Ohio on State Route 541 at the Woodbury Wildlife Preserve

Re-mining and FGD Seal Placement for AMD Abatement at Broken Aro Mine

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Abstract

Re-mining has the benefits of recovering an energy reserve not usually accessible because of abandoned underground mines.? The hidden dangers of abandoned underground mines during re-mining include: mine gases, unstable roof, volumes of acid water, and unstable highwall.? However, re-mining offers exposure of the AMD source and dewatering of the mine complex.? Additionally, re-mining allows for simple placement of a continuous mine seal which would be effective for multiple openings and additional entries.? Re-mining of the coal reserve is not economically feasible for the coal company due to AMD responsibilities.? Thus a joint effort between ODNR-DMR, R&F Coal, and AEP allowed for a controlled test site to evaluate re-mining as an AML restoration and AMD abatement technique.

An abandoned underground mine complex last mined in 1910 in Coshocton County, Ohio, Broken Aro mine is located on Woodbury wildlife area, seven miles west of Coshocton.? The site forms the headwaters of the Simmons Run Watershed.? This paper will present the planning and completion of the re-mining effort and the FGD seal placement.? Preliminary and post-mining water quality monitoring is used as an indicator as to the effectiveness of the AMD abatement.? Included in the environmental assessments are 24 surface water locations and 14 monitoring wells.? Mine inundation is evaluated through water levels in the wells and subsequent water quality monitoring is utilized to assess mine flooding effects on water quality both inside and outside of the mine openings.

Introduction

The Broken Aro Mine site is located about seven miles west of Coshocton, Ohio on State Route 541 at the Woodbury Wildlife Preserve.? The surface and groundwater runoff from the mine forms the headwaters of Simmons Run.? A No. 6 and a deeper No. 5 coal seam on the 40-acre site have been mined by means of underground mining in the 1910?s.? The mining operations produced acid mine drainage (AMD) which polluted receiving streams with acidity and heavy metals, killing aquatic and plant life.? To prevent this pollution from continuing, a design for keeping the water inside the mine was developed with the cooperation of the Ohio Department of Natural Resources (ODNR), R&F Coal Company, American Electric Power (AEP), and Ohio University.? This paper will give a background of the Broken Aro Project, describe the FGD seal design, and demonstrate its effectiveness.

Remining was selected as the best option to economically extract remaining coal deposits and provide an opportunity to employ abatement technology.? The groundwater was sealed inside the underground mine to inundate the mine voids with water, removing the air to minimize oxidation and reduce stream pollution.? The seal was made from a chemical by-product produced in coal-fired power plants called fixated flue gas desulfurization (FGD) sludge.? The FGD seal has a low hydraulic conductivity, which limits water from seeping out of the underground mine.? It also has high alkalinity which can neutralize the acidic waters of AMD if water does escape from the mine.

This document gives a brief background of acid mine drainage chemistry and its effects, and a discussion of the impact the fixated FGD seal has had on the water quality thus far.

Acid Mine Drainage (AMD) Chemistry

Acid mine drainage impacts streams, rivers, lakes, and groundwater in several ways and needs to be treated before entering into receiving waters.? Acidity, ferric ion (Fe^{3+}) precipitation, oxygen depletion, and the release of heavy metals, such as aluminum (Al^{3+}), zinc (Zn^{2+}), and manganese (Mn^{2+}) are the pollutants associated with coal mining.? Acid mine pollution is caused by the physical and chemical weathering of iron pyrite (FeS_2), also known as ?fool?s gold.?? The level of acidity and the concentration of the heavy metals is a function of the amount of pyrite in the area around the mine.

Physical weathering is essential to reduce the grain size of the pyrite.? The early miners inadvertently accelerated this process by grinding up the ore and dumping the overburden in mine tailings.? The next step in this geochemical process is the chemical oxidation of the pyrite shown below (Stumm and Morgan, 1996):

$2\ FeS_{2(s)} + 7\ O_{2(g)} + 2\ H_2O_{(l)}$?? ? ?$2\ Fe^{2+}{}_{(aq)} + 4\ SO_4{}^{2-}{}_{(aq)} + 4\ H^+{}_{(aq)}$???????? (1)

When the pyrite is exposed to oxygen and water, it reacts to form sulfuric acid (H_2SO_4), which is the combination of the hydrogen ions and the sulfate ions.? This causes a decrease in pH (acidic).? The Fe^{2+} ions (ferrous) are released into the runoff waters from drainage tunnels or tailings piles.? Next, the Fe^{2+} ions (ferrous) are oxidized to Fe^{3+} ions (ferric) as shown in the following reaction.

$4\ Fe^{2+}{}_{(aq)} + O_{2(g)} + 4\ H^+{}_{(aq)}$?? ??? $4\ Fe^{3+}{}_{(aq)} + 2\ H_2O_{(l)}$?????????(2)

The Fe^{3+} ions now hydrolyze in water to form iron (III) hydroxide [$Fe(OH)_3$].? This process releases more hydrogen ions into the environment that continues to reduce the pH.? The iron (III) hydroxide formed in this reaction is referred to as ?yellow boy,? which is a yellowish-orange precipitate that turns the acidic runoff in the streams to an orange-red color and covers the stream bed with a slimy coating.? The iron (III) hydroxide precipitate kills plants and fish by reducing the amount of light for photosynthesis and smothering aquatic life and their food resources on the stream bottom.? Also, the low pH of the water makes it difficult for aquatic life to survive.? The following equation describes this reaction.

$4\ Fe^{3+}{}_{(aq)} + 12\ H_2O_{(l)}$?? ? ?$4\ Fe(OH)_{3\ (s)} + 12\ H^+{}_{(aq)}$??????????(3)

Pyritic mine tailings leach AMD, in a large part due to the metabolic activity of *Thiobacillus ferrooxidans* (Wildeman et al, 1993).? These acidic-tolerant bacteria serve to catalyze the oxidation of the pyrite in Equation 1, 2, and 3 above, thereby increasing the amounts of acidity and iron imposed on the environment.

Complex systems in nature such as mine tailings and mine drainage tunnels cannot be described by just a few equations.? Other chemical reactions which may take place are shown in Equation 4 (Sobek et al, 1978).

$FeS_{2(aq)} + 14\ Fe^{2+}_{(aq)} + 8\ H_2O_{(l)}$? $15\ Fe^{3+}_{(aq)} + 2\ SO_4^{2-}{}_{(aq)} + 16\ H^{+}_{(aq)}$ (4)

In addition, sulfides of copper, zinc, cadmium, lead, and arsenic will undergo similar chemical reactions resulting in the contribution of toxic metal ions in polluted mine streams.

It is the oxygen requirement in Equations 1 and 2 that are exploited in mine sealing for AMD abatement.? Notice that, if the iron pyrite is never oxidized or exposed to the atmosphere, the pollution caused by AMD could be eliminated.? Therefore, if groundwater could be trapped inside to the point of inundation in an underground mine, the air in the mine voids would be forced out, thus preventing the oxidation reaction.? The FGD seal at Broken Aro was designed to retain the groundwater inside the mine to a level above the highest roof elevation, thus minimizing the availability of oxygen inside the mine.

Remining for the Purpose of FGD Seal Placement

Remining was the strategy used at Broken Aro to benefit the environment, industry, and the public.? Remining operations ultimately accomplished three goals.? First, it recovered remaining coal reserves left from previous mining operations.? Second, remining allowed for the reclamation of the Broken Aro site and the placement of the FGD seal in order to achieve current environmental standards.? Sites that are remined and reclaimed reduce environmental pollution, remove health and safety hazards, and considerably improve aesthetic properties (Skousen, 1996).? Third, the State of Ohio, AEP, and R&F Coal Company were able to share financial and regulatory burdens so that the remining operation was possible.? The normal barriers of an insufficient coal reserve, liabilities due to poor, preexisting water quality, and seal material experimentation can be overcome with this kind of cooperative partnership.

Installation of the FGD seal began concurrent with the continued remining effort in June 1997.? A series of open pits were excavated to recover remaining coal in the remining operation.? The construction of the seal started adjacent to the exposed highwall with the excavation of a keyway trench which was five feet wide and one foot deep in the pit floor. The FGD material was delivered to the site as needed with a moisture content of about 75%.? It must be placed and compacted within ten days of production to achieve optimum performance.? The FGD seal itself was constructed in two four-foot lifts at least 10 feet wide (Mafi et al, 1998).

The first lift of the seal was constructed by placing the FGD material into the open pit and the keyway trench.? The FGD material was forced into mine openings and compacted using a dozer.? The compacted first lift was sufficient to cover the face of the exposed coal seam.? After the first lift was installed, mine spoil from the adjacent pit was pushed into the current pit floor and used in the leveling of the first lift.? This allowed trucks to transport the second lift of FGD without damaging the first.

The second lift was placed on top of the first lift, and the FGD material was pushed into the highwall with a dozer to fill and compact the lift.? The now, compacted FGD seal was a minimum of eight feet above the pit floor.? The top surface of the second lift was sloped gradually away from the highwall.? This was to ensure that infiltration waters would be diverted away from the highwall and off the seal.

All deep mine openings that were encountered during seal placement were handled accordingly.? Openings were sealed from floor to roof by pushing FGD material as far back into the entrance as possible.? Also, care was taken to ensure that there were no gaps between mining pits.? This guaranteed that the mine seal was constructed continuously along the length of the highwall.? Additional compaction was produced from the placement of overburden above the mine seal from the next pit.

The Goal of the FGD Seal

The ultimate goal of the seal was to limit the amount of water escaping from the underground mine substantially, not to completely seal all the water in the mine.? It would be impossible to seal all the water in the mine especially with the increasing head pressure due to the rising water level.? Inside the mine, there is an infinite amount of pyrite but a small amount of oxygen, comparatively. Outside the mine, the amount of these two constituents is opposite.? Any pyrite that escapes is oxidized immediately, but the FGD seal limits the amount of pyrite that can escape.? The hope is that the amount of AMD that is produced can safely be treated by means of natural attenuation, and therefore it will not be a threat to water quality further downstream.? Also, the FGD seal limits the amount of oxygen that can infiltrate into the mine.? The oxidation reaction is the culprit of the pollution.? If the seal can limit the occurrence of this reaction, then a large amount of the AMD pollution has been prevented.? The water quality inside the mine will not improve until all the void space is filled with water so that remaining oxygen is forced out and pollution-causing reaction can be eliminated.

The main goal is to reduce the mass loadings of the pollutants, and that can be accomplished one of two ways.? Either the flowrate can be decreased, or the concentrations of the pollutants can be reduced.? The FGD seal obviously reduces the flowrates of water to the receiving streams, but the construction of limestone channels and sedimentation/settling ponds can help passively decrease the concentrations of pollutants such as iron, sulfate, and acidity.? Mass loadings will be the main part of discussion in the Results section of this report.

Environmental Monitoring

Sampling Locations

On the Broken Aro site, there are 15 surface water locations that are sampled and tested.? The surface water locations are D1, D1A, D4, DM2, DM2Z, DM4A, DM4B, S4, S5, U1, U4, U5, U6, U7, and U9; where D = downstream, DM = deep mine, S = seep, and U = upstream.? The locations are made up of underground seeps, ponds, streams, and stormwater runoff from the mine.? Also, there are 8 underground wells situated in four pairs that were drilled deep into the mine.? The wells are MW1, MW2, MW3, MW6, MW7, MW8, MW11, MW12; where MW = monitoring well.? Further, in September 1998, six additional monitoring wells were installed: MW4, MW5, MW9, MW10, MW14, MW15.? The groundwater within all of these wells are sampled and tested also.? Figure 1 depicts a map of all these locations on the Broken Aro site.? The samples at the 23 total locations are tested in the field and the laboratory for specific water quality indicators.? Sampling began April 23, 1997 with the first five sampling events performed in two-week intervals.? Subsequent sampling events occur once every month.

For each stream location, three tasks are performed in the field.? First, preserved and unpreserved samples are obtained.? Second, field evaluations for water quality indicators are performed.? Finally, the flowrate is measured for each stream location.? At the well locations, the water level elevation, and the depth of the well is measured first.? Then, unfiltered, unpreserved and filtered, preserved groundwater samples are obtained.? Finally, field evaluations for water quality indicators are performed.? The water quality field tests and their procedures are the same for the stream locations and the well locations and are reviewed in a subsequent section of this paper.

Once samples have been collected from each location, they are transported to Coshocton Environmental Testing (CET) for laboratory analysis.? This is done at the end of the same day of the sampling event.? A complete description of all analyses run on each sample is provided later in this paper.

Field Water Quality Assessments

The field tests must be conducted and recorded for each stream and/or well location.? The pH, temperature, specific conductivity, total dissolved solids (TDS), and the reduction/oxidation potential (ORP) are measured directly in the field using specific probes.? Then, 3% peroxide (H_2O_2) is added to the sample cup.? The peroxide causes the sample to fully oxidize if it has not done so already.? Next, the pH and ORP are tested for the oxidized sample to see if it has changed (Standard Methods, 1996).? Often, the pH goes down showing the release of hydrogen ions (H^+) in the oxidation process.? In the streams, the flowrates are measured using different devices such as a weir, flume, current meter, or culvert depending on the location.? This enables the calculations of mass loadings from concentration data obtained in the laboratory.

Laboratory Water Quality Assessments

Each location is tested in the laboratory for the following constituents: pH, total acidity, total alkalinity, bicarbonate alkalinity, carbonate alkalinity, specific conductance at 25 ?C, total non-filterable residue, total dissolved solids, sulfate, chloride, total calcium, total magnesium, total sodium, total potassium, total iron, total manganese, total aluminum, hardness.? The trace compounds analyzed are: total zinc, phosphate, copper, chromium, arsenic, barium, cadmium, lead, mercury, selenium, silver, cobalt, boron, total nickel, bromide, and total molybdenum.? All constituents were tested for the first year.? Subsequently, the trace metals are only analyzed on a quarterly basis.

Effectiveness of the FGD Seal

The effectiveness of the seal to date can be seen via examination of the data collected as a function of time.? Sampling events began on a regular basis two months prior to the start of the installation of the FGD seal.? Therefore, one can see the effects of remining and dewatering activities and any immediate effect the FGD seal had on the AMD pollution.? The FGD seal has been in place for about 17 months, and the last sampling event occurred on November 24, 1998.? Surface water location D1A is used as an indicator of effectiveness due to its critical location at the boundary of the mining areas.? Also, the water level elevations in the monitoring wells will be used to demonstrate how the FGD seal developed and maintained flooding of the underground mines.? Finally, chemical concentration profiles of the monitoring wells will be utilized to demonstrate water quality improvements inside the mine.

Figure 2 presents the water levels in the eight original monitoring wells as a function of time.? It is apparent that the water levels inside the underground mine has risen to an elevation of 1035 feet above sea level and decreased slowly to 1032 feet where it is starting to plateau.? The water inside the mine is monitored by wells MW3, MW7, and MW11.? Monitoring wells MW6, MW8, and MW12 are situated under the deep mine, and they describe the water level and water quality in that area.? Monitoring well MW2 is located in a perched aquifer, and the water level is much higher than in the other wells.? It should be noted that some vertical connectivity exist between the mine and MW8 as seen by the water elevation in that well.? Also, MW1 has remained dry since the start of the project and is therefore not presented.

The strongest indicator of an effective mine seal is that the water levels in the wells increased at a rate of approximately 1.0 to 1.5 feet per month ever since the completion of the FGD seal in August 1997 through May 1998.? The negative slopes in the early dates in this study represent a decrease in the water level in the wells.? This is due to the fact that the mining activity and the FGD seal construction during the spring/summer 1997 sampling events disturbed some of the mine openings and allowed for dewatering of the underground mine complex.? In general, the wells screened within the mine consistently show water levels 8-10 feet above pre-mining levels and approximately 15 feet above the dewatered mine levels.

The water levels and quality of MW3 and MW6 will be used as typical of groundwater conditions since one is located under the mine and the other is located within the underground mine.? As can be seen in Figures 3, 4, and 5, the water quality of MW6 has remained relatively unchanged throughout the testing period with respect to acidity, sulfate, and total iron concentrations.? This is a good indicator that the AMD has remained inside the mine and has not descended into a lower geologic formation.

Figures 6 and 7 present sulfate and total iron loadings at location D1A.? Sulfate loadings were over 1100 kg/day during the remining in May of 1997, decreasing to 480 kg/day at the end of 1998.? This constitutes a reduction in sulfate load to the watershed of 56%.? The iron loadings have decreased in even a more drastic manner, from 43 kg/day during remining operations to about 1.5 kg/day at the end of November of 1998.? This is equal to a 96% reduction in total iron load off-site.? It is important to either lower the concentration of the contaminants or the flowrate so that ultimately the loading decreases.? In this case, the concentrations and the flowrate have consistently decreased, which is optimal for reduction.

Discussion

There is a seep at location S5 where it?s flowrate has increased ever since construction was performed near the site of this seep.? It is believed that the drainage from this seep flows from the underground mine on the east side of County Road 17, where the FGD seal was not installed (see Figure 1).? The sulfate, iron, and acidity loadings have increased substantially due to the higher flowrates which were caused by the exposure of the seep.? For example, the acid load has increased from a net zero acidity to an average of 14 kg/day after exposure.? This is more of an observation than a problem area due to the low loading rate in which natural attenuation can provide reduction.? However, some environmental load to Simmons Run does originate from outside the study area.

The impact of the additional hydrostatic head which is a result of mine sealing will continue to be monitored.? New seeps appearing outside of the FGD seal will be added to the monthly sampling schedule and carefully observed.? It may be a number of years until a hydrogeologic steady state is established.

Surface water location DM2Z was added to the list of surface water locations in May 1998 to investigate the effect of an oxic limestone channel (OLC) on the waters coming from the underground mine itself.? The OLC carries flow from the outlet of the perforated pipe (DM2Z) into the sedimentation pond at location DM2.? The OLC has increased the pH and reduced the sulfate and iron concentrations.? Further studies, including non-native ion tracers, will be employed using the newly installed monitoring wells to determine the origin of the seeps outside of the FGD seal.

Water quality within the mine complex has begun to show signs of improvement.? It is believed that the mine has become fully inundated and most air was forced out so that the oxidation reaction can be eliminated.? In MW3, the sulfate, iron, and acidity concentrations have slowly decreased since remining and dewatering activities.? This is apparent in Figures 3, 4, and 5 of water quality in MW3.

Conclusion

The Broken Aro Project will continue to be monitored in years to come to determine the level of success of the fixated FGD seal.? To date, the FGD seal has shown that it has improved water quality inside the mine and has reduced loads to Simmons Run.? The site still needs to reach its hydrogeologic equilibrium to completely determine its effectiveness.? Acid mine drainage needs to be addressed in order to preserve our fish and wildlife, and the utilization of new materials such as FGD might prove to serve as a ?rising? technology.

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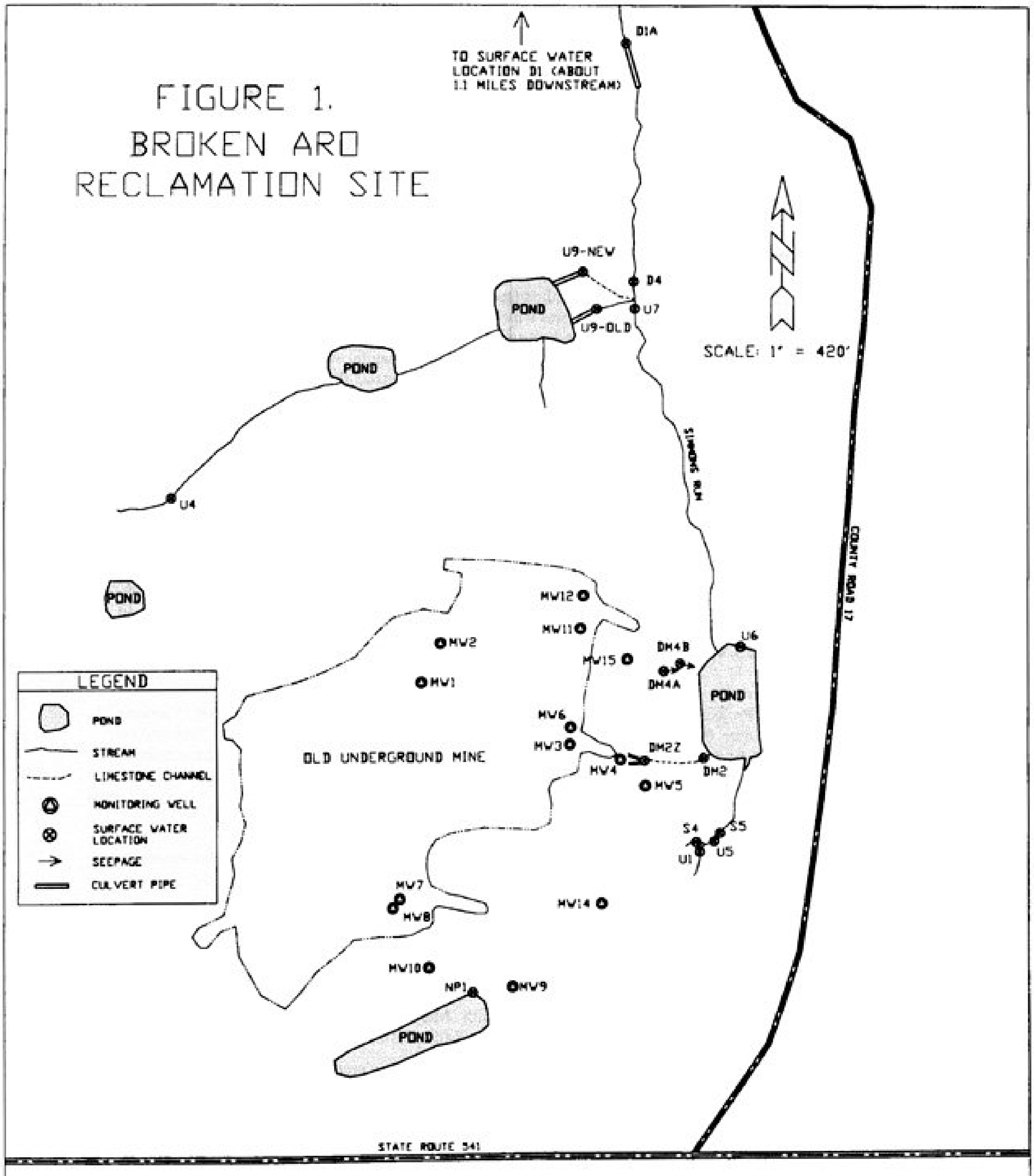
FIGURE 1.
BROKEN ARO RECLAMATION SITE



Broken Aro Reclamation Project
Drawn By: MTR
Drawn On: AutoCAD
Surveyed By: MTR & RAJ
Date: 8-18-98

FIGURE 2.
Water Level in Wells vs. Time

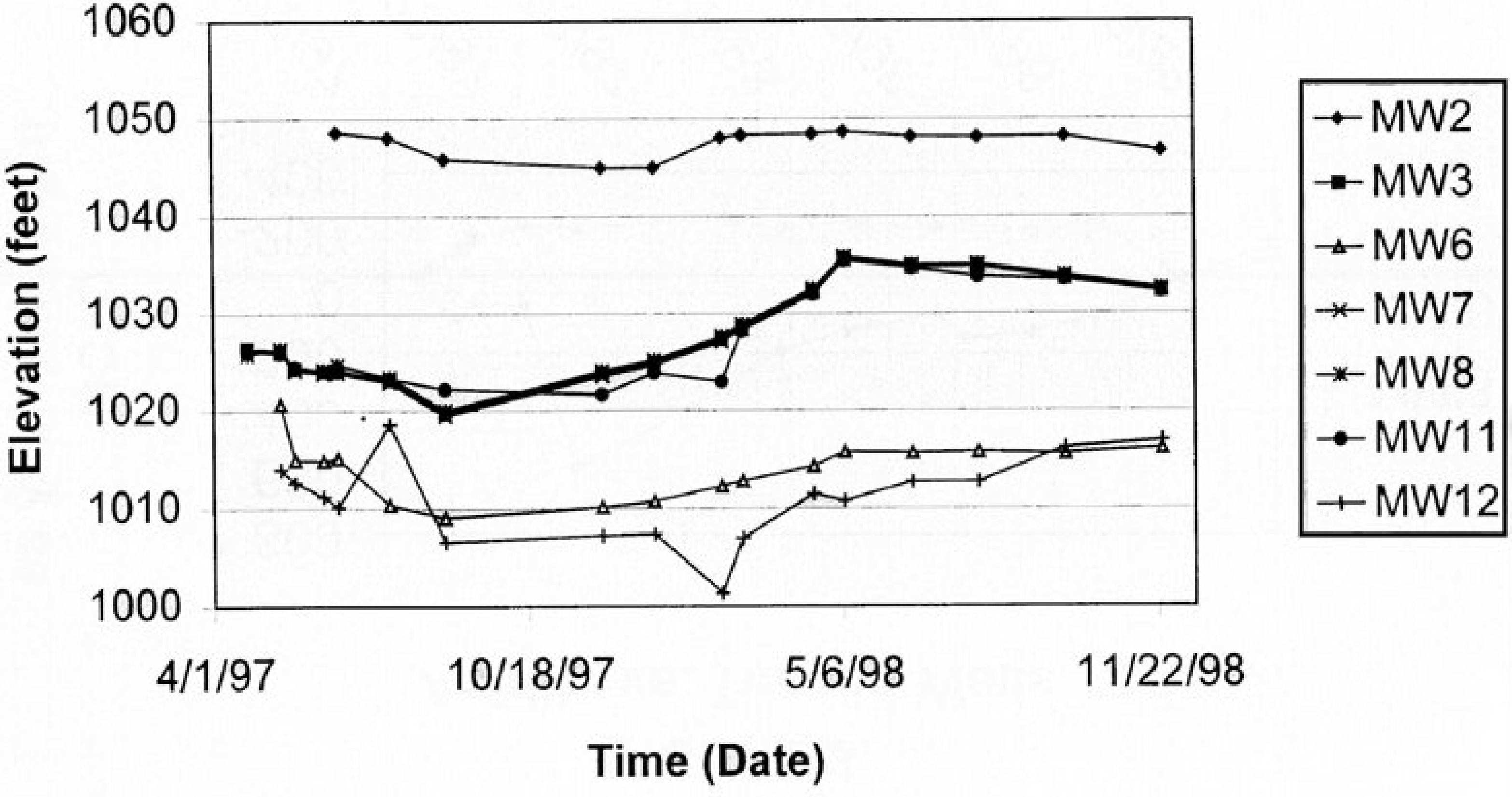


FIGURE 3.
Acidity vs. Time in Wells

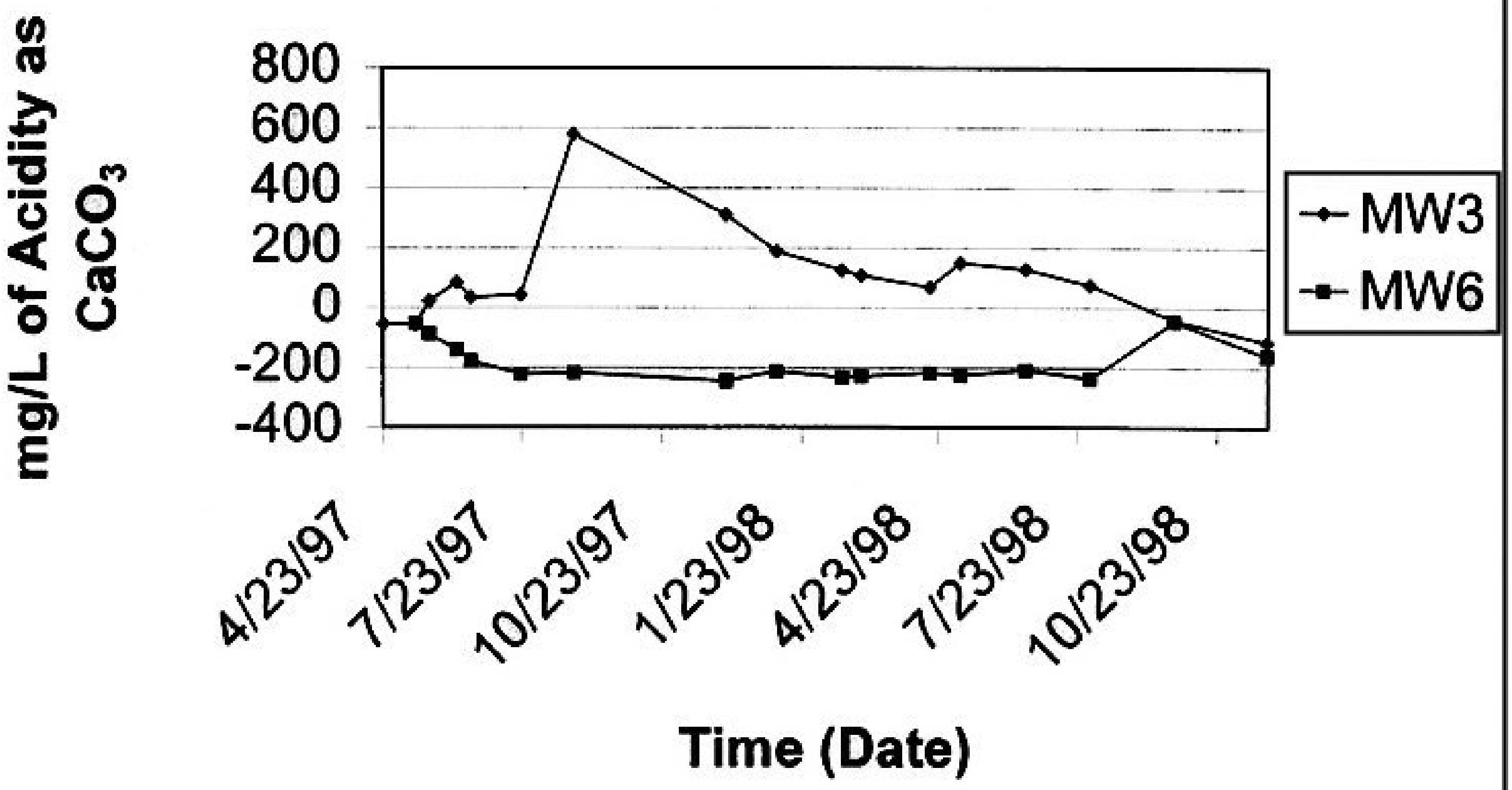


FIGURE 4.
Sulfate Concentration vs. Time

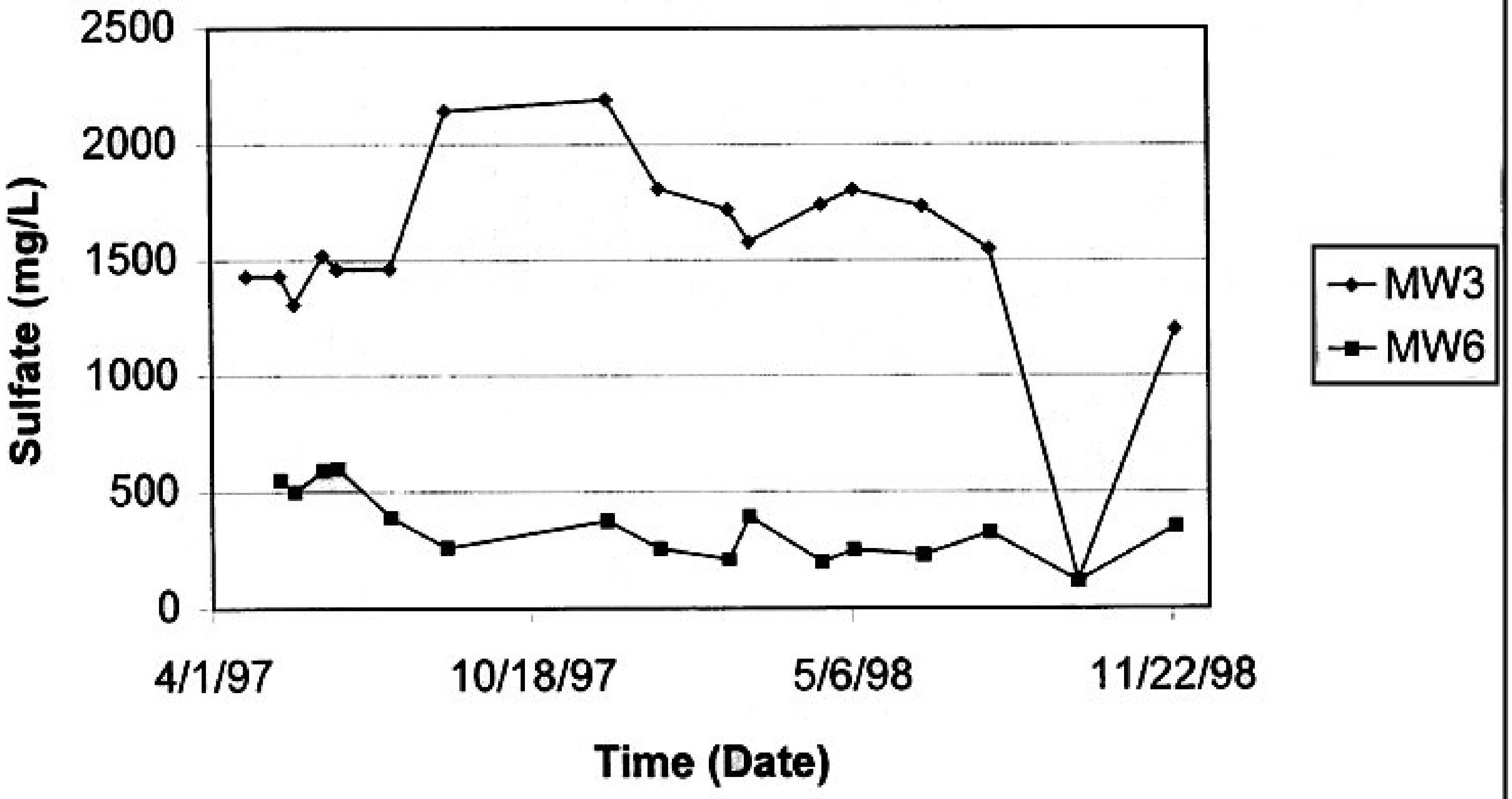


FIGURE 5.
Total Iron Concentration vs. Time

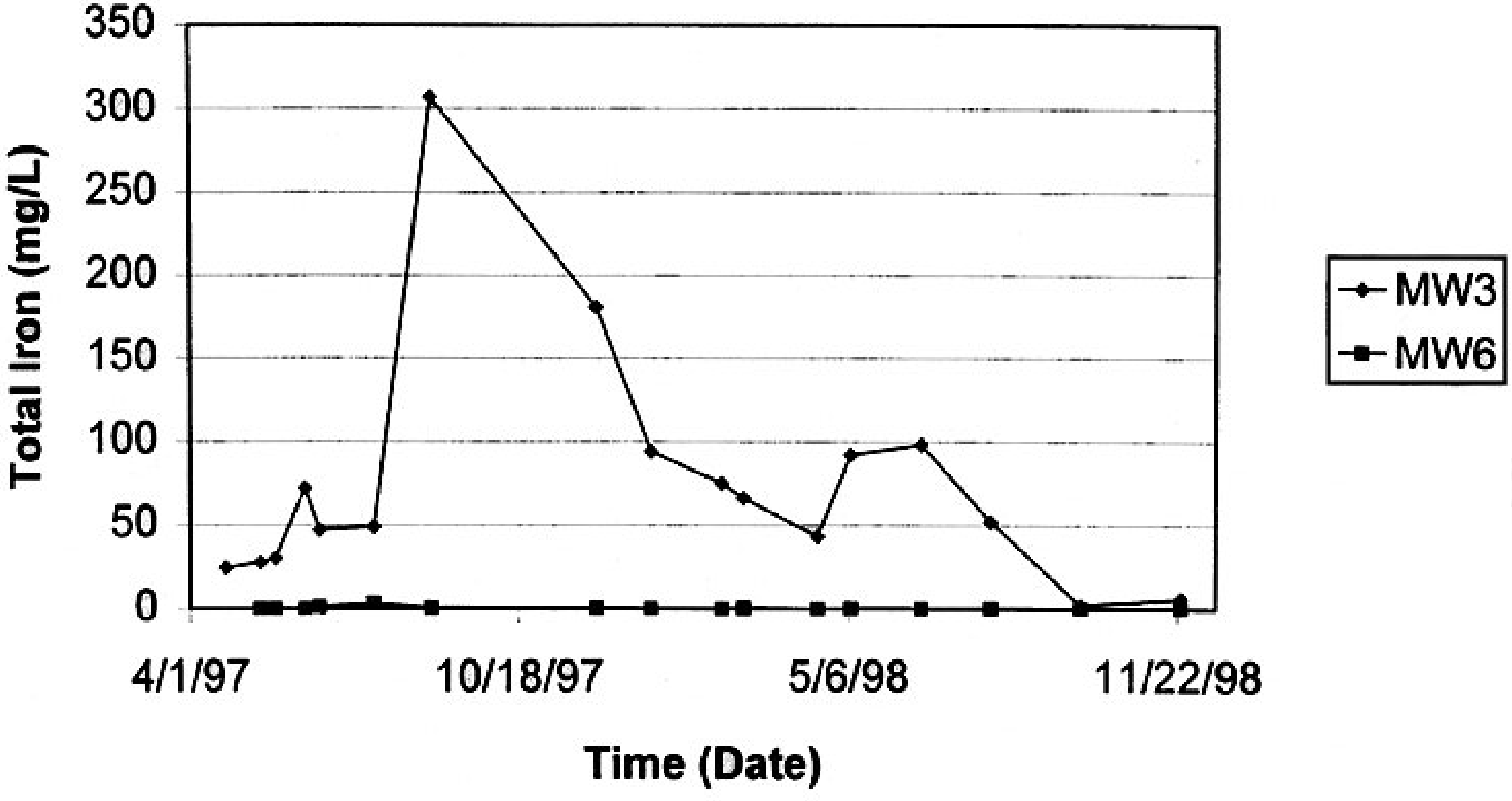


FIGURE 6.
Sulfate Load at Location D1A

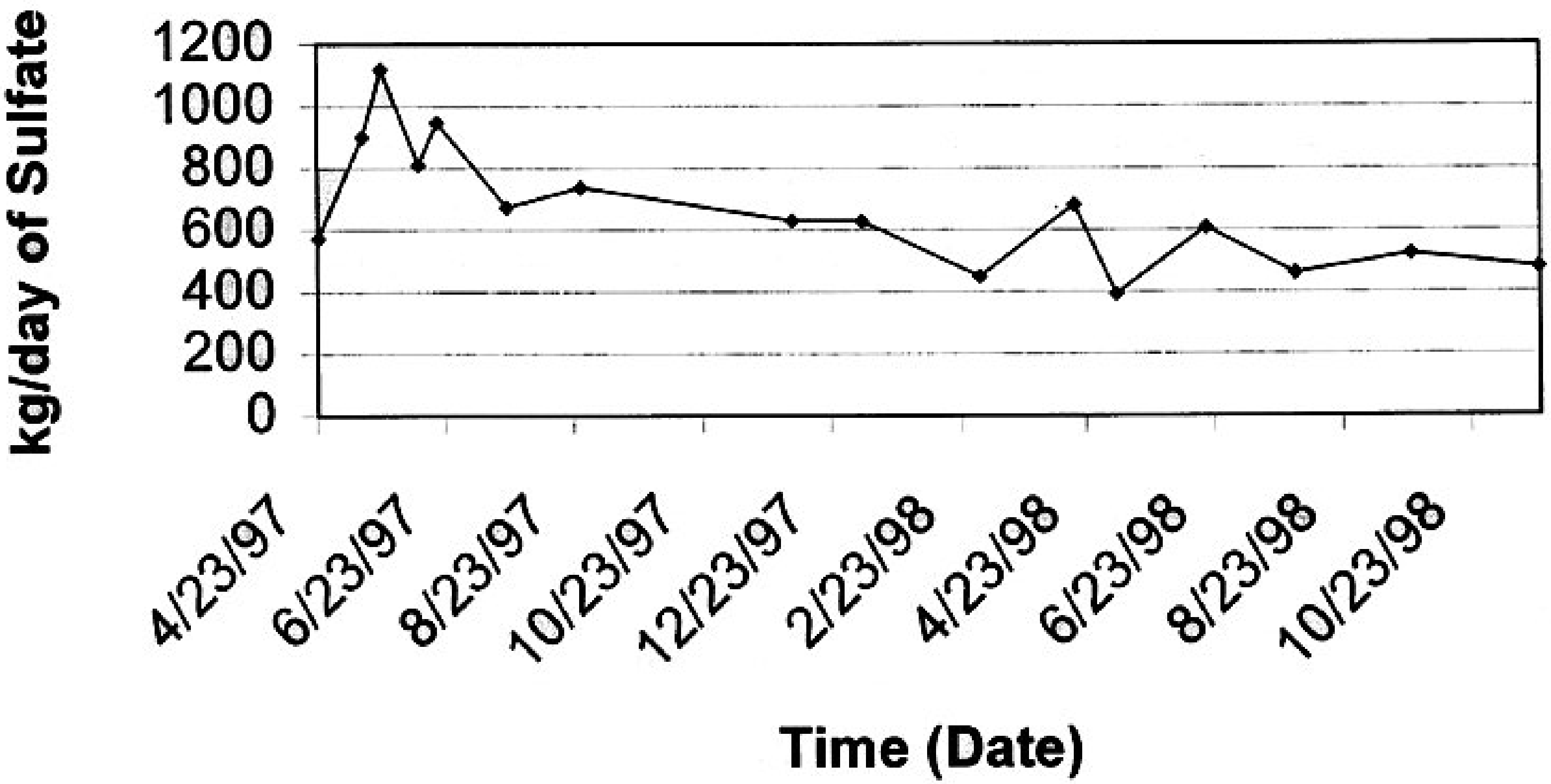


FIGURE 7.
Iron Load at Location D1A