18.369	14.675	15.577	7.009			
SD	6.770	5.228	6.575	9.809			

*ND = Not determined.

Table 8. Effectiveness of a constructed wetland to remove zinc. Percent removal was calculated by the formula (inlet zinc concentration - cell 15 or outlet or below zinc concentration/inlet zinc concentration.

Sampling Date	Inlet Zn (mg/L)	Cell 15 Zn (mg/L)	Outlet Zn (mg/L)	Below Zn (mg/L)	% Removal at Cell 15	% Removal at Outlet	% Removal Below
June 28 89	0.388	0.085	0.014	ND*	78.1	96.4	-
July 13 89	0.263	0.057	0.007	ND	78.3	97.3	-
Aug 8 89	0.264	0.018	0.020	ND	93.2	92.4	-
Aug 31 89	0.405	0.029	0.018	0.012	92.8	95.6	97.0
Sep 21 89	0.211	0	ND	ND	100.0	-	-
Nov 14 89	0.224	0.168	0.127	0.008	25.0	43.3	96.4
Dec 14 89	0.309	0.255	0.145	0.003	17.5	53.1	99.0
Jan 17 90	0.366	0.163	0.071	0.013	55.5	80.6	96.4
Feb 14 90	0.158	0.045	0.072	0	71.5	54.4	100.0
Mar 14 90	0.362	0.290	0.266	0.019	19.9	26.5	94.8
Apr 23 90	0.237	0.251	0.278	0.016	-5.9	-17.3	93.2
May 9 90	0.196	0	ND	0	100.0	-	100.0
June 11 90	0.489	0.190	ND	0.021	61.1	-	95.7
July 10 90	0.326	0.337	0.333	0.145	-3.4	-2.1	55.5
Aug 14 90	0.297	0.262	0.254	0.196	11.8	14.5	34.0
Oct 15 90	0.460	0.376	0.354	0.070	18.3	23.0	84.8
Nov 14 90	0.414	0.262	0.310	0.015	36.7	25.1	96.4
Jan 14 91	0.194	0.230	0.299	0.005	-18.6	-54.1	97.4
Feb 26 91	0.241	0.194	0.161	0.009	19.5	33.2	96.3
Mar 25 91	0.277	0.164	0.260	0.003	40.8	6.1	98.9
Apr 22 91	0.380	0.400	0.337	0	-5.3	11.3	100.0
May 28 91	0.293	0.233	0.336	0	20.5	-14.7	100.0
June 24 91	0.370	0.511	0.542	0.114	-38.1	-46.5	69.2
July 28 91	0.555	0.428	0.436	0.216	22.9	21.4	61.1
Aug 25 91	0.527	ND	ND	0.159	-	-	69.8
Sep 23 91	0.643	0.608	ND	0.293	5.4	-	54.4
Oct 28 91	0.624	ND	0.211	ND	-	66.2	-
Nov 18 91	0.700	0.691	0.659	0.597	1.3	5.9	14.7
Jan 28 92	0.506	0.285	ND	0.015	43.7	-	97.0

Table 8 -
continued

Sampling Date	Inlet Zn (mg/L)	Cell 15 Zn (mg/L)	Outlet Zn (mg/L)	Below Zn (mg/L)	% Removal at Cell 15	% Removal at Outlet	% Removal Below
Feb 25 92	0.761	0.744	0.763	0.013	2.2	-0.3	98.3
Mar 30 92	0.713	0.560	0.528	0.032	21.5	25.9	95.5
Apr 20 92	0.675	0.657	0.699	0.177	2.7	-3.6	73.8
May 18 92	0.532	ND	ND	0.002	-	-	99.6
Overall Mean	0.405	0.283	0.288	0.077			
SD	0.171	0.212	0.215	0.131			
Mean Zn June/89 - Jan/90	0.304	0.097	0.057	0.009			
SD	0.075	0.090	0.058	0.005			
Mean Zn Feb/90 - May/92	0.437	0.351	0.374	0.088			
SD	0.181	0.204	0.186	0.138			

*ND = Not determined

Table 9. Effectiveness of a constructed wetland to remove sulfate. Percent removal was calculated by the formula (inlet sulfate concentration - cell 15 or outlet or below sulfate concentration/inlet sulfate concentration.

Sampling Date	Inlet SO_4 (mg/L)	Cell 15 SO_4 (mg/L)	Outlet SO_4 (mg/L)	Below SO_4 (mg/L)	% Removal at Cell 15	% Removal at Outlet	% Removal Below
June 28 89	3960	175	20.5	ND*	95.6	99.5	-
July 13 89	2990	12.0	12.0	ND	99.6	99.6	-
Aug 8 89	4580	1173	528	ND	74.4	88.5	-
Aug 31 89	5290	1860	545	111	64.8	89.7	97.9
Sep 21 89	4580	895	ND	ND	80.5	-	-
Nov 14 89	3490	1195	1013	25.3	65.8	71.0	99.3
Dec 14 89	4800	2130	2460	34.9	55.6	48.8	99.3
Jan 17 90	2800	2000	2000	54.0	28.6	28.6	98.1
Feb 14 90	2400	1800	1550	34.0	25.0	35.4	98.6
Mar 14 90	3900	3230	3600	198	17.2	7.7	94.9
Apr 23 90	2700	2700	3700	175	0	-37.0	93.5
May 9 90	4100	1600	ND	39.0	61.0	-	99
June 11 90	4600	2550	ND	350	44.6	-	92.4
July 10 90	4600	4600	3500	2100	0	23.9	54.3
Aug 14 90	3800	3600	3800	2800	5.3	0	26.3
Oct 15 90	4050	3960	3070	632	2.2	24.2	84.4
Nov 14 90	4600	2900	3000	125	37.0	34.8	97.3
Jan 14 91	2000	2345	3050	30.0	-17.3	-52.5	98.5
Feb 26 91	2840	2250	1650	40.0	20.8	41.9	98.6
Mar 25 91	2800	1350	1780	26.0	51.8	36.4	99.1
Apr 22 91	3760	3320	2680	143	11.7	28.7	96.2
May 28 91	3100	2100	2610	114	32.3	15.8	96.3
June 24 91	4050	3580	3230	727	11.6	20.2	82
July 28 91	4100	3100	3000	2100	24.4	26.8	48.8
Aug 25 91	4200	ND	ND	2400	-	-	42.9
Sep 23 91	4200	3900	ND	3100	7.1	-	26.2
Oct 28 91	4360	ND	2050	ND	-	53.0	-
Nov 18 91	4800	4200	3900	4000	12.5	18.8	16.7
Jan 28 92	4400	2200	ND	80.0	50.0	-	98.2

Table 9 -
continued

Sampling Date	Inlet SO_4 (mg/L)	Cell 15 SO_4 (mg/L)	Outlet SO_4 (mg/L)	Below SO_4 (mg/L)	% Removal at Cell 15	% Removal at Outlet	% Removal Below
Feb 25 92	4200	4300	4400	170	-2.4	-4.8	96.0
Mar 30 92	4100	3400	3100	260	17.1	24.4	93.7
Apr 20 92	4500	4400	4500	1000	2.2	0	77.8
May 18 92	4500	ND	ND	340	-	-	92.4
Overall Mean	3914	2561	2490	757			
SD	792	1239	1294	1128			
Mean SO_4 June/89 - Jan/90	4061	1180	940	56.3			
SD	900	801	955	38.4			
Mean SO_4 Feb/90 - May/92	3866	3063	3062	874			
SD	768	956	861	1181			

*ND = Not determined.

Table 10. Effectiveness of a constructed wetland to remove aluminum. Percent removal was calculated by the formula (inlet aluminum concentration - cell 15 or outlet or below aluminum concentration/inlet aluminum concentration.

Sampling Date	Inelt Al (mg/L)	Cell 15 Al (mg/L)	Outlet Al (mg/L)	Below Al (mg/L)	% Removal at Cell 15	% Removal at Outlet	% Removal Below
June 28 89	8.096	0.381	0.182	ND*	95.3	97.8	-
July 13 89	10.836	0.314	0.256	ND	97.1	97.6	-
Aug 8 89	10.736	0.595	0.549	ND	94.5	94.9	-
Aug 31 89	11.499	0.860	0.675	0.071	92.5	94.1	99.4
Sep 21 89	20.575	0.435	ND	ND	97.9	-	-
Nov 14 89	10.355	6.521	0.507	0.077	37.0	95.1	99.3
Dec 14 89	13.516	3.364	0.610	0.188	75.1	95.5	98.6
Jan 17 90	11.333	6.104	0.539	0.237	46.1	95.2	97.9
Feb 14 90	6.788	5.205	4.957	0.115	23.3	27.0	98.3
Mar 14 90	10.724	8.925	6.683	0.403	16.8	37.7	96.2
Apr 23 90	10.816	11.745	12.160	0.553	-8.6	-12.4	94.9
May 9 90	10.224	2.316	ND	0.145	77.3	-	98.6
June 11 90	9.506	5.949	ND	0.578	37.4	-	93.9
July 10 90	14.287	13.051	12.302	0.426	8.7	13.9	97.0
Aug 14 90	12.424	10.770	10.112	6.821	13.3	18.6	45.1
Oct 15 90	9.410	8.476	9.279	1.500	9.9	1.4	84.1
Nov 14 90	8.869	6.788	9.482	0.320	23.5	-6.9	96.4
Jan 14 91	3.923	4.711	6.088	0.099	-20.1	-55.2	97.5
Feb 26 91	5.046	4.944	4.076	0.167	2.0	19.2	96.7
Mar 25 91	5.244	3.197	5.487	0.076	39.0	-4.6	98.6
Apr 22 91	11.372	10.794	9.325	0.509	5.1	18.0	95.5
May 28 91	4.923	9.144	11.451	0.394	-85.7	-132.6	92.0
June 24 91	9.555	16.261	16.896	0.821	-70.2	-76.8	91.4
July 28 91	25.666	16.921	15.583	1.460	34.1	39.3	94.3
Aug 25 91	16.340	ND	ND	1.959	-	-	88.0
Sep 23 91	32.300	26.738	ND	2.500	17.2	-	92.3
Oct 28 91	35.853	ND	13.191	ND	-	63.2	-
Nov 18 91	38.767	36.251	25.929	21.205	6.5	33.1	45.3
Jan 28 92	26.333	12.803	ND	0.419	51.4	-	98.4

Table 10 -
continued

Sampling Date	Inlet Al (mg/L)	Cell 15 Al (mg/L)	Outlet Al (mg/L)	Below Al (mg/L)	% Removal at Cell 15	% Removal at Outlet	% Removal Below
Feb 25 92	42.109	38.190	35.287	1.179	9.3	16.2	97.2
Mar 30 92	39.433	30.494	26.485	2.281	22.7	32.8	94.2
Apr 20 92	39.540	38.710	39.660	8.450	2.1	-0.3	78.6
May 18 92	26.919	ND	ND	0.876	-	-	96.7
Overall Mean	16.767	11.365	10.683	1.922			
SD	11.690	11.439	10.728	4.253			
Mean Al June/89 - Jan/90	12.118	2.322	0.471	0.143			
SD	3.729	2.659	0.184	0.082			
Mean Al Feb/90 - May/92	18.255	14.654	14.444	2.219			
SD	12.987	11.656	10.217	4.538			

*ND = Not determined.

Table 11. Flow rate and loading data for conductivity in a constructed wetland treating acid mine drainage. Flow rates determined at inlet and outlet of wetland. Loading data expressed as μmhos-L/sec, calculated by multiplying conductivity and flow rate. Ratio of loading out/loading in is given to evaluate the effectiveness of reduction of conductivity over time.

Sampling Date	Inlet Cond. (μmhos)	Flow Rate Inlet (L/sec)	Loading Inlet (μmhos-L/sec)	Outlet Cond. (μmhos)	Flow Rate Outlet (L/sec)	Loading Outlet (μmhos-L/sec)	Out/In
Aug 31 89	5390	5.95	32070.5	1501	0.57	855.57	0.027
Sep 21 89	5460	5.95	32487.0	2250*	0	0	0
Nov 14 89	4380	53.23	233147.4	2230	9.63	21474.9	0.092
Dec 14 89	4620	126.29	583459.8	4310	5.95	25644.5	0.044
Jan 17 90	4180	19.25	80465.0	3000	32.28	96840.0	1.204
Feb 14 90	3250	305.25	992062.5	2720	32.00	87040.0	0.088
Mar 14 90	4690	133.93	628131.7	4750	343.47	1631483.0	2.597
Apr 23 90	4420	0	0	4650	22.37	104020.5	-
May 9 90	4620	378.30	1747746.0	3920	261.36	1024531.0	0.586
June 11 90	5560	3.68	20460.8	4000	2.27	9080.0	0.444
July 10 90	4950	63.43	313978.5	5260	16.99	89367.4	0.285
Aug 14 90	4870	24.07	117220.9	4310	17.56	75683.6	0.646
Oct 15 90	5300	420.21	2227113.0	4310	7.65	32971.5	0.015
May 28 91	4180	0.28	1170.4	3760	1.01	3778.8	3.229
June 24 91	5250	29.17	153142.5	4700	12.74	59878.0	0.391
July 28 91	4770	86.36	411937.2	3900	-	0	0
Aug 25 91	5240	78.44	411025.6	4820	1.13	5446.6	0.013
Sep 23 91	5130	99.11	508434.3	4400	123.74	544456.0	1.071
Oct 28 91	5140	51.82	266354.8	3110*	32.00	99520.0	0.374
Nov 18 91	5200	45.02	234104.0	5050	19.82	100091.0	0.428
Jan 28 92	4790	7.08	33913.2	2930	0.57	1670.1	0.049
Feb 25 92	4800	116.38	558624.0	4800	178.39	856272.0	1.533
Mar 30 92	4490	81.27	364902.3	3820	156.02	595996.4	1.633
Apr 20 92	4840	174.43	844241.2	4990	141.30	705087.0	0.835
May 18 92	4960	34.55	171368.0	4600	3.68	16928.0	0.099
Mean Flow (L/sec)		93.7			59.3		

*Value estimated from level reported in Cell 24 because low flow prevented obtaining adequate water sample.

Table 12. Flow rate and loading data for iron in a constructed wetland treating acid mine drainage. Flow rates determined at inlet and outlet of wetland. Loading data expressed as mg Fe/sec, calculated by multiplying iron concentration and flow rate. Ratio of loading out/loading in is given to evaluate the effectiveness of removal of iron over time.

Sampling Date	Inlet Fe (mg/L)	Flow Rate Inlet (L/sec)	Loading Inlet (mg/sec)	Outlet Fe (mg/L)	Flow Rate Outlet (L/sec)	Loading Outlet (mg/sec)	Out/In
Aug 31 89	1413.075	5.95	8407.8	0.208	0.57	0.12	0
Sep 21 89	1242.656	5.95	7393.8	0.137*	0	0	0
Nov 14 89	960.338	53.23	51118.8	0.181	9.63	1.74	0
Dec 14 89	1296.575	126.29	163744.5	231.347	5.95	1376.51	0.008
Jan 17 90	560.053	19.25	10781.0	168.716	32.28	5446.15	0.505
Feb 14 90	627.711	305.25	191608.8	272.212	32.00	8710.78	0.045
Mar 14 90	988.161	133.93	132344.4	767.763	343.47	263703.6	1.993
Apr 23 90	928.144	0	0	755.486	22.37	16900.22	-
May 9 90	1022.387	378.30	386769.0	200.833	261.36	52489.71	0.136
June 11 90	1109.963	3.68	4084.7	179.013	2.27	406.36	0.099
July 10 90	941.436	63.43	59715.2	145.071	16.99	2464.76	0.041
Aug 14 90	895.506	24.07	21554.8	476.051	17.56	8359.46	0.388
Oct 15 90	1075.750	420.21	452040.9	584.183	7.65	4469.00	0.010
May 28 91	933.090	0.28	261.3	523.231	1.01	525.85	2.013
June 24 91	1168.180	29.17	34075.8	662.765	12.74	8443.63	0.248
July 28 91	1226.767	86.36	105943.6	335.197	-	-	-
Aug 25 91	1090.859	78.44	85567.0	314.510	1.13	355.40	0.004
Sep 23 91	1322.160	99.11	131039.3	624.500	123.74	77275.63	0.590
Oct 28 91	1302.025	51.82	67470.9	223.190*	32.00	7142.08	0.106
Nov 18 91	1240.018	45.02	55825.6	856.054	19.82	16966.99	0.304
Jan 28 92	1403.714	7.08	9938.3	383.413	0.57	218.55	0.022
Feb 25 92	1150.037	116.38	133841.3	904.995	178.39	161442.1	1.206
Mar 30 92	1056.405	81.27	85854.0	558.233	156.02	87095.51	1.014
Apr 20 92	1240.300	174.43	216345.5	1038.150	141.30	146690.6	0.678
May 18 92	1439.623	34.55	49739.0	759.525	3.68	2795.05	0.056

*Value estimated from level reported in Cell 24 because low flow prevented obtaining adequate water sample.

Table 13. Flow rate and loading data for aluminum in a constructed wetland treating acid mine drainage. Flow rates determined at inlet and outlet of wetland. Loading data expressed as mg Al/sec, calculated by multiplying aluminum concentration and flow rate. Ratio of loading out/loading in is given to evaluate the effectiveness of removal of aluminum over time.

Sampling Date	Inlet Al (mg/L)	Flow Rate Inlet (L/sec)	Loading Inlet (mg/sec)	Outlet Al (mg/L)	Flow Rate Outlet (L/sec)	Loading Outlet (mg/sec)	Out/In
Aug 31 89	11.499	5.95	68.42	0.675	0.57	0.38	0.006
Sep 21 89	20.575	5.95	122.42	0.408*	0	0	0
Nov 14 89	10.355	53.23	551.20	0.507	9.63	4.88	0.009
Dec 14 89	13.516	126.29	1706.94	0.610	5.95	3.63	0.002
Jan 17 90	11.333	19.25	218.16	0.539	32.28	17.40	0.080
Feb 14 90	6.788	305.25	2072.04	4.957	32.00	158.62	0.077
Mar 14 90	10.724	133.93	1436.27	6.683	343.47	2295.41	1.598
Apr 23 90	10.816	0	0	12.160	22.37	272.02	-
May 9 90	10.224	378.30	3867.74	2.492	261.36	651.31	0.168
June 11 90	9.506	3.68	34.98	8.135	2.27	18.47	0.528
July 10 90	14.287	63.43	906.22	12.302	16.99	209.01	0.231
Aug 14 90	12.424	24.07	299.05	10.112	17.56	177.57	0.594
Oct 15 90	9.410	420.21	3954.18	9.279	7.65	70.98	0.018
May 28 91	4.923	0.28	1.38	11.451	1.01	11.51	8.341
June 24 91	9.555	29.17	278.72	16.896	12.74	215.26	0.772
July 28 91	25.666	86.36	2216.52	15.583	-	-	-
Aug 25 91	16.340	78.44	1281.71	20.644	1.13	23.33	0.018
Sep 23 91	32.300	99.11	3201.25	25.522	123.74	3158.09	0.987
Oct 28 91	35.853	51.82	1857.90	13.191*	32.00	422.11	0.227
Nov 18 91	38.767	45.02	1745.29	25.929	19.82	513.91	0.294
Jan 28 92	26.333	7.08	186.44	9.690	0.57	5.52	0.030
Feb 25 92	42.109	116.38	4900.65	35.287	178.39	6294.85	1.284
Mar 30 92	39.433	81.27	3204.72	26.485	156.02	4132.19	1.289
Apr 20 92	39.540	174.43	6896.96	39.660	141.30	5603.96	0.813
May 18 92	26.919	34.55	930.05	36.017	3.68	132.54	0.143

*Value estimated from level reported in Cell 24 because low flow prevented obtaining adequate water sample.

Table 14. Flow rate and loading data for manganese in a constructed wetland treating acid mine drainage. Flow rates determined at inlet and outlet of wetland. Loading data expressed as mg Mn/sec, calculated by multiplying manganese concentration and flow rate. Ratio of loading out/loading in is given to evaluate the effectiveness of removal of manganese over time.

Sampling Date	Inlet Mn (mg/L)	Flow Rate Inlet (L/sec)	Loading Inlet (mg/sec)	Outlet Mn (mg/L)	Flow Rate Outlet (L/sec)	Loading Outlet (mg/sec)	Out/In
Aug 31 89	21.327	5.95	126.90	0.684	0.57	0.39	0.003
Sep 21 89	37.326	5.95	222.09	1.442*	0	0	0
Nov 14 89	15.759	53.23	838.85	9.083	9.63	87.47	0.104
Dec 14 89	18.700	126.29	2361.62	13.673	5.95	81.35	0.034
Jan 17 90	15.217	19.25	292.93	8.484	32.28	273.86	0.935
Feb 14 90	10.354	305.25	3160.56	7.686	32.00	245.95	0.078
Mar 14 90	15.672	133.93	2098.95	14.627	343.47	5023.94	2.394
Apr 23 90	15.755	0	0	16.083	22.37	359.78	-
May 9 90	17.456	378.30	6603.60	11.731	261.36	3066.01	0.464
June 11 90	18.744	3.68	68.98	13.763	2.27	31.24	0.453
July 10 90	18.618	63.43	1180.94	20.333	16.99	345.46	0.293
Aug 14 90	17.038	24.07	410.10	15.070	17.56	264.63	0.645
Oct 15 90	21.580	420.21	9068.13	17.048	7.65	130.42	0.014
May 28 91	47.049	0.28	13.17	38.814	1.01	39.01	2.962
June 24 91	17.399	29.17	507.53	16.559	12.74	210.96	0.416
July 28 91	19.381	86.36	1673.74	15.441	-	-	-
Aug 25 91	19.907	78.44	1561.51	19.272	1.13	21.78	0.014
Sep 23 91	18.085	99.11	1792.40	17.487	123.74	2163.84	1.207
Oct 28 91	19.353	51.82	1002.87	9.637*	32.00	308.38	0.307
Nov 18 91	17.452	45.02	785.69	17.330	19.82	343.48	0.437
Jan 28 92	20.249	7.08	143.36	9.343	0.57	5.33	0.037
Feb 25 92	17.472	116.38	2033.39	17.767	178.39	3169.46	1.559
Mar 30 92	17.396	81.27	1413.77	13.103	156.02	2044.33	1.446
Apr 20 92	16.250	174.43	2834.49	16.310	141.30	2304.60	0.813
May 18 92	19.819	34.55	684.75	16.603	3.68	61.10	0.089

*Value estimated from level reported in Cell 24 because low flow prevented obtaining adequate water sample.

Table 15. Flow rate and loading data for zinc in a constructed wetland treating acid mine drainage. Flow rates determined at inlet and outlet of wetland. Loading data expressed as mg Zn/sec, calculated by multiplying zinc concentration and flow rate. Ratio of loading out/loading in is given to evaluate the effectiveness of removal of zinc over time.

Sampling Date	Inlet Zn (mg/L)	Flow Rate Inlet (L/sec)	Loading Inlet (mg/sec)	Outlet Zn (mg/L)	Flow Rate Outlet (L/sec)	Loading Outlet (mg/sec)	Out/In
Aug 31 89	0.405	5.95	2.41	0.018	0.57	0.01	0.004
Sep 21 89	0.211	5.95	1.26	0*	0	0	0
Nov 14 89	0.224	53.23	11.92	0.127	9.63	1.22	0.102
Dec 14 89	0.309	126.29	39.02	0.145	5.95	0.86	0.022
Jan 17 90	0.366	19.25	7.05	0.071	32.28	2.29	0.325
Feb 14 90	0.158	305.25	48.23	0.072	32.00	2.30	0.048
Mar 14 90	0.362	133.93	48.48	0.266	343.47	91.36	1.884
Apr 23 90	0.237	0	0	0.278	22.37	6.22	-
May 9 90	0.196	378.30	74.15	0.155	261.36	40.51	0.546
June 11 90	0.489	3.68	1.80	0.267	2.27	0.61	0.339
July 10 90	0.326	63.43	20.68	0.333	16.99	5.66	0.274
Aug 14 90	0.297	24.07	7.15	0.254	17.56	4.46	0.624
Oct 15 90	0.460	420.21	193.30	0.354	7.65	2.71	0.014
May 28 91	0.293	0.28	0.08	0.336	1.01	0.34	4.250
June 24 91	0.370	29.17	10.79	0.542	12.74	6.91	0.640
July 28 91	0.555	86.36	47.93	0.436	-	-	0
Aug 25 91	0.527	78.44	41.34	0.467	1.13	0.53	0.013
Sep 23 91	0.643	99.11	63.73	0.627	123.74	77.58	1.217
Oct 28 91	0.624	51.82	32.34	0.211*	32.00	6.75	0.209
Nov 18 91	0.700	45.02	31.51	0.659	19.82	13.06	0.414
Jan 28 92	0.506	7.08	3.58	0.236	0.57	0.13	0.036
Feb 25 92	0.761	116.38	88.57	0.763	178.39	136.11	1.537
Mar 30 92	0.713	81.27	57.95	0.528	156.02	82.38	1.422
Apr 20 92	0.675	174.43	117.74	0.699	141.30	98.77	0.839
May 18 92	0.532	34.55	18.38	0.613	3.68	2.26	0.123

*Value estimated from level reported in Cell 24 because low flow prevented obtaining adequate water sample.

Table 16. Flow rate and loading data for boron in a constructed wetland treating acid mine drainage. Flow rates determined at inlet and outlet of wetland. Loading data expressed as mg B/sec, calculated by multiplying boron concentration and flow rate. Ratio of loading out/loading in is given to evaluate the effectiveness of removal of boron over time.

Sampling Date	Inlet B (mg/L)	Flow Rate Inlet (L/sec)	Loading Inlet (mg/sec)	Outlet B (mg/L)	Flow Rate Outlet (L/sec)	Loading Outlet (mg/sec)	Out/In
Aug 31 89	0.988	5.95	5.88	0.157	0.57	0.09	0.015
Sep 21 89	0.796	5.95	4.74	0.145*	0	0	0
Nov 14 89	0.647	53.23	34.44	0.269	9.63	2.59	0.075
Dec 14 89	0.772	126.29	97.50	0.393	5.95	2.34	0.024
Jan 17 90	0.686	19.25	13.21	0.270	32.28	8.72	0.660
Feb 14 90	0.475	305.25	144.99	0.353	32.00	11.30	0.078
Mar 14 90	0.793	133.93	106.21	0.744	343.47	255.54	2.406
Apr 23 90	0.772	0	0	0.788	22.37	17.63	-
May 9 90	0.803	378.30	303.77	0.621	261.36	162.30	0.534
June 11 90	1.345	3.68	4.95	0.668	2.27	1.52	0.307
July 10 90	0.910	63.43	57.72	1.106	16.99	18.79	0.326
Aug 14 90	0.887	24.07	21.35	0.882	17.56	15.49	0.726
Oct 15 90	0.860	420.21	361.38	0.937	7.65	7.17	0.020
May 28 91	1.133	0.28	0.32	1.003	1.01	1.01	3.156
June 24 91	1.472	29.17	42.94	1.754	12.74	22.35	0.520
July 28 91	1.196	86.36	103.29	1.103	-	-	-
Aug 25 91	0.694	78.44	54.44	0.566	1.13	0.64	0.012
Sep 23 91	1.364	99.11	135.19	1.419	123.74	175.59	1.299
Oct 28 91	0.764	51.82	39.59	0.361*	32.00	11.55	0.292
Nov 18 91	1.486	45.02	66.90	1.649	19.82	32.68	0.488
Jan 28 92	0.813	7.08	5.76	0.350	0.57	0.20	0.035
Feb 25 92	1.444	116.38	168.05	1.419	178.39	253.14	1.506
Mar 30 92	1.481	81.27	120.36	1.097	156.02	171.15	1.422
Apr 20 92	1.535	174.43	267.75	1.530	141.3	216.19	0.807
May 18 92	0.783	34.55	27.05	0.873	3.68	3.21	0.119

*Value estimated from level reported in Cell 24 because low flow prevented obtaining adequate water sample.

Table 17. Flow rate and loading data for cobalt in a constructed wetland treating acid mine drainage. Flow rates determined at inlet and outlet of wetland. Loading data expressed as mg Co/sec, calculated by multiplying cobalt concentration and flow rate. Ratio of loading out/loading in is given to evaluate the effectiveness of removal of cobalt over time.

Sampling Date	Inlet Co (mg/L)	Flow Rate Inlet (L/sec)	Loading Inlet (mg/sec)	Outlet Co (mg/L)	Flow Rate Outlet (L/sec)	Loading Outlet (mg/sec)	Out/In
Aug 31 89	0.149	5.95	0.89	0.053	0.57	0.03	0.034
Sep 21 89	0.227	5.95	1.35	0.046*	0	0	0
Nov 14 89	0.192	53.23	10.22	0.130	9.63	1.25	0.122
Dec 14 89	0.236	126.29	29.80	0.081	5.95	0.48	0.016
Jan 17 90	0.131	19.25	2.52	0.058	32.28	1.87	0.742
Feb 14 90	0.139	305.25	42.43	0.095	32.00	3.04	0.072
Mar 14 90	0.104	133.93	13.93	0.108	343.47	37.09	2.663
Apr 23 90	0.188	0	0	0.194	22.37	4.34	-
May 9 90	0.189	378.30	71.50	0.134	261.36	35.02	0.490
June 11 90	0.164	3.68	0.60	0.074	2.27	0.17	0.283
July 10 90	0.229	63.43	14.53	0.240	16.99	4.08	0.281
Aug 14 90	0.207	24.07	4.98	0.196	17.56	3.44	0.691
Oct 15 90	0.120	420.21	50.43	0.094	7.65	0.72	0.014
May 28 91	0.393	0.28	0.11	0.284	1.01	0.29	2.636
June 24 91	0.529	29.17	15.43	0.818	12.74	10.42	0.675
July 28 91	0.364	86.36	31.44	0.359	-	0	0
Aug 25 91	0.132	78.44	10.35	0.108	1.13	0.12	0.012
Sep 23 91	0.520	99.11	51.54	0.510	123.74	63.11	1.224
Oct 28 91	0.151	51.82	7.82	0.052*	32.00	1.66	0.212
Nov 18 91	0.594	45.02	26.74	0.672	19.82	13.32	0.498
Jan 28 92	0.138	7.08	0.98	0.061	0.57	0.03	0.031
Feb 25 92	0.643	116.38	74.83	0.488	178.39	87.05	1.163
Mar 30 92	0.416	81.27	33.81	0.369	156.02	57.57	1.703
Apr 20 92	0.635	174.43	110.76	0.659	141.30	93.12	0.841
May 18 92	0.131	34.55	4.53	0.146	3.68	0.54	0.119

*Value estimated from level reported in Cell 24 because low flow prevented obtaining adequate water sample.

Table 18. Flow rate and loading data for sulfate in a constructed wetland treating acid mine drainage. Flow rates determined at inlet and outlet of wetland. Loading data expressed as mg SO_4/sec, calculated by multiplying sulfate concentration and flow rate. Ratio of loading out/loading in is given to evaluate the effectiveness of removal of sulfate over time.

Sampling Date	Inlet SO4 (mg/L)	Flow Rate Inlet (L/sec)	Loading Inlet (mg/sec)	Outlet SO4 (mg/L)	Flow Rate Outlet (L/sec)	Loading Outlet (mg/sec)	Out/In
Aug 31 89	5290	5.95	31476	545	0.57	310.65	0.01
Sep 21 89	4580	5.95	27251	688*	0	0	0
Nov 14 89	3490	53.23	185773	1013	9.63	9750.38	0.052
Dec 14 89	4800	126.29	606192	2460	5.95	14637	0.024
Jan 17 90	2800	19.25	53900	2000	32.28	64560	1.198
Feb 14 90	2400	305.25	732600	1550	32.00	49600	0.068
Mar 14 90	3900	133.93	522327	3600	343.47	1236492	2.367
Apr 23 90	2700	0	0	3700	22.37	82769	-
May 9 90	4100	378.30	1551030	3000	261.36	784080	0.506
June 11 90	4600	3.68	16928	2800	2.27	6356	0.375
July 10 90	4600	63.43	291778	3500	16.99	59465	0.204
Aug 14 90	3800	24.07	91466	3800	17.56	66728	0.73
Oct 15 90	4050	420.21	1701851	3070	7.65	23485.5	0.014
May 28 91	3100	0.28	868	2610	1.005	2623.05	3.022
June 24 91	4050	29.17	118139	3230	12.74	41150.2	0.348
July 28 91	4100	86.36	354076	3000	-	-	-
Aug 25 91	4200	78.44	329448	3600	1.13	4068	0.012
Sep 23 91	4200	99.11	416262	3800	123.74	470212	1.13
Oct 28 91	4360	51.82	225935	2050*	32.00	65600	0.29
Nov 18 91	4800	45.02	216096	3900	19.82	77298	0.358
Jan 28 92	4400	7.08	31152	2000	0.57	1140	0.037
Feb 25 92	4200	116.38	488796	4400	178.39	784916	1.606
Mar 30 92	4100	81.27	333207	3100	156.02	483662	1.452
Apr 20 92	4500	174.43	784935	4500	141.3	635850	0.81
May 18 92	4500	34.55	155475	4100	3.68	15088	0.097

*Value estimated from level reported in Cell 24 because low flow prevented obtaining adequate water sample.

Table 19. Toxicity of water from a constructed wetland system treating acid mine drainage, as determined in a 48-hour static test with fathead minnow larvae (June, 1991).

PERCENT SURVIVAL							
Percent Sample	**Stream Above**	**Wetland Inlet**	**Cell 8**	**Cell 15**	**Cell 20**	**Outlet**	**Stream Below**
100.0	0	0	0	0	0	0	0
50.0	100	-	-	-	-	-	-
25.0	100	-	-	-	-	-	0
12.5	100	0	0	0	0	0	100
6.25	-	0	0	0	0	0	100
3.1	100	0	0	0	0	40	100
1.6	-	95	95	100	95	100	-
0 (Control)	100	100	100	100	100	100	100

Table 20. LC$_{50}$ values for acid mine drainage treated by a constructed wetland determined with fathead minnow larvae in a 48-hour static test.

LC$_{50}$ Values (Percent Sample)							
DATE	**STREAM ABOVE**	**WETLAND INLET**	**CELL 8**	**CELL 15**	**CELL 20**	**OUTLET**	**STREAM BELOW**
7/90	-	2.25	3.16	3.16	2.59	3.16	7.63
8/90	-	2.11	2.52	2.83	3.87	4.32	3.74
9/90	-	-	-	-	-	5.45	32.7
10/90	70.7	2.21	3.59	3.85	4.12	3.35	17.7
11/90	-	-	-	-	-	5.08	50.0
1/91	70.7	4.90	4.42	4.27	4.42	4.42	50.0
2/91	70.7	2.21	2.45	4.42	4.27	6.93	48.0
3/91	70.7	1.50	4.27	4.90	4.42	5.26	47.5
4/91	68.2	2.21	2.21	2.45	3.84	4.42	46.1
5/91	70.7	4.12	1.59	4.42	2.92	2.54	50.0
6/91	70.7	1.52	1.52	2.21	1.52	2.92	17.7
7/91	-	1.52	1.78	4.27	2.74	4.42	8.84
8/91	-	2.21	4.42	-	4.27	-	7.43
9/91	-	1.44	2.21	2.21	3.02	-	8.84
10/91	-	2.21	2.21	2.29	4.27	6.47	5.44
11/91	-	2.15	2.07	2.15	2.15	2.15	0.01
1/92	70.7	2.21	2.21	4.12	4.12	-	-
2/92	70.7	1.44	1.44	2.21	2.21	2.21	50.0
3/92	33.9	0.93	2.21	2.84	0.40	2.18	47.5
4/92	68.3	2.21	1.44	2.21	2.21	1.44	8.54
5/92	70.7	2.21	2.29	-	2.21	-	50.0

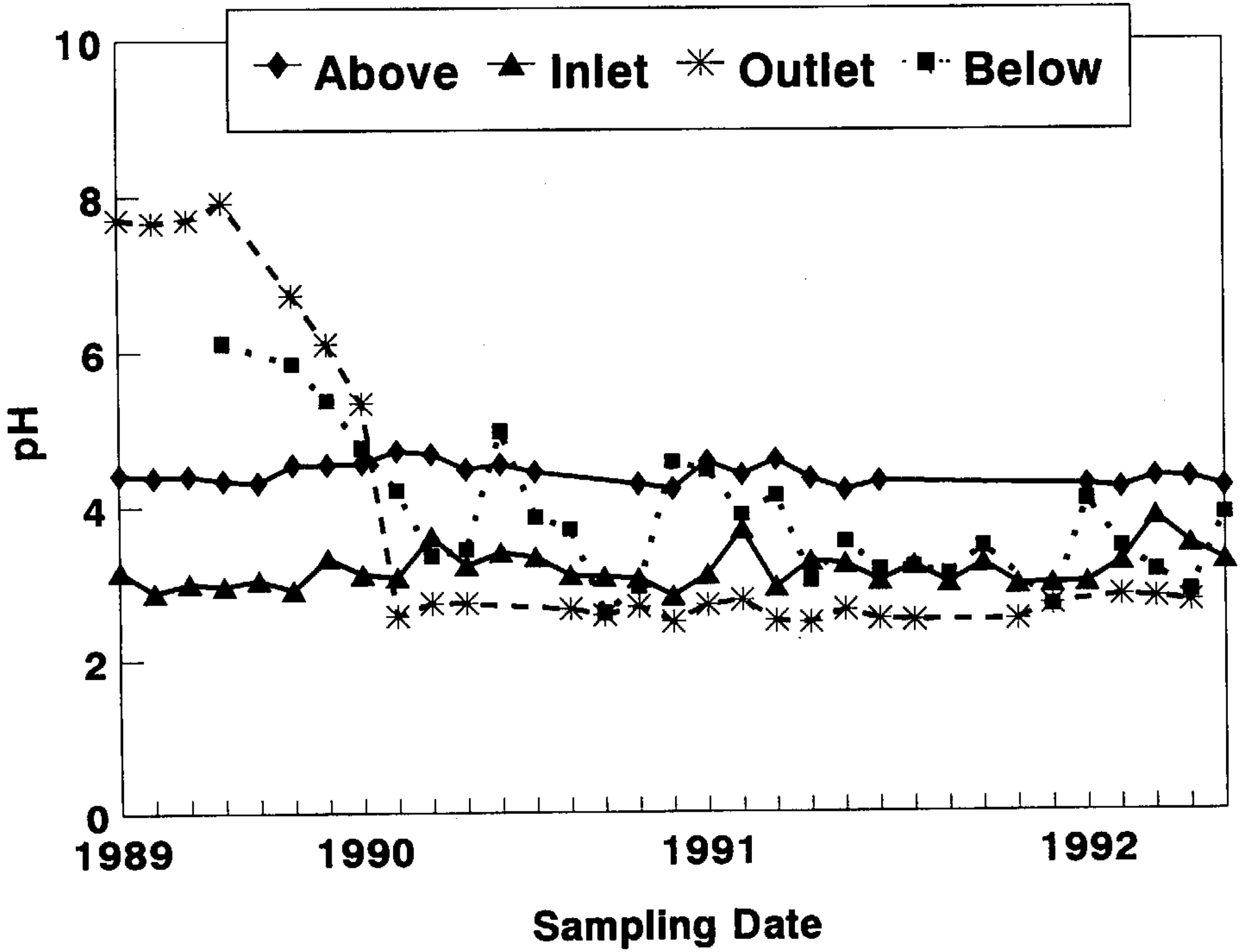

Figure 2. pH in a constructed wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

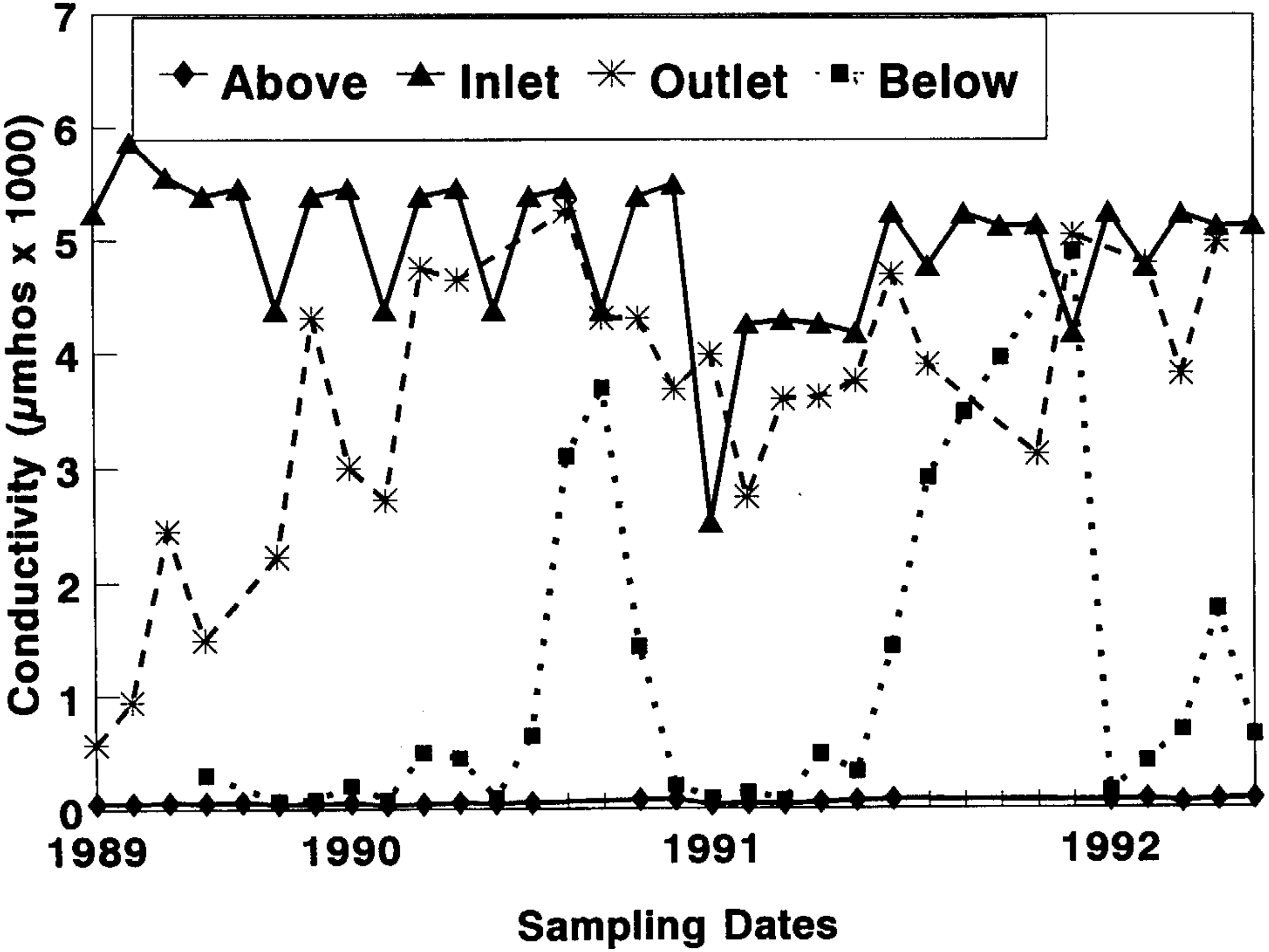

Figure 3. Conductivity in a constructed wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

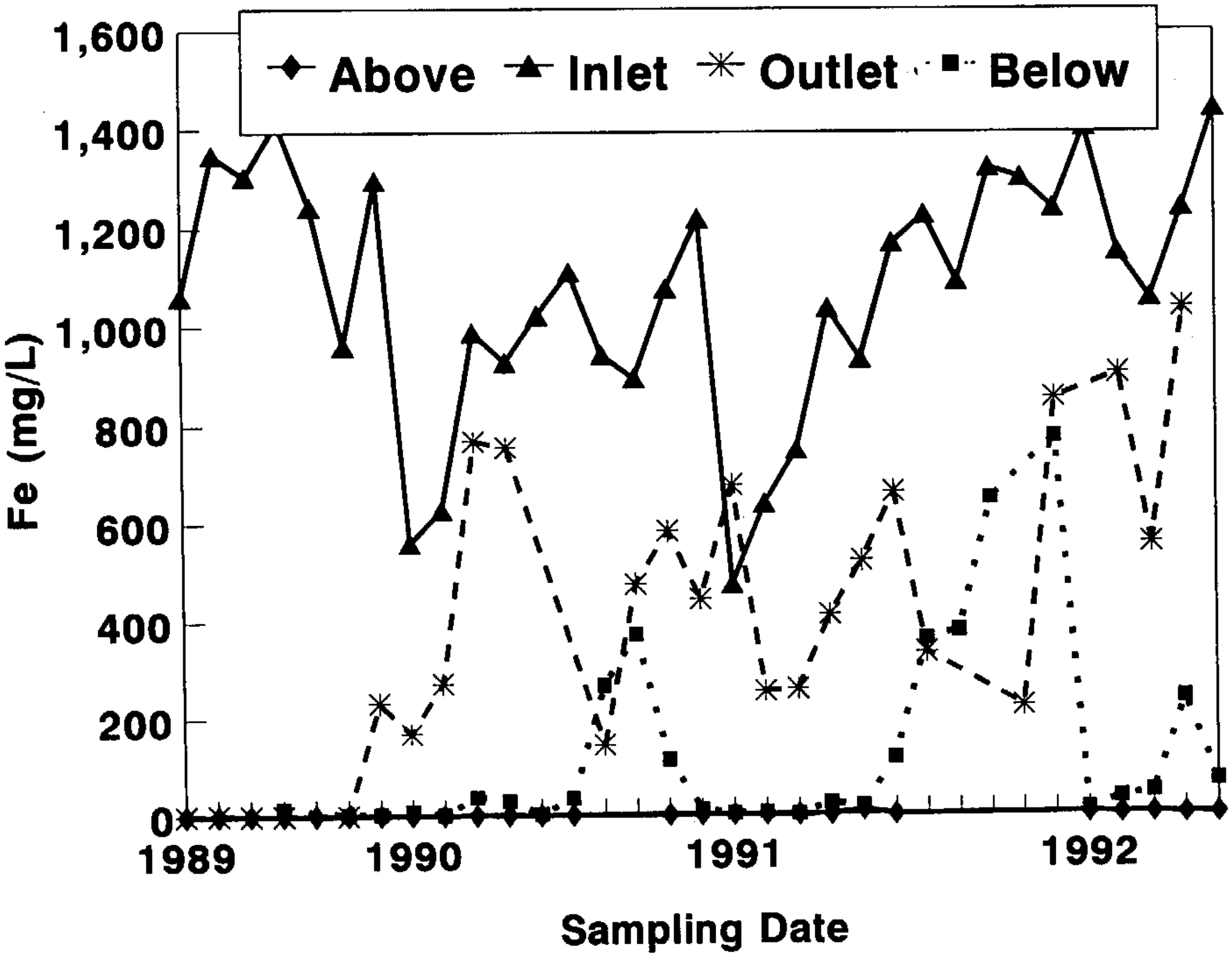

Figure 4. Iron in a constructed wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

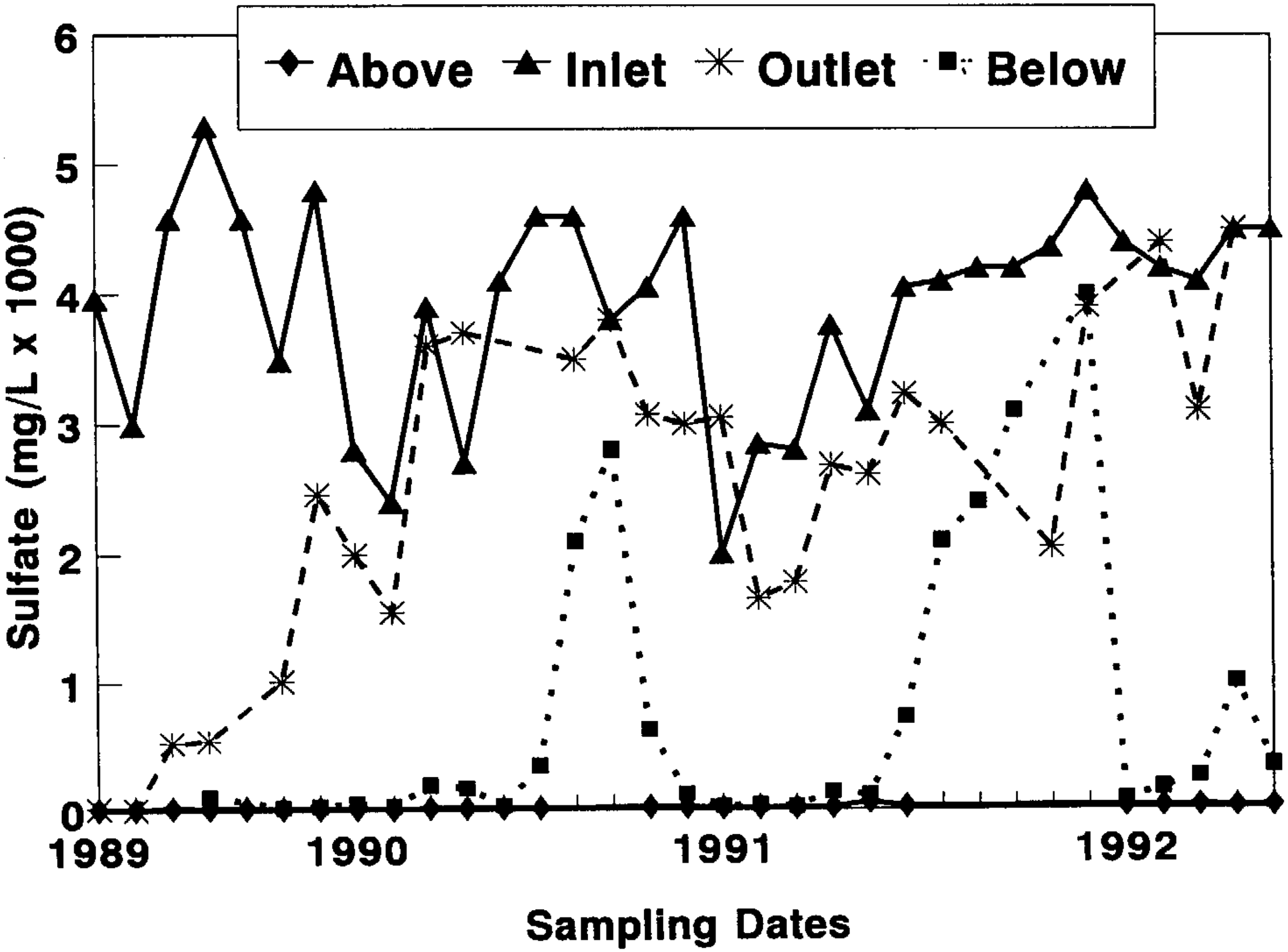

Figure 5. Sulfate in a constructed wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

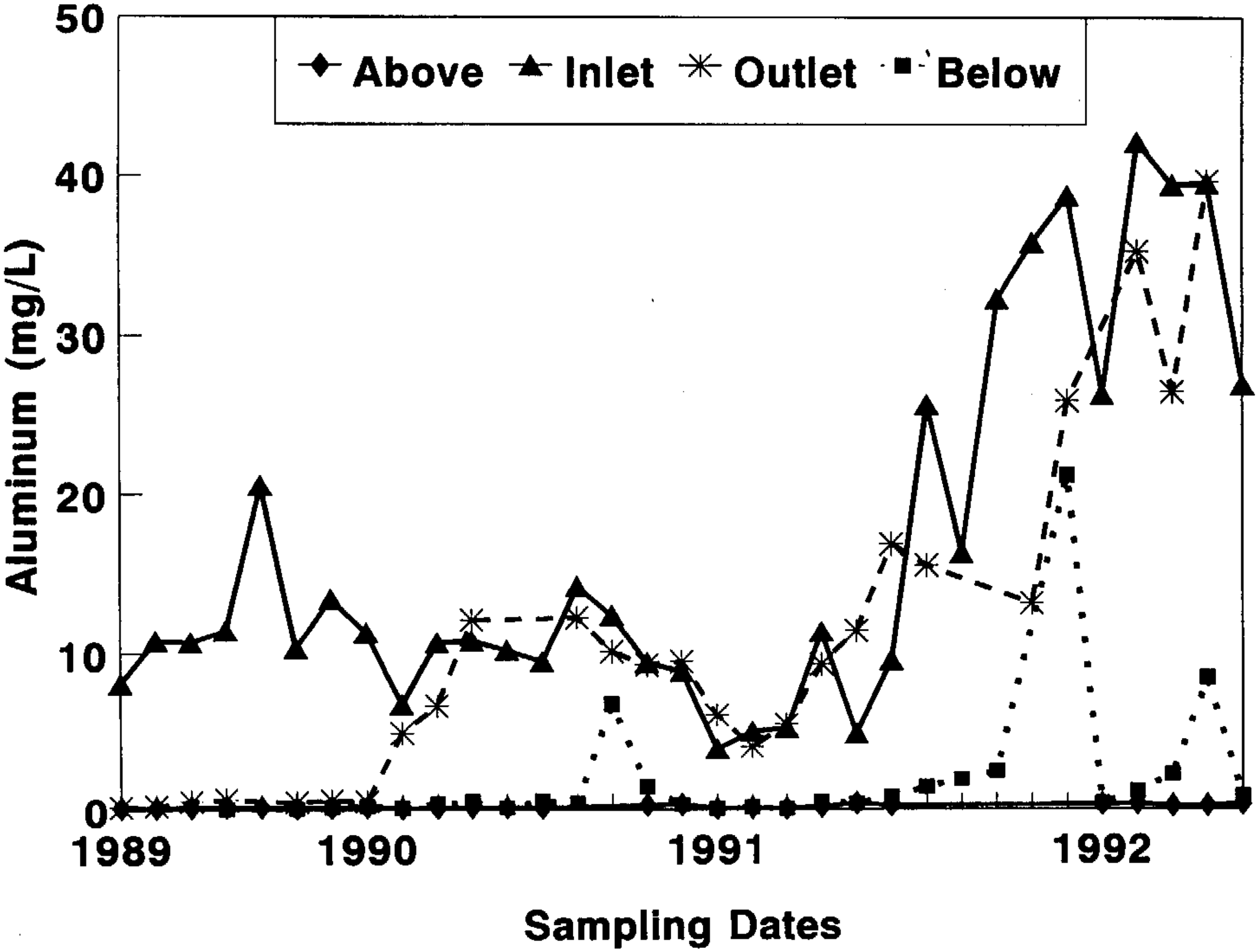

Figure 6. Aluminum in a constructed wetland system on Jones Branch treeating acid mine drainage (June 1989 - May 1992).

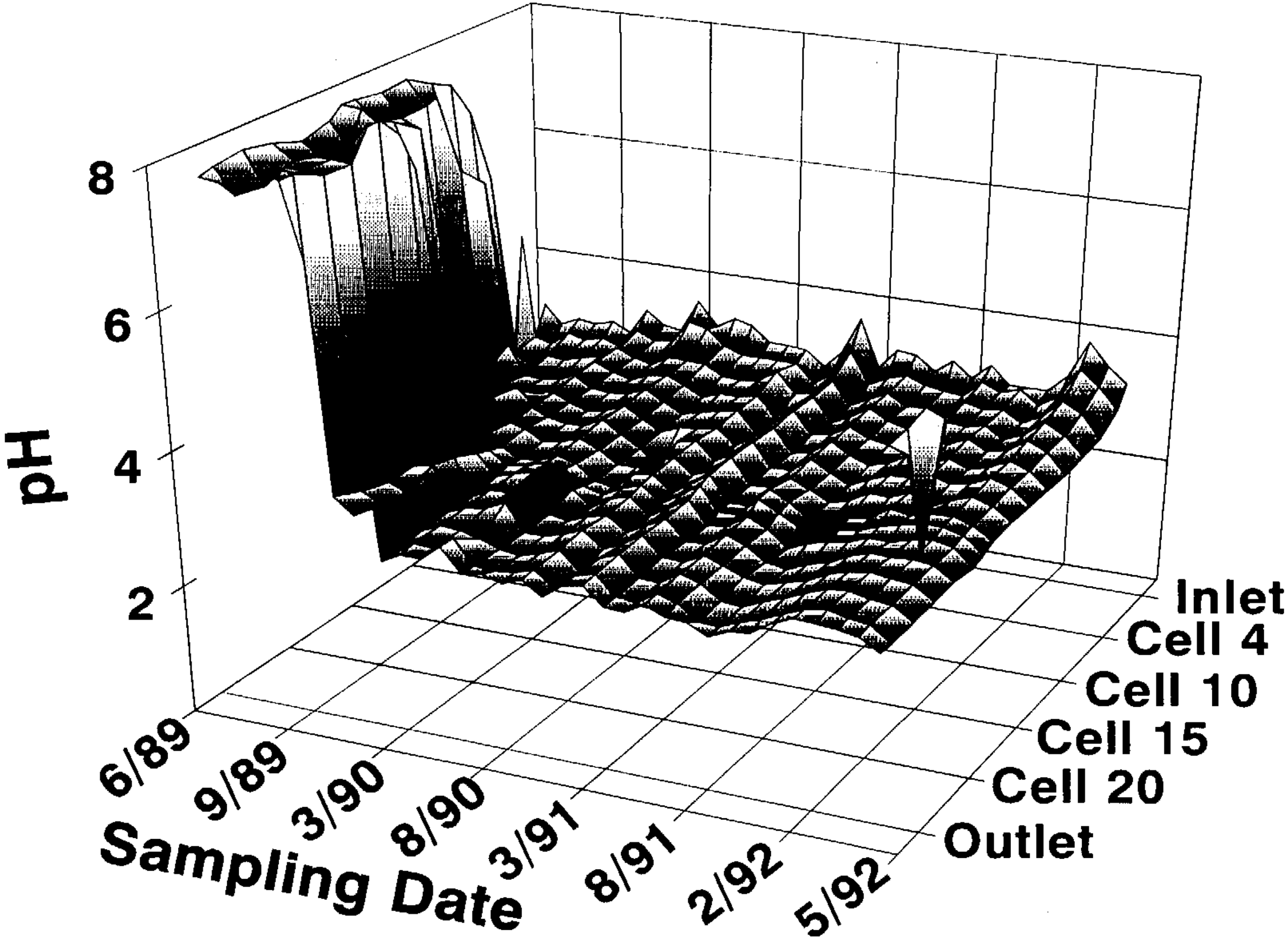

Figure 7. pH in a constructed wetland treating acid mine drainage between inlet and outlet (June 1989 - May 1992).

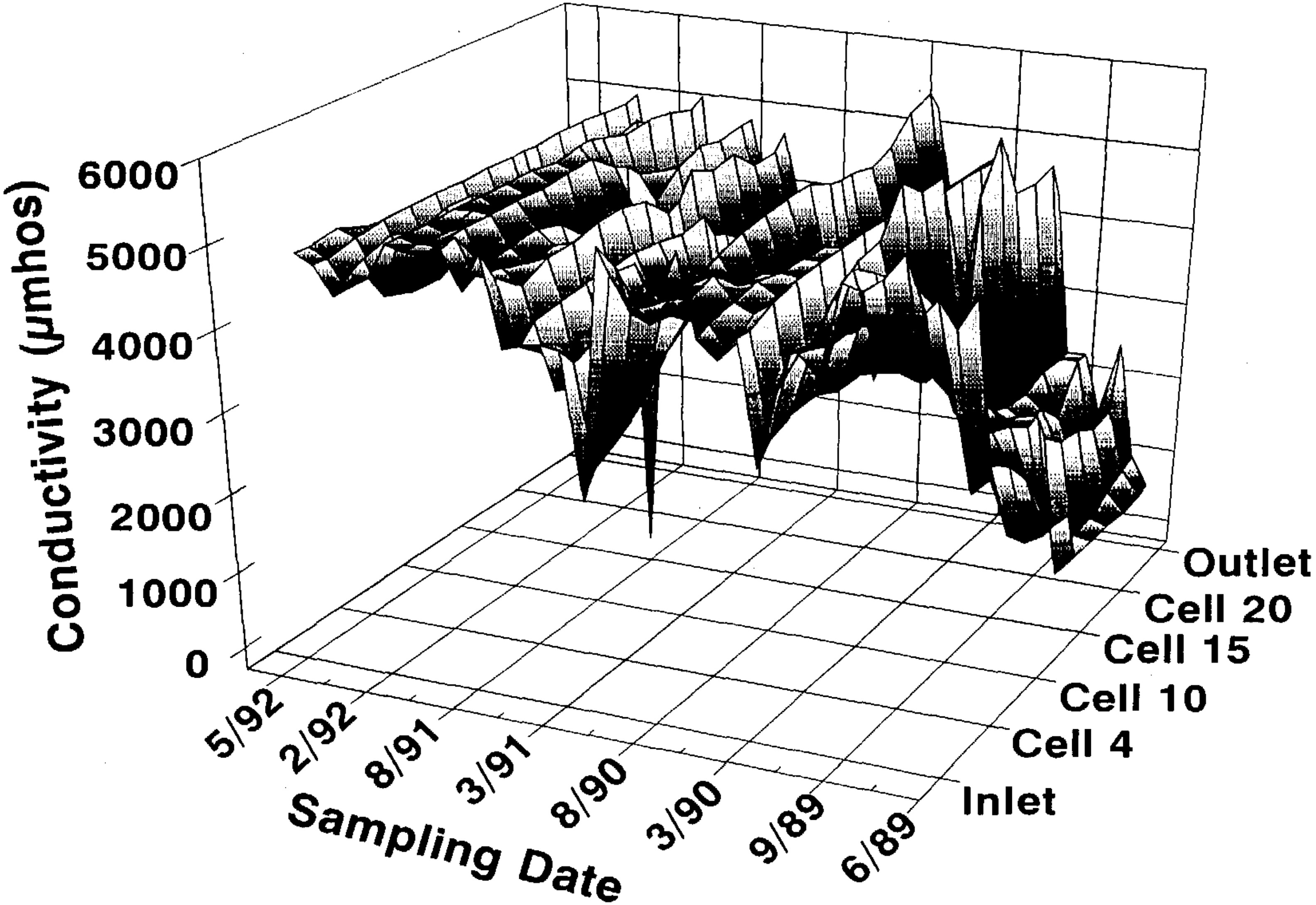

Figure 8. Conductivity in a constructed wetland treating acid mine drainage between inlet and outlet (June 1989 - May 1992).

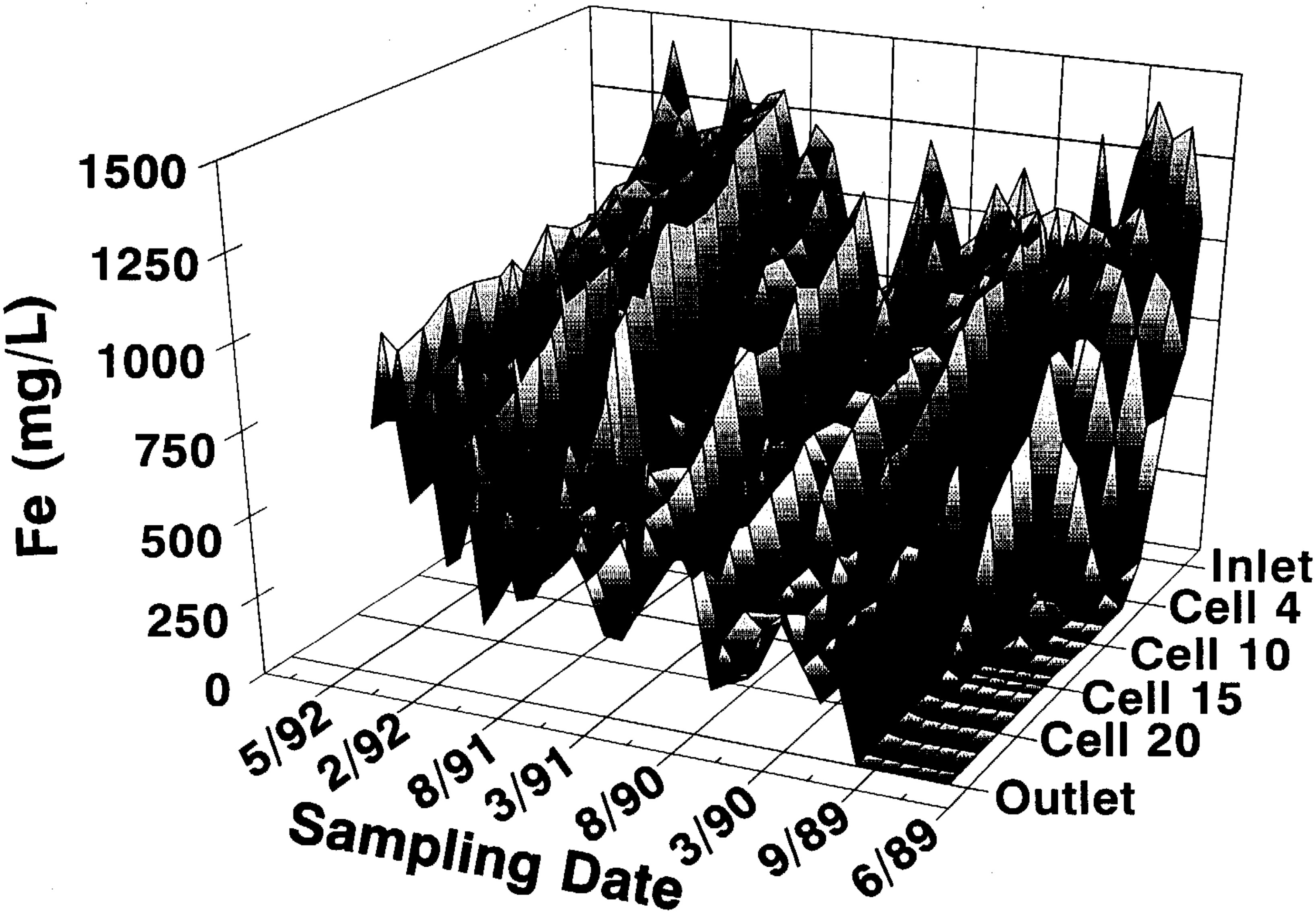

Figure 9. Iron in a constructed wetland treating acid mine drainage between inlet and outlet (June 1989 - May 1992).

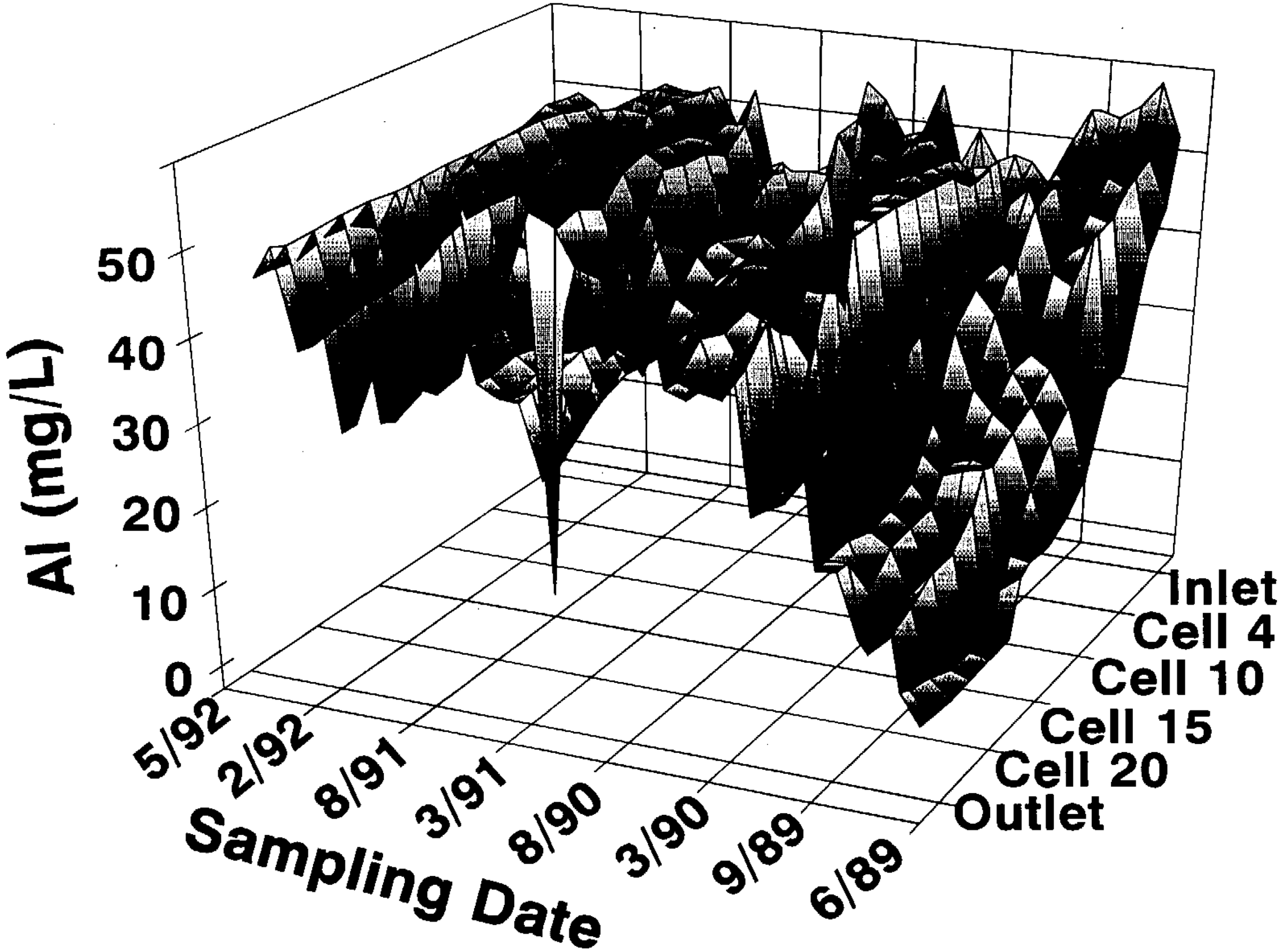

Figure 10. Aluminum in a constructed wetland treating acid mine drainage between inlet and outlet (June 1989 - May 1992).

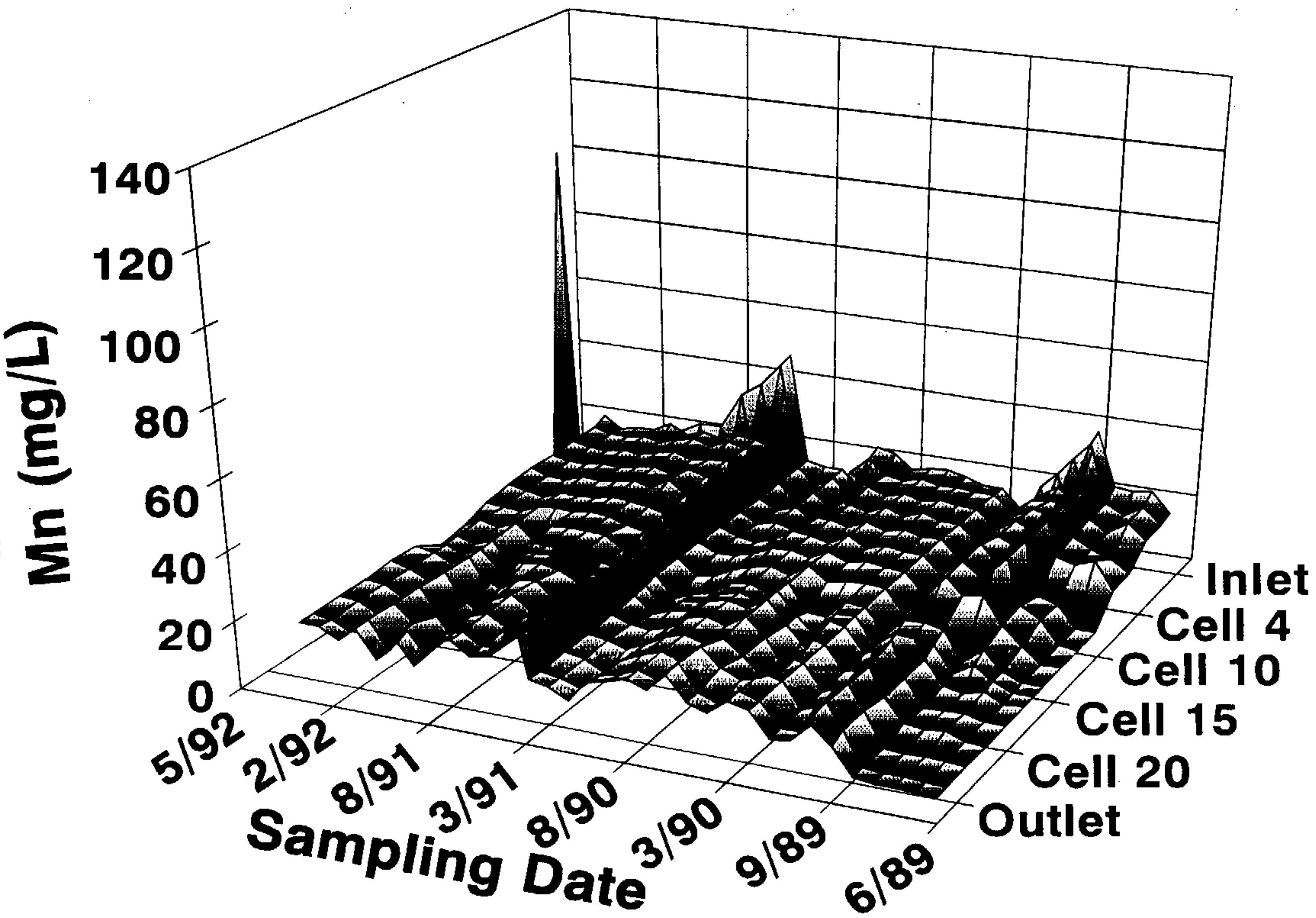

Figure 11. Manganese in a constructed wetland treating acid mine drainage between inlet and outlet (June 1989 - May 1992).

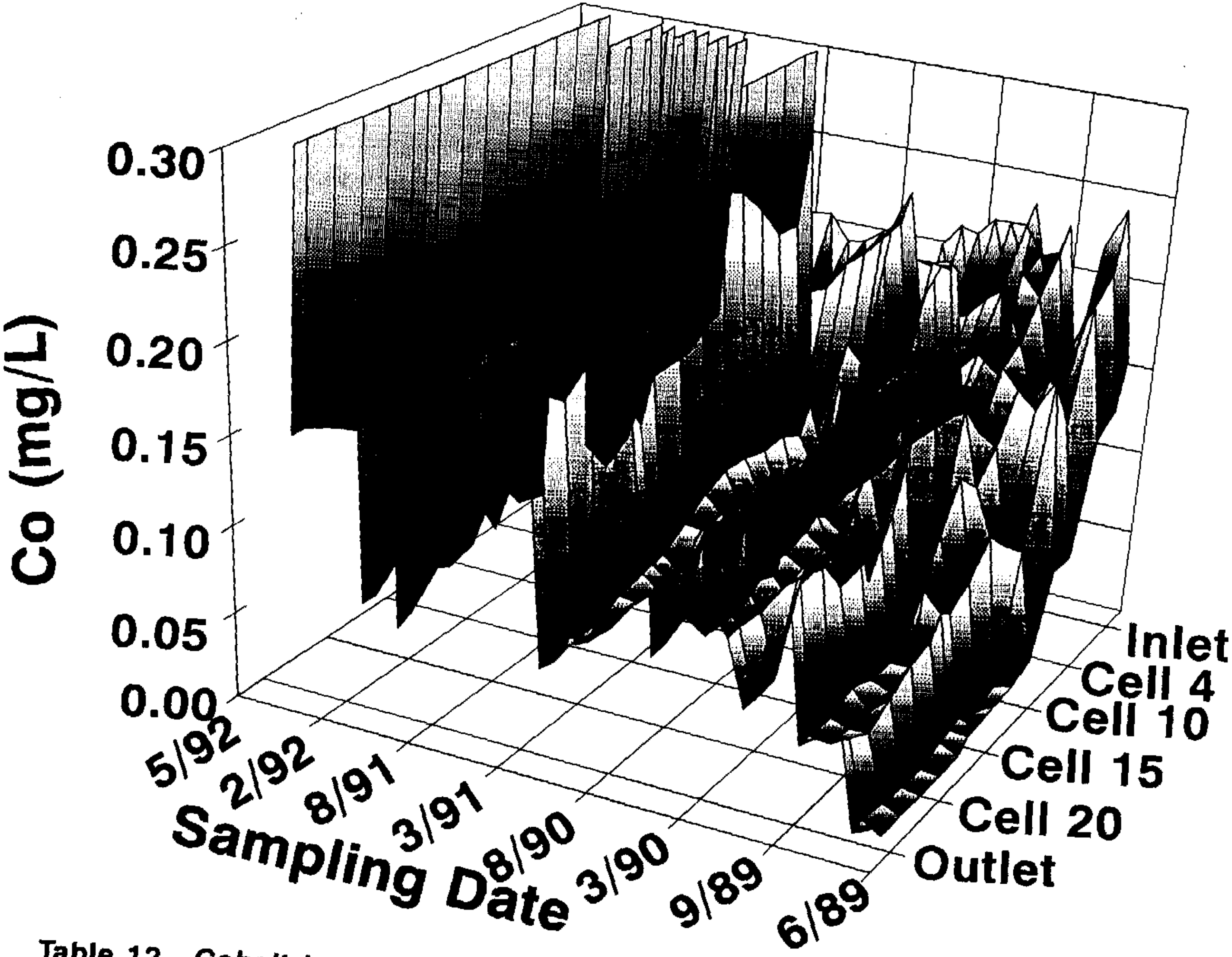

Table 12. Cobalt in a constructed wetland treating acid mine drainage between inlet and outlet (June 1989 - May 1992).

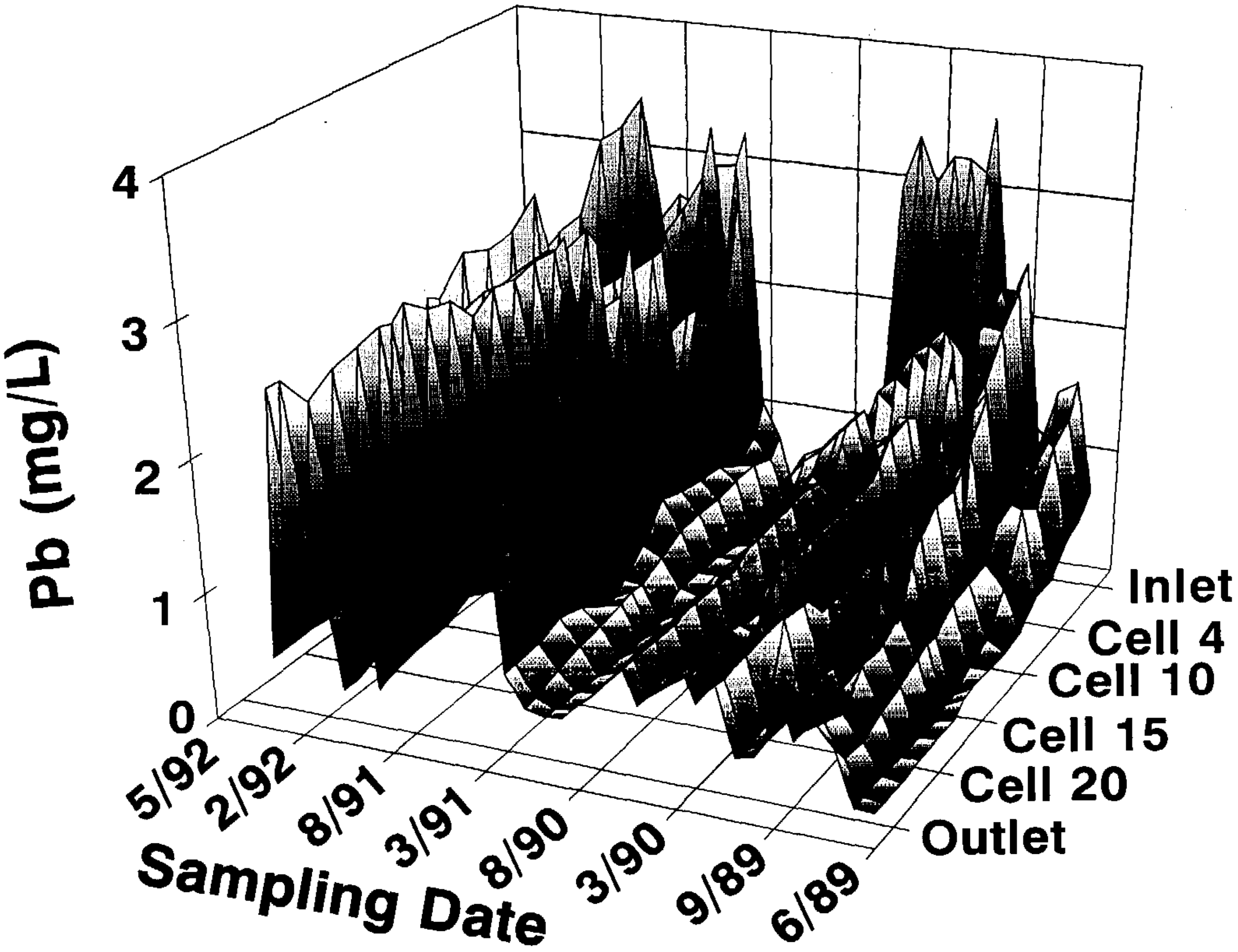

Figure 13. Lead in a constructed wetland treating acid mine drainage between inlet and outlet (June 1989 - May 1992).

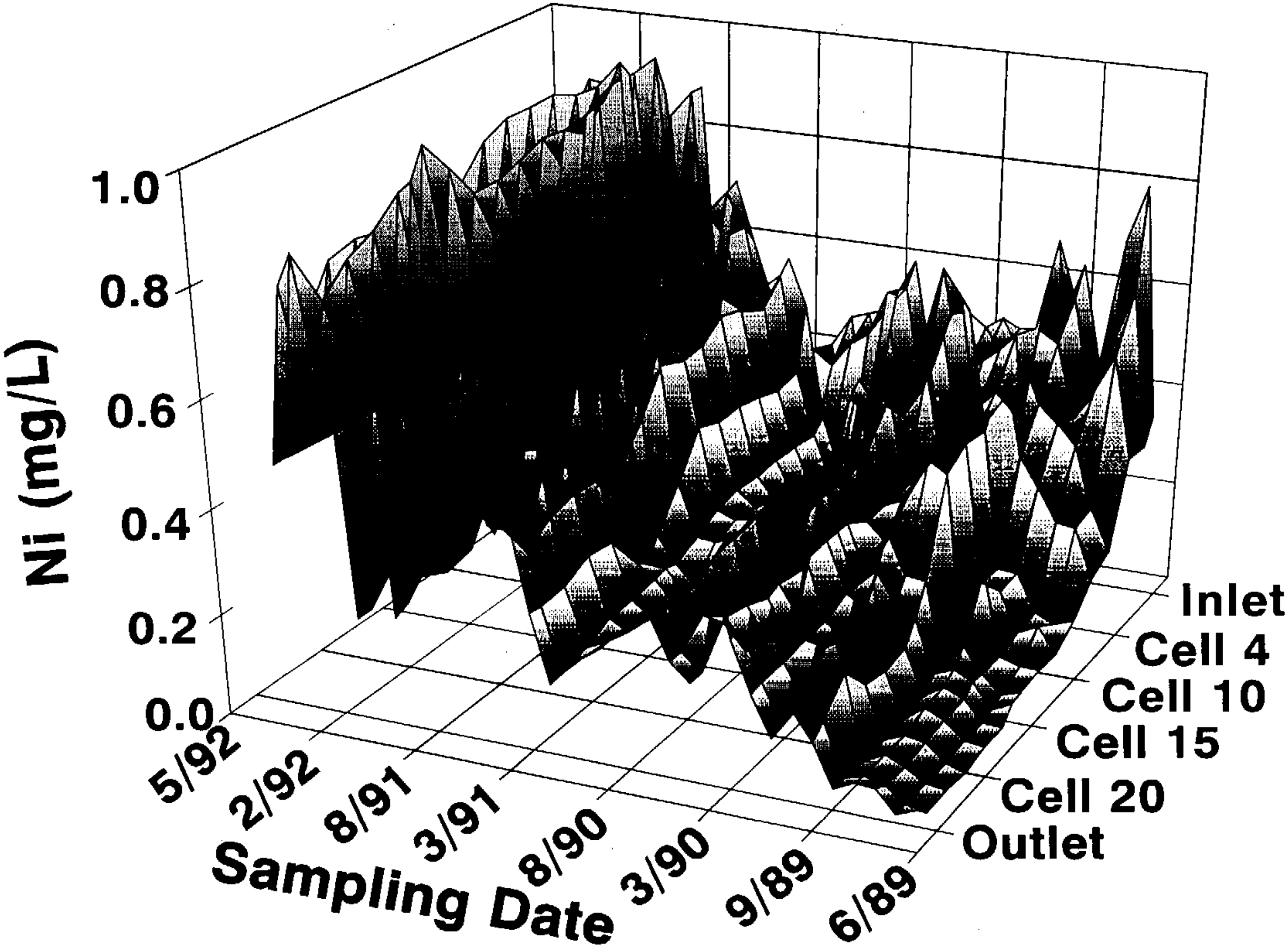

Table 14. Nickel in a constructed wetland treating acid mine drainage between inlet and outlet (June 1989 - May 1992).

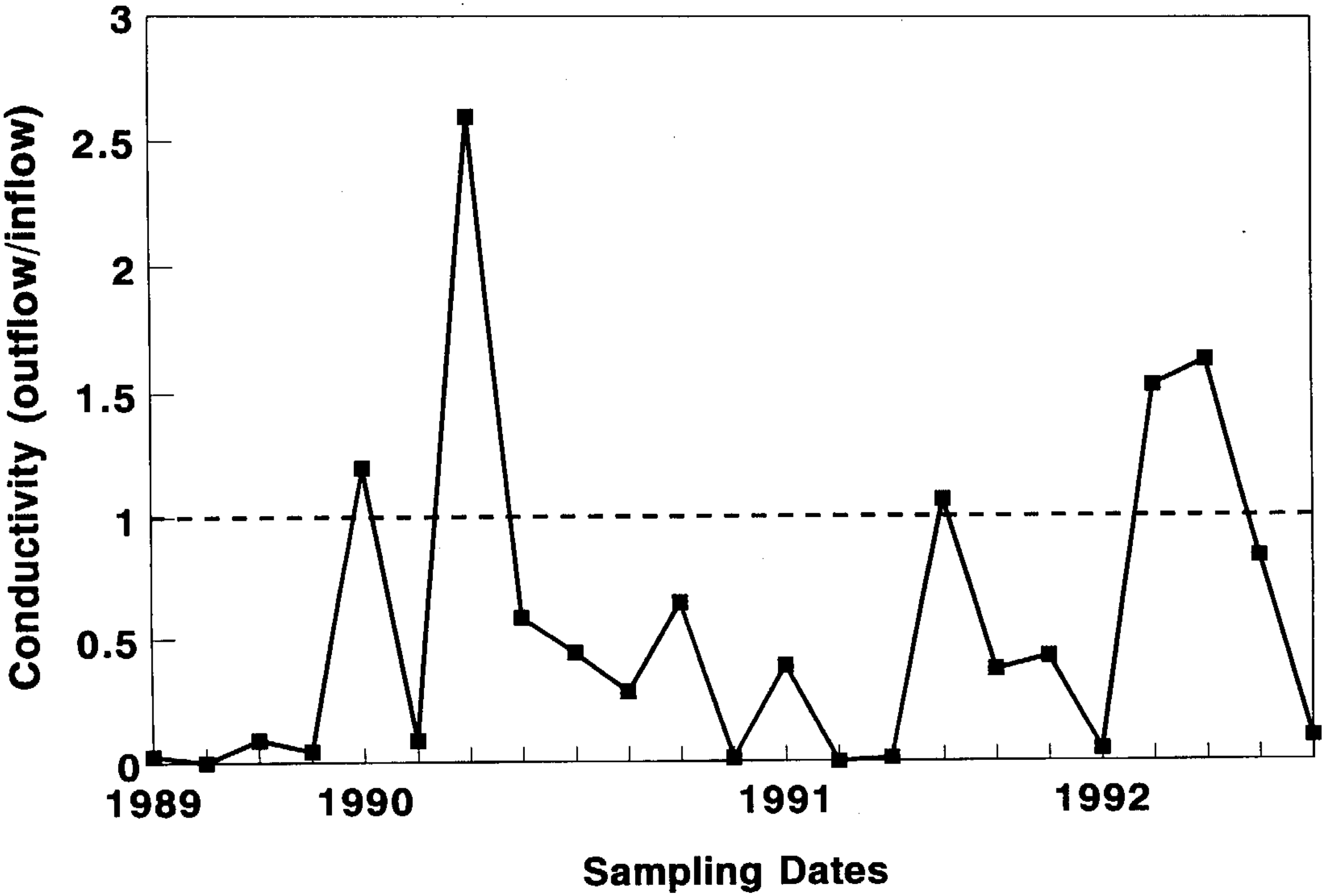

Figure 15. Reduction in conductivity by a constsructed wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

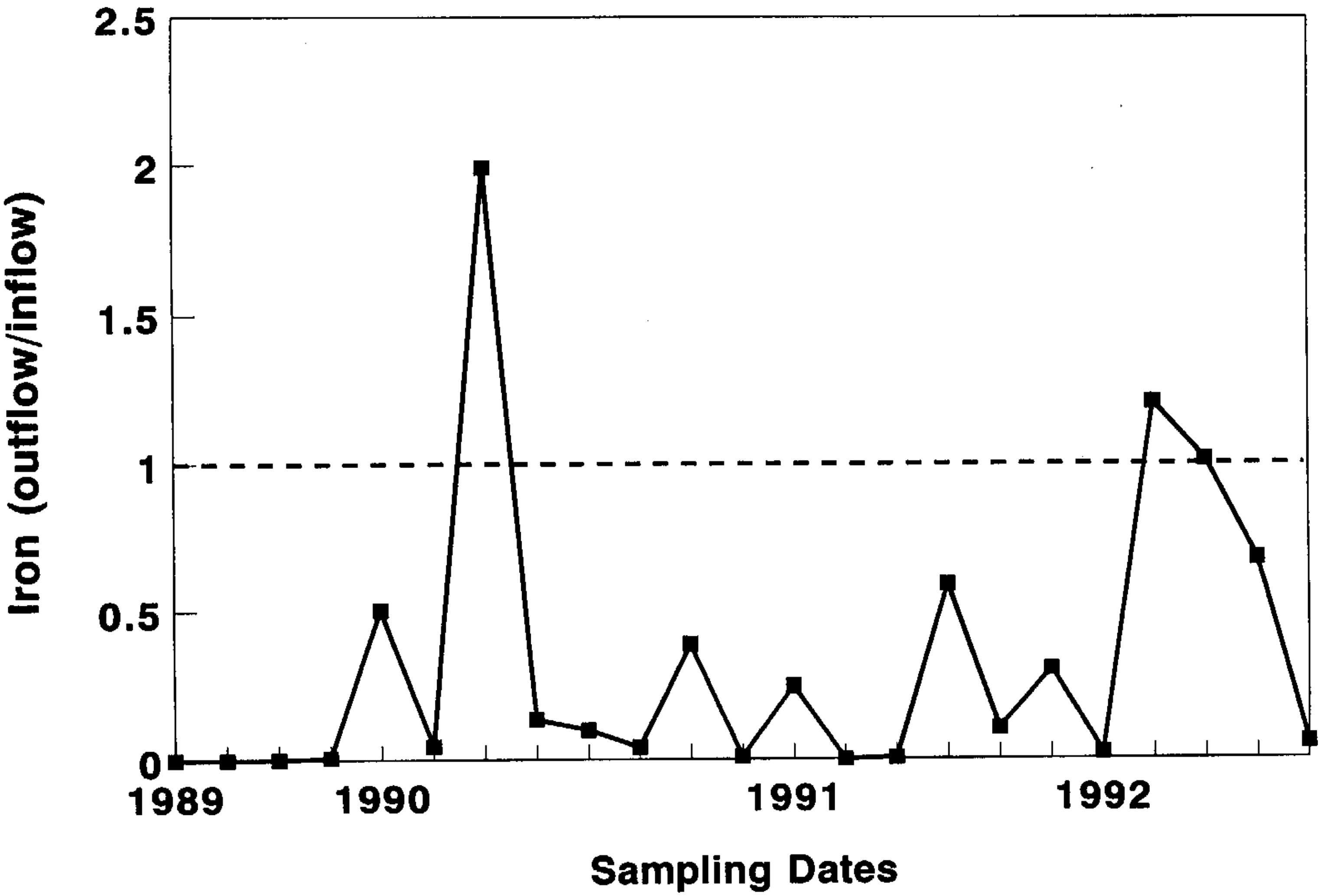

Figure 16. Removal of iron by a constrsucted wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

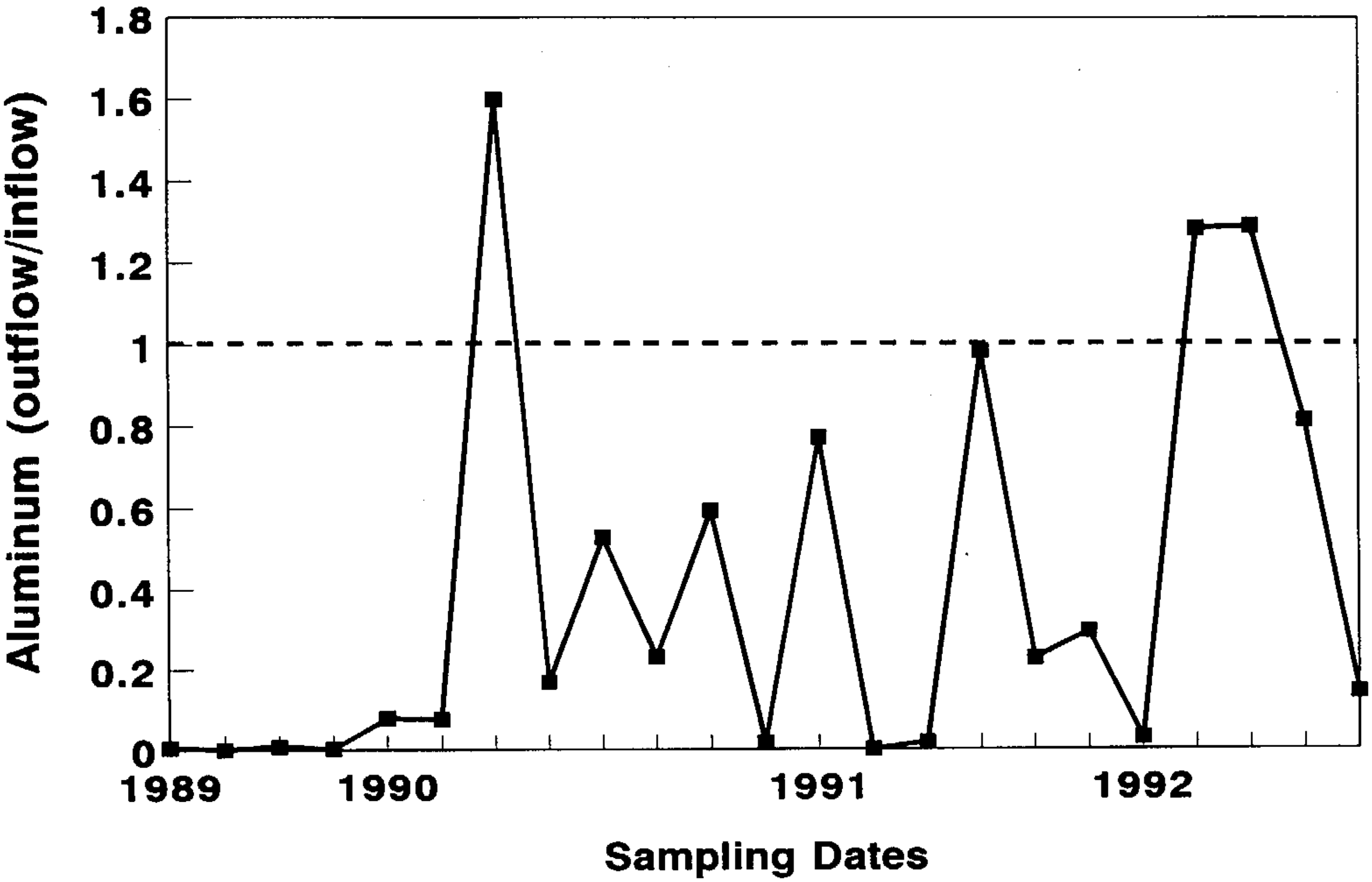

Figure 17. Removal of aluminum by a constructed wetland system on Jones Branch treating acid mine drainage between inlet and outlet (June 1989 - May 1992).

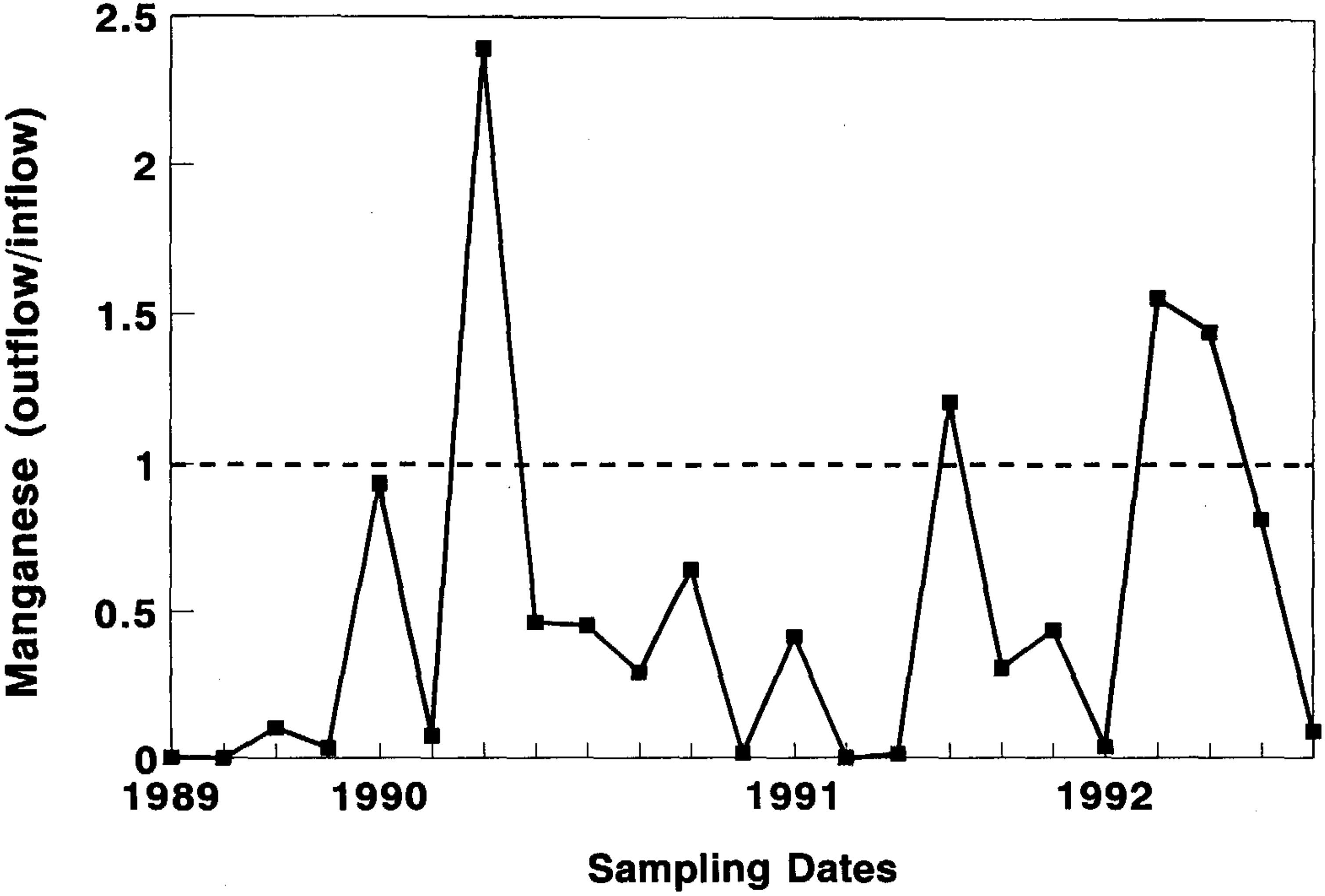

Figure 18. Removal of manganese by a constructed wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

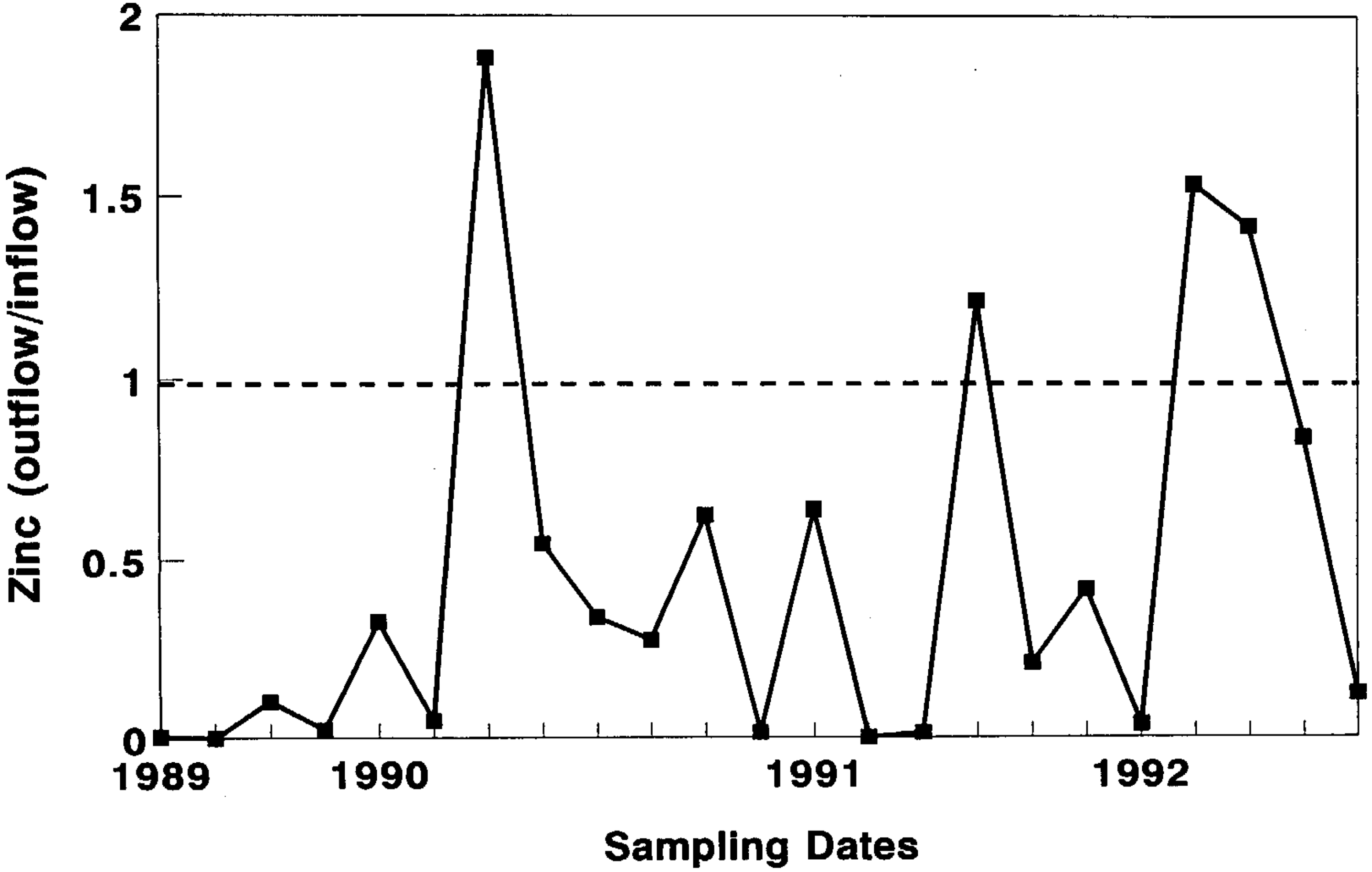

Figure 19. Removal of zinc by a constructed wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

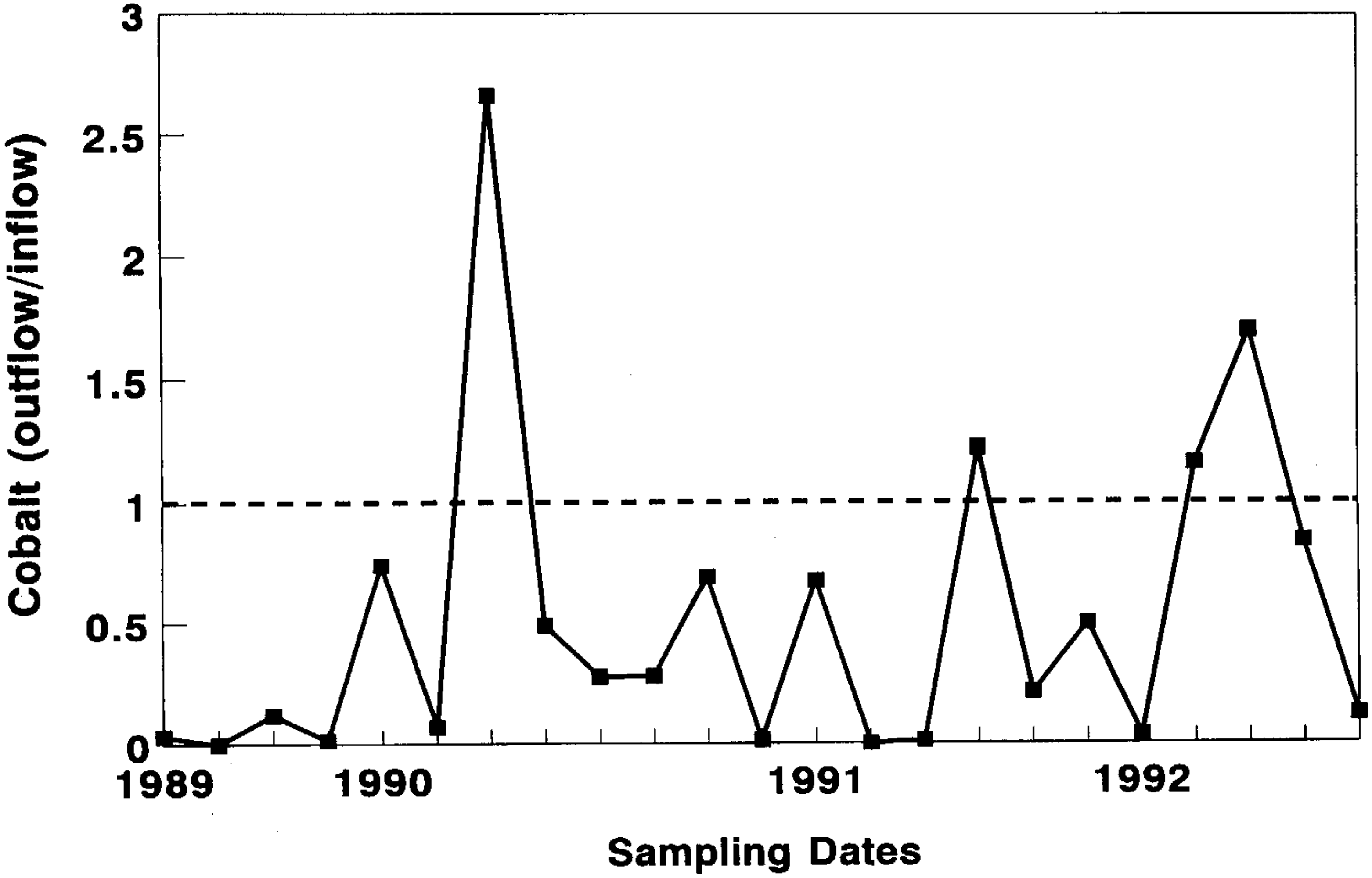

Figure 20. Removal of cobalt by a constructed wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

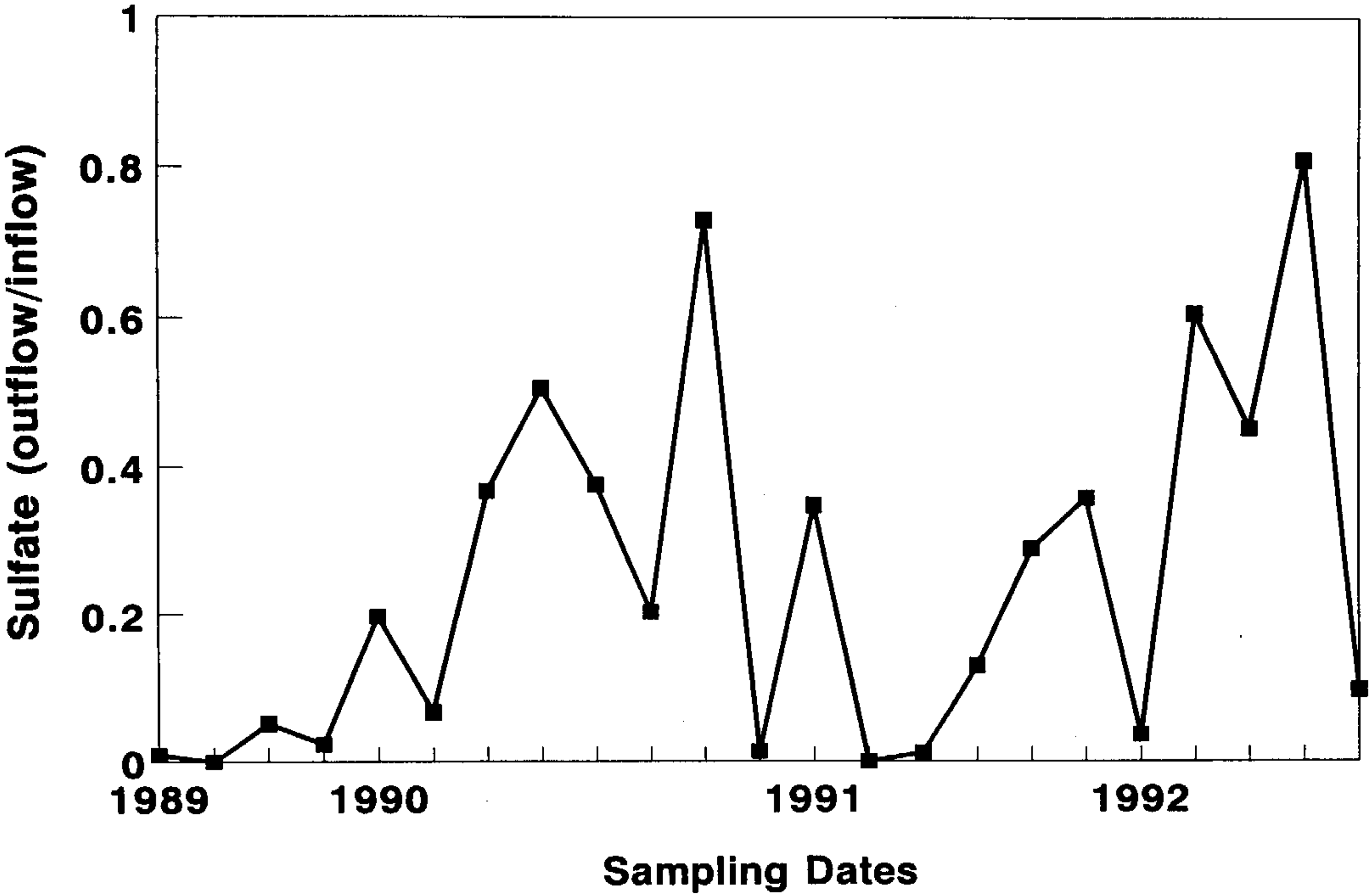

Figure 21. Removal of sulfate by a constructed wetland system on Jones Branch treating acid mine drainage (June 1989 - May 1992).

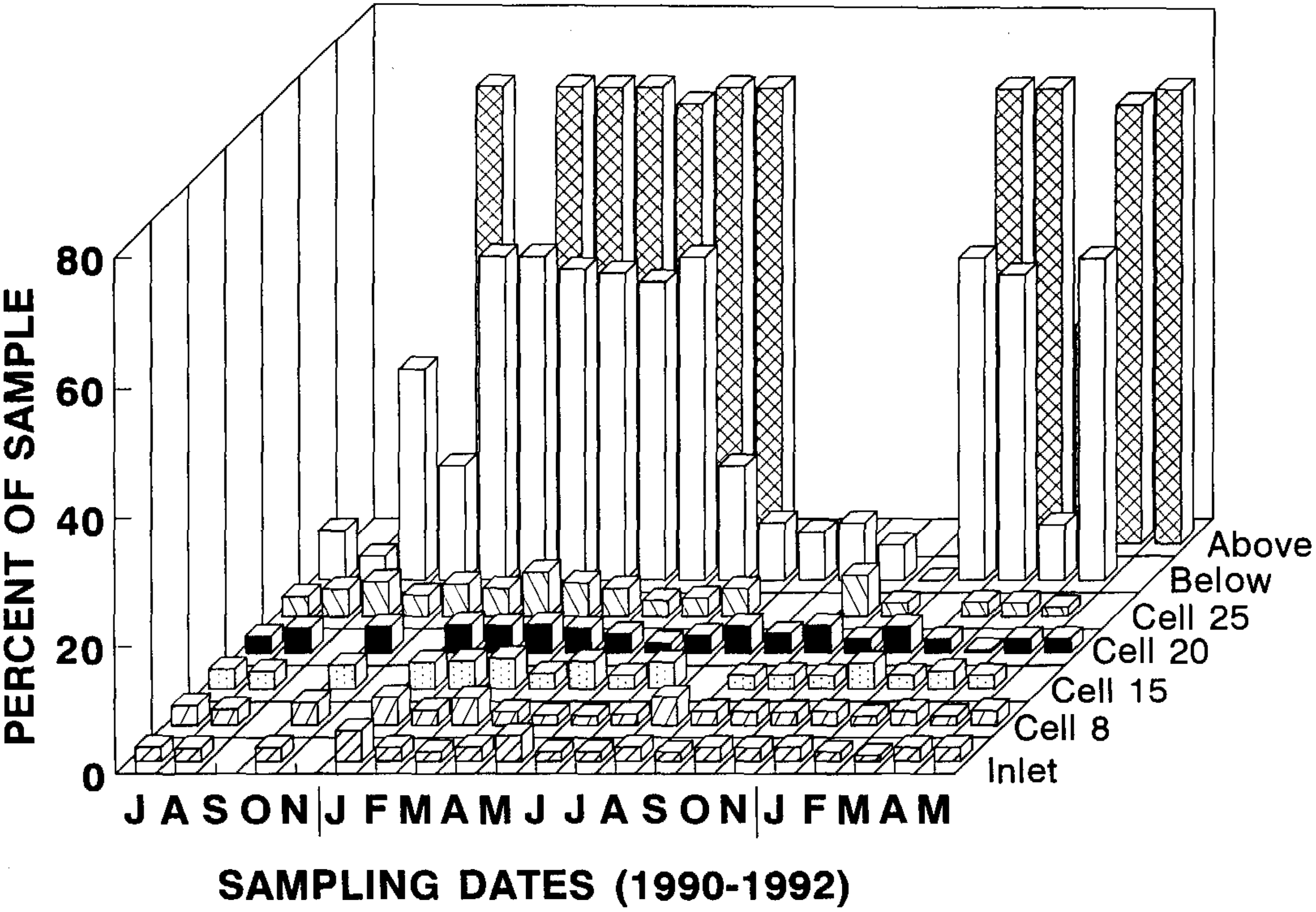

Figure 22. LC_{50} values for water from a constructed wetland system treating acid mine drainage, determined in a 48-hr static test with 1-3 day fathead minnow larvae.

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APPENDIX

TABLE A-1. Comparison of water quality characteristics of initial (field) samples of acid mine drainage water from a constructed wetland system with the same samples held for up to 72 hours (lab) at 4°C and used in 48-hour static bioassays with fathead minnow larvae.

SITE	DATE	WATER SAMP.	pH	COND µmhos	Al mg/L	B mg/L	Co mg/L	Fe mg/L	Mg mg/L	Mn mg/L	Ni mg/L	Pb mg/L	Zn mg/L	SO4 mg/L
Above	2/92	Field	4.22	82	0.39	0.01	0.003	1.57	1.97	0.17	0.01	ND[1]	0.01	26
		Lab	4.10	92	0.32	0.01	0.001	0.10	1.78	0.14	0.01	0.09	0.03	24
	3/92	Field	4.36	56	0.22	0.01	ND	1.91	1.49	0.09	0.003	ND	0.01	29
		Lab	ND	ND	0.18	ND	0.003	0.51	1.44	0.07	ND	ND	0.03	18
	4/92	Field	4.35	75	0.25	0.01	ND	0.45	1.81	0.15	0.01	ND	0.02	21
		Lab	4.42	65	0.23	0.01	0.001	0.06	1.59	0.14	ND	ND	ND	23
	5/92	Field	4.23	85	0.33	0.004	ND	0.18	1.93	0.19	ND	ND	ND	24
		Lab	4.17	85	0.30	0.01	0.001	0.716	2.04	0.20	0.01	0.002	0.04	31
Inlet	2/92	Field	3.26	4800	42.1	1.44	0.64	1150	127	17.5	0.89	2.20	0.76	4200
		Lab	2.68	4860	42.8	1.21	0.44	888	128	17.6	0.89	1.84	0.71	4600
	3/92	Field	3.85	4490	39.4	1.48	0.42	1056	128	17.4	0.87	1.26	0.71	4100
		Lab	ND	ND	39.4	0.81	0.13	1232	126	16.9	0.48	0.50	0.68	4500
	4/92	Field	3.49	4840	39.5	1.54	0.64	1240	129	16.3	0.83	2.22	0.68	4500
		Lab	3.60	4430	42.0	0.72	0.13	1257	127	17.2	0.47	0.32	0.65	4100
	5/92	Field	3.27	4960	26.9	0.78	0.13	1440	148	19.8	0.40	0.51	0.53	4500
		Lab	3.26	4960	25.4	0.78	0.14	1389	145	19.7	0.41	0.40	0.73	4500

TABLE A-1 - continued.

SITE	DATE	WATER SAMP.	pH	COND μmhos	Al mg/L	B mg/L	Co mg/L	Fe mg/L	Mg mg/L	Mn mg/L	Ni mg/L	Pb mg/L	Zn mg/L	SO4 mg/L
Cell 8	2/92	Field	2.89	5000	42.7	1.59	0.74	1001	128	17.5	0.92	2.35	0.84	4400
		Lab	2.56	4420	37.5	1.19	0.43	780	130	17.4	0.81	2.05	0.79	4420
	3/92	Field	3.04	4330	33.7	1.18	0.40	913	114	15.4	0.69	1.27	0.62	3600
		Lab	ND	ND	34.8	0.76	0.11	1060	115	15.5	0.42	0.46	0.72	3900
	4/92	Field	2.94	4980	40.0	1.45	0.60	1048	120	16.5	0.77	2.05	0.67	4200
		Lab	2.93	4480	40.2	0.71	0.14	1172	122	16.7	0.48	0.32	0.66	4100
	5/92	Field	2.69	4720	36.8	0.81	0.13	961	133	17.7	0.47	0.42	0.61	4000
		Lab	2.67	4720	36.4	0.74	0.13	1179	137	17.9	0.46	0.38	0.69	4100
Cell 15	2/92	Field	2.93	4800	38.2	1.45	0.67	947	119	16.3	0.83	2.13	0.74	4300
		Lab	2.61	4280	42.5	1.25	0.45	849	129	17.7	0.92	1.88	0.73	4100
	3/92	Field	2.93	4120	30.5	1.10	0.37	750	104	14.1	0.64	1.19	0.56	3400
		Lab	ND	ND	31.7	0.68	0.10	970	105	14.2	0.39	0.43	0.58	3800
	4/92	Field	2.86	4950	38.7	1.59	0.59	1048	116	16.0	0.85	2.37	0.66	4400
		Lab	3.01	4600	39.4	0.70	0.13	1116	123	16.6	0.47	0.31	0.64	4000
Cell 20	2/92	Field	2.88	4800	38.6	1.52	0.74	891	126	17.1	0.84	2.22	0.79	4300
		Lab	2.70	4080	37.5	1.16	0.42	813	119	16.4	0.84	1.73	0.67	3800
	3/92	Field	2.83	3950	28.0	1.06	0.35	651	99.6	13.4	0.61	1.12	0.52	4600
		Lab	ND	ND	29.3	0.66	0.10	827	102	13.6	0.37	0.65	0.53	3400
	4/92	Field	2.80	4980	40.0	1.55	0.75	1048	118	16.1	0.78	2.32	0.66	4600
		Lab	2.88	4570	37.9	0.69	0.13	1086	122	16.4	0.47	0.30	0.65	4100

TABLE A-1 - continued.

SITE	DATE	WATER SAMP.	pH	COND µmhos	Al mg/L	B mg/L	Co mg/L	Fe mg/L	Mg mg/L	Mn mg/L	Ni mg/L	Pb mg/L	Zn mg/L	SO4 mg/L
	5/92	Field	2.60	4680	35.8	0.81	0.13	803	125	16.8	0.45	0.37	0.63	4000
		Lab	2.56	4680	37.9	0.70	0.12	942	133	17.7	0.47	0.37	1.63	4000
Out-let	2/92	Field	2.82	4800	35.3	1.42	0.49	905	121	17.8	0.79	1.42	0.76	4400
		Lab	2.61	4210	39.4	1.21	0.45	770	127	17.4	0.84	1.91	0.72	3900
	3/92	Field	2.79	3820	26.5	1.10	0.37	558	97.3	13.1	0.60	1.16	0.53	3100
		Lab	ND	ND	28.1	0.60	0.09	732	99.6	13.2	0.36	0.63	0.54	3500
	4/92	Field	2.74	4990	39.7	1.53	0.66	1038	135	16.3	0.79	2.08	0.70	4500
		Lab	2.78	4640	39.3	0.69	0.12	1008	124	16.8	0.46	0.30	0.64	3900
Below	2/92	Field	3.45	420	1.18	0.06	0.05	34.9	6.77	0.93	0.17	0.08	0.01	170
		Lab	3.03	529	1.22	0.04	0.03	40.5	6.54	0.90	0.03	0.06	0.05	190
	3/92	Field	3.14	692	2.28	0.09	0.04	46.4	8.79	1.20	0.05	0.10	0.03	260
		Lab	ND	ND	2.22	0.05	0.01	47.7	9.01	1.14	0.03	0.05	0.04	310
	4/92	Field	2.87	1760	8.45	0.38	0.17	240	29.8	3.96	0.19	0.51	0.18	1000
		Lab	2.93	1530	8.54	0.17	0.03	202	28.1	3.95	0.10	0.05	0.12	826
	5/92	Field	3.88	647	0.99	0.06	0.01	69.3	13.7	2.52	0.02	0.06	0.002	340
		Lab	3.92	647	0.99	0.06	0.02	61.9	13.2	2.52	0.03	0.04	0.04	340

[1] ND = not determined