ACID MINE DRAINAGE FROM INACTIVE EASTERN COAL OPERATIONS

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ABSTRACT

The most widely used technique for abatement of acid drainage from inactive surface mines and refuse disposal areas is revegetation of a soil cover applied to the waste material. Nonetheless, acid production often persists and, in some cases, limits establishment of vegetation. This paper reports on several field studies intended to determine the location of pyrite oxidation zones and migration pathways of oxidation products at inactive spoil and refuse sites.

Oxygen required for pyrite oxidation is believed to be provided in the gaseous state from the atmosphere. Therefore, the oxygen concentration in unsaturated mine waste should provide an estimate of the weathering tendency in the local environment. We are currently monitoring gas composition in refuse and spoil at six sites. Barren refuse appeared to be oxygenated ($>$2% O_2) in a shallow zone extending less than 1 meter below the surface during most of the year. Preliminary data from coal spoil showed that oxygen can be available throughout the unsaturated thickness, even at a revegetated site. Gas composition varied vertically and laterally at a single site and also appeared to show seasonal dependence.

Hydrologic factors are also important in acid production and transport. Discharge monitoring alone does not adequately describe the mass transport of acid products through the spoil. For example, at one reclaimed mine the

mean sulfate content in six monitoring wells ranged from 24% to 240% of the mean concentration at the discharge point. Sources of recharge and relative flow rates determine the contribution of a particular zone to overall discharge quality.

These basic studies of acid production and transport indicate some shortcomings of standard reclamation practices at certain sites. This information will be used to develop alternative abatement technology designed to mitigate acid production at the source.

INTRODUCTION

Acid production from coal mining wastes at inactive operations in the Eastern United States is a significant environmental problem. Applying soil cover and revegetating coal mine spoil and preparation plant refuse can significantly reduce the acid load that discharges from some inactive sites; at other sites, discharge water remains heavily contaminated. These latter sites require additional effort to control the pyrite oxidation responsible for acid drainage.

The Bureau of Mines is investigating the formation and transport of pyrite oxidation products at a variety of coal refuse disposal areas and inactive surface mines. Oxygen required for pyrite oxidation is probably supplied from the atmosphere. We are, therefore, studying the pore space gas composition within unsaturated refuse and spoil to identify probable zones of active pyrite oxidation. Hydrologic studies are being used to monitor acid loading in saturated coal mine spoil and the migration of pyrite oxidation products toward discharge points. A better conceptual model of these processes is required for the design of abatement strategies.

Pyrite Oxidation

Pyrite oxidation occurs by either of two pathways that can be differentiated by the oxidant. Oxidation of pyrite by oxygen can be summarized:

$$FeS_2 + 3.5O_2 + H_2O \longrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad (1)$$

This may occur as a purely chemical process or with catalysis by bacteria such as Thiobacillus ferrooxidans (1, 2). The ferric iron oxidation pathway is expressed:

$$FeS_2 + 14Fe^{3+} + 8H_2O \longrightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad (2)$$

This reaction is generally significant only under the acidic conditions necessary for ferric ion solubility (3). The oxidant must be supplied by ferrous iron oxidation:

$$14Fe^{2+} + 3.5O_2 + 14H^+ \longrightarrow 14Fe^{3+} + 7H_2O \qquad (3)$$

Catalysis by iron-oxidizing bacteria is required for this reaction to proceed at a significant rate in acidic solution (3-5). Both pathways result in the overall reaction stoichiometry shown in equation (1): 3.5 moles of molecular oxygen are consumed to produce 2 moles of sulfate.

The Role of Oxygen

Observed levels of acidity and sulfate in water that discharges from mined lands are orders of magnitude higher than could be produced from the oxidation of pyrite by oxygen dissolved in recharge ground or surface water (6). Dissolved oxygen concentration at saturation is on the order of 3 x 10^{-4} mol/L (7). According to the reaction stoichiometry, complete consumption of this oxygen by pyrite would yield 1.7 x 10^{-4} mol/L or 16 mg/L sulfate. Additional oxygen must be supplied from the atmosphere to produce the observed contaminant levels.

The rate dependence of the relevant reactions on oxygen partial pressure is not well understood. One published study describes oxidation of coal crusher reject in columns maintained under various gas atmospheres (8). Acidity and iron concentrations in drainage from the columns were used to monitor pyrite oxidation. Acidity production showed a two-thirds order dependence on oxygen concentration in the gas phase over the range 0.02% to 20% oxygen. Morth, et al (9) cite a study by Lau, et al (10) as evidence that the rate of pyrite oxidation is independent of oxygen at gas phase concentrations greater than 2%.

The iron-oxidizing bacteria that catalyze ferrous iron oxidation and accelerate the oxidation of pyrite by ferric iron are aerobic; however, they apparently have a low requirement for oxygen. Growth of Thiobacillus ferrooxidans cultures on pyrite was found to be independent of oxygen above a concentration of about 0.9% (11). In one unpublished study, large columns of crushed pyritic rock maintained under simulated field conditions stopped producing significant quantities of acidity when oxygen decreased below 1.6% of the gas volume (12). A field experiment conducted in a small underground mine showed that the acid production rate decreased when gaseous oxygen decreased to a few percent by volume (13).

The actual zero- or first-order dependence of the rate of pyrite oxidation on oxygen is important in determining the effectiveness of limiting oxygen availability as a means of pyrite oxidation abatement. If the reaction is first-order, the rate of acid production will be reduced by any decrease in oxygen availability. If, however, the reaction is zero-order above a certain limiting concentration, oxygen must be more rigorously excluded to reduce acid production. For the purpose of this paper, we will consider that gaseous oxygen concentrations of less than 2% by volume are potentially limiting to pyrite oxidation.

Several methods have been published for mathematical modeling of the oxygen gradient in mine wastes (9, 14, 15), but few data are available for confirmation of the models. Hons (16) reported oxygen and carbon dioxide concentrations within experimental reclamation plots of lignite spoil but provided no data on pyrite oxidation. Jaynes, et al (17) monitored gas composition within a regraded surface coal mine. They have developed a model for surface mine drainage quality that considers the oxygen content of pore space gas (18).

The Role of Water

Water has three roles in the formation and discharge of acid mine drainage (AMD): (1) as a reactant in the oxidation process; (2) as a medium for the bacteria and inorganic pyrite oxidation; and (3) as transport medium for reactants and products. The role of water as a reactant is described in the oxidation equations 1-3. As only 1 mole of water is consumed per 2 moles of sulfate produced, the volume of water required to supply water as a reactant is less than 0.02 mm of rainfall per hectare per year for a typical surface mine. Even at the most impermeable sites, it is unlikely that the consumptive use of water is limiting to the pyrite oxidation process.

The role of water as a medium for *T. ferrooxidans* was investigated in detail by Brock (19). He conducted laboratory studies of the changes in bacteria populations as a function of changes in water potential, and concluded that water availability could be limiting to the growth of *T. ferrooxidans* under conditions that might be associated with coal mine wastes. Similarly, Kleinmann and Crerar (20) found that the frequency of wetting crushed pyritic coal influenced the amount of acid produced.

The role of water as a transport medium is a function of the spoil hydrology. Numerous studies have been done on the hydrology and water quality of watersheds subject to surface mining. These include studies of mining impact on ground water (21, 22), infiltration and percolation (23, 24), streamflow (25-27), and small watershed hydrology (28, 29). The role of water as a transport medium is the primary focus of the hydrologic studies described in this paper.

The transport system consists of three major components: recharge, storage, and discharge. The most common sources of spoil water recharge at eastern surface mines are direct infiltration and ground water seepage from adjacent undisturbed bedrock. Additional sources may include last-cut lakes, flooded underground mines, and sludge dewatering pits on the spoil surface. The character and magnitude of the discharge are directly related to the source and persistence of the recharge.

If one assumes an impermeable mine floor and neglects soil water losses, all of the recharge immediately following reclamation will contribute to spoil water storage. As storage requirements decrease, discharge begins to occur on the down-gradient parts of the site. When a recharge-storage-discharge equilibrium is attained, the volume of discharge is equal to the volume of recharge. The time required for equilibration depends primarily on the recharge rate, spoil water storage requirement, and physical characteristics of the backfill. Contamination will continue to occur as acid products are flushed into the spoil water system by fresh recharge and are transported to the discharge area.

GAS COMPOSITION STUDIES

Coal Refuse

The atmosphere within unsaturated coal refuse was sampled with soil gas probes similar to those described by Staley (30). The probes consist of hollow stainless steel tubes, with 6.4 mm outer diameter and 2.5 mm inner diameter. A solid steel tip is swaged on one end of the probe to facilitate insertion into the refuse. A 1.5-mm hole drilled through the hollow probe 10 mm above the solid tip allows access to the refuse atmosphere. Probes ranging in length from 20 to 170 cm were pushed into the refuse by hand. The hollow tube extending above the surface was inserted into gas-tight nylon tubing that was clamped closed between samplings. Gas stored in the probe and tubing was withdrawn into a 10-mL evacuated tube immediately before sampling. The analytical sample was then drawn into a 20-mL evacuated tube and subsequently analyzed by gas chromatography. Because of the small inlet port, this type of probe is frequently blocked by fine particles, particularly under wet conditions.

A preliminary survey of gas compositions within unsaturated coarse refuse was conducted at three sites. Gas probes were installed in two active refuse disposal areas in Allegheny County, PA. At both sites the probes were placed in inactive sections that appeared to be old, weathered, highly compacted, and removed from refuse bank slopes. The third site, located in Wise County, VA, was a 100-m-long ridge of coal refuse constructed in 1980 for reclamation research (31). For our purposes, five of the subplots on this site could be considered as barren refuse: one plot which received no amendments and four plots which were treated with soil amendments and seeded directly on the refuse. Vegetation covered less than 5% of the surface of the seeded plots at the time of this study (32). Gas probes were installed at depths ranging from 15 to 91 cm, and samples were taken three to five times at each site during 1982.

The oxygen concentrations observed during the sampling periods are shown in Table 1. Oxygen concentrations decreased with depth at each site, as one would expect if the atmosphere is the major oxygen source (9, 14). The consistency of data from the three sites is interesting. The oxygen concentration within 20 cm of the surface was only slightly lower than the nominal concentration of 20.95% for air. Below 60 cm, the refuse was poorly oxygenated, approaching the values considered rate-limiting for acid production. The intervening zone showed a wide range of oxygen concentrations.

TABLE 1
Range of oxygen concentrations observed in
three barren refuse disposal areas as a function of depth.

DEPTH, cm	OXYGEN CONCENTRATION RANGE, moisture-free volume percent		
	Allegheny Co., PA		Wise Co., VA
	Site A	Site B	
15	20.5 - 20.7		20.2 - 20.8
20	18.9 - 19.9	20.2 - 20.4	
30			9.1 - 20.7
35	6.5 - 14.9	5.7 - 17.2	
66		0.4 - 3.5	
91			0.2 - 9.6
Sampling period:	1/82 - 8/82	1/82 - 4/82	5/82 - 9/82

In the uppermost, well-oxygenated zones of these sites, either the rates of oxygen consumption and oxygen replacement from the atmosphere are nearly equal or the zone may have a low pyrite content due to previous weathering. The nonoxygenated zone results from the predominance of oxygen consumption over oxygen replenishment. The intermediate zone (approximately 20 to 60 cm below surface) reflects the variable balance between oxygen consuming and replacing processes. The relative rates depend on a variety of factors such as temperature, moisture conditions, and changes in atmospheric pressure.

A more detailed study of gas composition within coal refuse is being conducted at an inactive, unreclaimed disposal area in Morgan County, Ohio. Refuse from the Meigs Creek No. 9 (Sewickley) seam covers a 1.6 ha abandoned surface mine with a thickness of 5.5 to 9.8 m. The compacted refuse is relatively impermeable to infiltration. Runoff mainly flows in a deeply eroded channel to a pond. Runoff is severely contaminated, with sulfate concentrations on the order of 10,000 to 20,000 mg/L. Ground water sulfate concentrations, monitored in three wells located parallel to the highwall, usually range between 4,000 and 8,000 mg/L. Four sets of gas probes were installed in the refuse in May 1982 to sample depths ranging from 15 to 81 cm. Thirteen sets of samples have been analyzed since the study began.

Typical summer oxygen profiles are shown in Figure 1. Oxygen is depleted rapidly with depth near the surface, resulting in concentrations at the 15-cm depth that are 36% to 88% lower than the oxygen content of air. The rate of decreasing oxygen concentration is sharpest in the uppermost 15 cm of refuse in sets 2 and 4 and in the uppermost 30 cm of refuse in sets 1 and 3. Variable oxygen consumption and replacement rates in the heterogeneous material may explain this observation.

There was an apparent seasonal effect reflected in the oxygen profiles. Data from samples taken in January and February 1983 are shown in Figure 2. In contrast to summer profiles, the refuse is well oxygenated at all sampled depths during the coldest months. The rates of most chemical reactions tend to decrease with decreasing temperature (33), and catalysis by <u>T. ferrooxidans</u> is highest between 25° and $40^{\circ}C$ (34). It is likely that the higher oxygen content in the gas phase in winter results from decreased acid production. However, we do not have sufficient water quality data to determine if the acid load decreased during winter.

Carbon dioxide content of the gas at this site was inversely related to oxygen content (figure 3). On a barren site such as this, microbial respiration probably accounts for only a fraction of the CO_2. Another source of carbon dioxide is the acid dissolution of carbonate minerals, such as limestone:

$$2H^{+} + CaCO_3 \longrightarrow Ca^{2+} + H_2O + CO_2 \qquad (4)$$

The complex carbonate equilibria determine to what extent this reaction occurs (35). However, evidence of carbonate dissolution is observed in water quality data. Acidity to sulfate molar ratios are usually about 0.87 for runnoff samples and 0.65 for ground water samples, suggesting that some of the acidity is neutralized as the water moves through the refuse (see equation 1).

Further evidence to suggest that respiration is not the major CO_2 source is found in the gas composition data shown in Table 2. The 79-cm probe of set 2 yielded a sample on five occasions. Nitrogen content of the gas samples ranged as low as one-third that of an air atmosphere. Since it is relatively inert, it is unlikely that nitrogen is consumed in chemical reactions in the refuse. The result is probably due more to the net evolution of CO_2, which decreases the nitrogen fraction in the total gas volume. In soils, the sum of oxygen and carbon dioxide is usually approximately equal to the sum of 20.98% in air (36). With the exception of the February sample, the carbon dioxide values were higher than values that could be expected for soil reactions. Data from other probes at depths of 76 to 81 cm showed a similar trend.

TABLE 2
Gas composition within coal refuse at the Morgan County site, 79 cm depth.

Date	GAS COMPOSITION, moisture-free volume percent		
	Oxygen	Carbon dioxide	Nitrogen
06/23/82	6.0	56.3	37.3
01/06/83	7.8	22.2	69.2
02/15/83	18.2	2.8	78.1
04/28/83	1.0	23.7	63.5
07/14/83	0.6	73.9	25.2

These studies of gas composition, while far from complete, are providing insight into acid production in coal refuse disposal areas. Oxygen content of the gas phase decreased within the uppermost meter of refuse to levels that may be limiting for pyrite oxidation. The oxygenated zone, and thus the acid-producing zone, at these sites was a small fraction of the total waste material volume during summer. Our findings are consistent with Good's description of a thin, near-surface reactive zone, although his conceptual model was based on physical properties of coal refuse (36). Deeper oxygen penetration during winter, observed at one site in this study, may reflect decreased oxygen consumption at low temperature. The effects of this seasonal oxygenation trend on pyrite oxidation need to be examined.

Coal Mine Spoil

Spoil atmosphere sampling devices were similar to nested ground water piezometers. Each sampling port consisted of a 15-cm length of slotted PVC pipe sealed at both ends with rubber stoppers cemented to the inner pipe wall. A piece of flexible tubing longer than the desired port depth was inserted through one stopper of the port. The ports were coupled to lengths of solid PVC pipe to provide the desired sampling depths. Tubing from lower ports was run through both stoppers of each higher port to the surface. All stopper-tubing seals and stopper-pipe seals were tested for leakage with a suction pump. The assembly is placed in a 15-cm boring in the spoil. The annular space is backfilled with sand at each port and with bentonite slurry seals between ports. Each piece of tubing is labeled at the surface according to port depth and closed by means of a spring or screw clamp.

The port tubing, a dust-sampling pump, and an evacuated, 20-mL sampling tube were connected to a three-way gas-tight valve prior to each sampling. At a rate of approximately 3 L/min, gas was drawn through the tubing and pump for a sufficient time to remove at least three times the void volume of the port and tubing. The valve was then repositioned to allow flow from the tubing to the sample container.

Spoil atmosphere monitoring is being conducted at several regraded surface mines; two of the sites are discussed in this paper. The first site, located in Clarion County, PA, was mined in the early 1960's for the Upper Clarion seam; a portion of the site was also mined for the Lower Clarion coal. Seven gas samplers (GS) and five ground water monitoring wells were installed during 1982. The site remains unvegetated except for evergreen trees planted near GS 7.

Eight sets of gas samples were collected between November 1982 and September 1983. In general, oxygen concentrations decreased with depth in the samplers, although with different gradients, as shown in figure 4. The spoil atmosphere was well oxygenated to a much greater depth than were the refuse atmospheres described earlier. Except in GS 7, the ports at 7.6 m below surface were sufficiently oxygenated for rapid pyrite oxidation at least during part of the year.

Oxygen concentrations at the 4.6- and 7.6-m ports of GS 7 ranged from 0.2% to 1.5%. The vegetative cover around GS 7 is probably responsible for this observation. GS 9, located in unvegetated spoil less than 40 m from GS 7, contained as much as 16% oxygen at the 4.6-m port.

Significant temporal variations in gas composition have been observed, but no simple trends are apparent yet. Oxygen diffusion and consumption may be influenced by a variety of factors such as temperature, atmospheric pressure, biological activity, and moisture status of the spoil.

Gas composition is also being investigated at a site in Upshur County, WV. The site is a 6-ha subarea of a 32-ha surface mine operated in the mid-1970's and reclaimed shortly after mining was completed. Present site topography consists of a steep slope at the old highwall, a flat bench over the mined area, and a steep outslope. The mine floor dips gently to the northwest under a maximum spoil thickness of about 8 m. Following reclamation, a perennial acidic seep having a mean annual discharge of 1.1 L/s developed at the toe of the spoil.

Gas samplers were installed in two distinct environments identified by electromagnetic conductivity surveys (38) at the Upshur County site. GS 5 is located in unsaturated spoil on the outslope. Ports range from 0.6 to 5.2 m below surface at 1.5-m intervals. GS 8 is located on the mining bench down-gradient from an area used for disposal of black, pyritic material believed to be scrapings from the pavement. The unsaturated spoil thickness at GS 8 is approximately 2.5 to 3 m. Sampling ports are 0.5, 1.2, and 2.0 m below surface. Gas composition data from five sets of samples taken between May 1983 and February 1984 are summarized in Tables 3 and 4.

TABLE 3
Gas composition in samples from GS 5,
May 1983 - February 1984.

DEPTH, m	CONCENTRATION RANGE, moisture-free volume percent Oxygen	Carbon dioxide
0.6	7.3 - 14.9	2.2 - 4.9
2.1	10.4 - 17.6	1.8 - 4.5
3.7	16.2 - 16.4	1.8 - 4.3
5.2	12.1 - 20.9	0.1 - 8.8

TABLE 4

Gas composition in samples from GS 8,
May 1983 - February 1984.

DEPTH, m	CONCENTRATION RANGE, moisture-free volume percent Oxygen	Carbon dioxide	Methane
0.5	15.3 - 20.3	0.9 - 5.0	ND - 0.9
1.2	1.9 - 3.1	1.8 - 4.0	0.7 - 3.4
2.0	0.6 - 3.8	3.1 - 10.9	20.7 - 33.0

With the exception of high methane content, the gas composition at GS 8 is similar to that observed in coal refuse. Oxygen decreases and carbon dioxide increases with depth. Near the surface, the combined O_2 and CO_2 contents are approximately equal to the 20.98% sum for an air atmosphere. At greater depth in the spoil, there appears to be net O_2 consumption, probably as a result of pyrite oxidation. The nearby zone containing the black pyritic material has been identified by ground water quality analyses as the largest source of contamination. The sharp decrease in oxygen concentration in the uppermost 2 m of spoil at GS 8 is consistent with rapid consumption of oxygen and may represent a profile characteristic of active pyrite oxidation. At the 2.0-m depth, the oxygen concentration is less than the 2% thought to be required for rapid acid production.

The profile for GS 5 is unlike other oxygen profiles we have observed in coal refuse and spoil at locations distant from slopes. The highest mean oxygen concentration in GS 5 occurred at the 3.7-m depth. Both the shape of the profile and the location of the sampler on the outslope suggest that there may be air flow laterally through the slope face. Such gas flow patterns have been observed in mine waste leaching operations (39). A preliminary analysis of water quality data indicated that the spoil around well 5 did not contribute significantly to the total pyrite oxidation product load. Oxygen consumption here may result mainly from ferrous iron oxidation. Spoil moisture analysis is needed to further elucidate chemical processes occurring in this zone.

Oxygen penetration appears to occur at greater depths in spoil than in refuse, particularly at the Clarion County site. Varying particle size distributions and moisture-retention properties may be responsible for higher diffusion rates in spoil. Alternatively, the sharp profiles in coal refuse may reflect more rapid acid production in the preparation plant waste, which contains a higher fraction of pyrite. Further studies are needed to relate the observed gas composition profiles to chemical and physical processes.

SPOIL WATER QUALITY FIELD STUDIES

Once acid products have formed, their discharge is a function of aqueous transport through the spoil. The Bureau of Mines is currently studying the transport process at several surface mines in the Appalachian region. One phase of the study has been to instrument three surface mine sites receiving both direct infiltration and bedrock seepage recharge. At each site, a series of observation wells are being monitored for water quality and water levels. Some results of the study are summarized in Table 5.

TABLE 5
Water quality data summary for three reclaimed surface mines.

SAMPLING POINT	MEAN CONCENTRATION, mg/L		
	Sulfate	Total Iron	Acidity
SITE 1			
Discharge	460	36	230
All Wells	470	88	180
Well Nearest Recharge	110	26	10
SITE 2			
Discharge	3500	470	2000
All Wells	1300	130	170
Well Nearest Recharge	340	3	13
SITE 3			
Discharge	3200	37	1100
All Wells	2900	NA	1200
Well Nearest Recharge	580	NA	240

NA: not available

At all three sites, extreme spatial variations in water quality were observed. In each case, water quality in wells located near the bedrock seepage areas was significantly better than the quality at the respective discharge. This implies degradation of the influent water as it flows through the spoil. In all three cases, simple diversion of the recharge prior to flowing through the spoil would significantly reduce the discharge volume.

The ultimate effect of flow reduction on contaminant transport can be estimated by comparing discharge concentrations at various flow rates. Figure 5 is a plot of sulfate load (mass/time) versus discharge flow rate derived from data collected over a 1-year period at the Upshur County site described earlier. As might be expected, the sulfate load increased as the flow increased. The magnitude of the change in load was less than the magnitude of the change in flow due to some dilution at higher flow rates: a 50% reduction in peak flow rate at the Upshur County site would correspond to approximately a 35% reduction in the peak loading rate.

The importance of defining variations in spoil water quality is clearly illustrated by the plots shown in figures 6 and 7 for the Upshur County site. The plots show temporal variations in sulfate and acidity concentrations for the discharge and two monitoring wells: well 7, located near the bedrock seepage area; and well 4, located down-gradient near the buried pyritic material.

Sulfate concentrations in well 7, the lowest observed in any of the wells, were approximately one-fifth of the discharge sulfate concentrations for the same period. Temporal variations at well 7 were small, with sulfate concentration remaining near 100 mg/L for the May-January sampling period. Conversely, sulfate concentrations in well 4 were the highest observed, as much as four times higher than the discharge in the spring months. Water quality in well 4 was also highly variable, with sulfate decreasing by more than 50% during low water levels in late August and September. Similar relationships were found for acidity and iron concentrations.

The large differences in water quality between wells 4 and 7 suggest different abatement strategies. For example, a subsurface drain to intercept clean bedrock seepage near well 7 may be all that is necessary for reduction in discharge volume and loading, and therefore in treatment costs. The pyritic material near well 4, however, may require special treatment such as localized alkaline loading of the spoil or concentrated application of a bacterial inhibitor. Development of an abatement program based solely on a few discharge measurements and ignoring the site-specific characteristics of the spoil environment would likely lead to deficiencies in the technical strategy and consequently wasted time and money.

SUMMARY

Oxygen profiles in coal preparation plant refuse appeared to be related to acid production, as one would expect from knowledge of the pyrite oxidation processes. In barren refuse, oxygen content of the gas phase decreased rapidly with depth. Oxygen consumption probably occurred primarily from pyrite oxidation, particularly at the Morgan County site, where runoff water quality indicates rapid near-surface acid production. The bulk of the waste material beneath the weathering zone probably contributes relatively little to the total acid load. Covering the refuse with a non-polluting material which consumes oxygen as efficiently as pyrite should greatly reduce acid drainage. Overburden spoil does not appear to be a good cover material, in view of the deep oxygen penetration observed in spoil. Alternatively, a cover of material with low gas diffusivity may be effective.

Coal mine spoil is oxygenated to greater depths than is coal refuse. A lower O_2 consumption rate in spoil is consistent with the majority of gas composition profiles derived from this study. Exceptions were GS 8 at the Upshur County site in the vicinity of oxidizing pyritic waste and GS 7 in vegetated spoil at the Clarion County site.

The Upshur County site illustrates the value of both gas and hydrologic studies. The oxygen profile at GS8, which was similar to the coal refuse profiles, appeared to indicate a zone of acid production. In the future, it may be possible to survey the oxygen status across a site with gas probes to identify such zones. Special reclamation practices or pyrite oxidation inhibitors, too costly to apply to an entire site, may be useful for acid abatement in selected zones.

The hydrologic studies summarized in this paper emphasize the role of water as a transport medium for pyrite oxidation products. The results indicate that monitoring wells are important in obtaining a conceptual understanding of spoil hydrology. The patterns of loading and migration of pyrite oxidation products at a particular site can then be used to develop efficient mine drainage abatement strategies.

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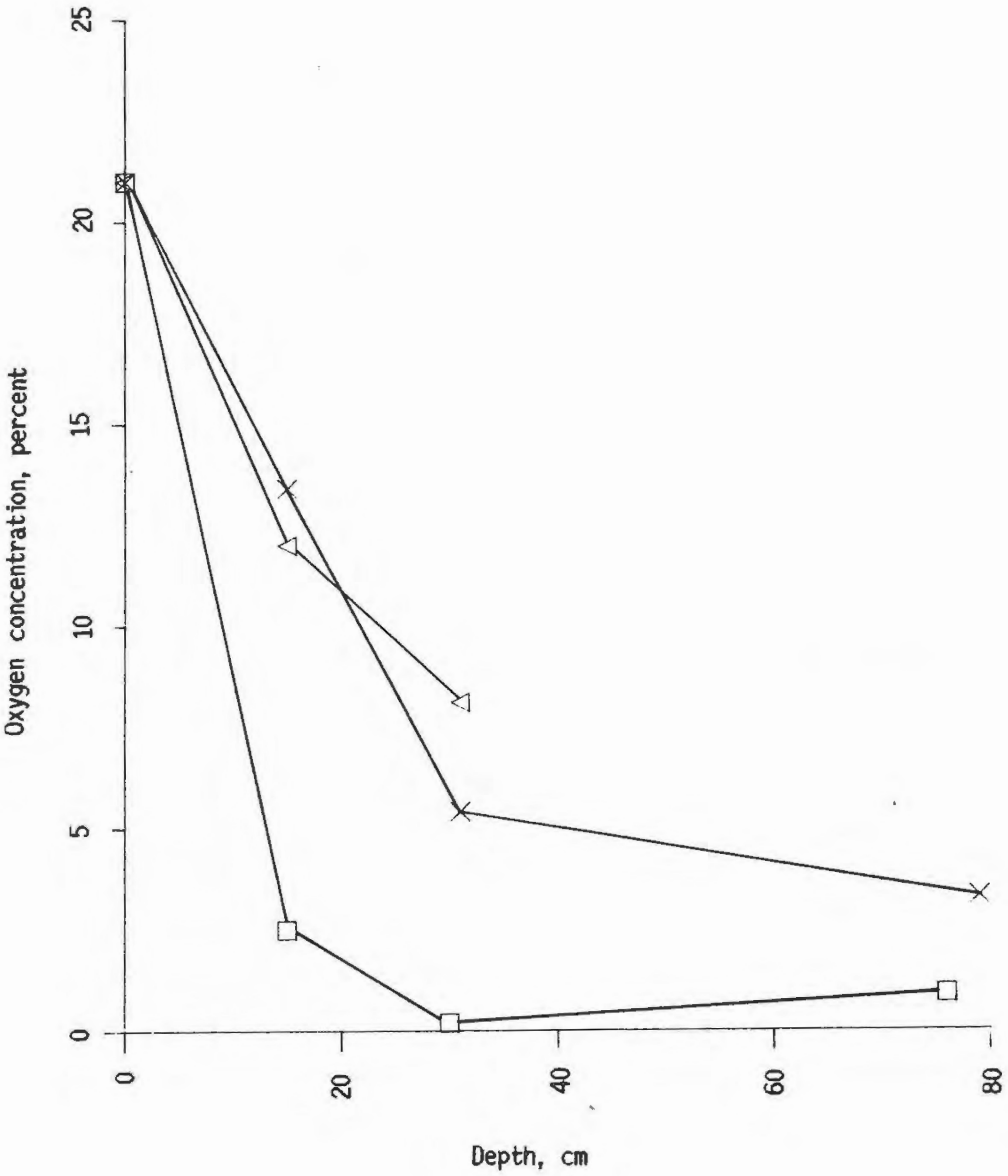

Figure 1. - August 1983 oxygen profiles at the Morgan County site at gas probe sets 1 (△), 3 (x) and 4 (□).

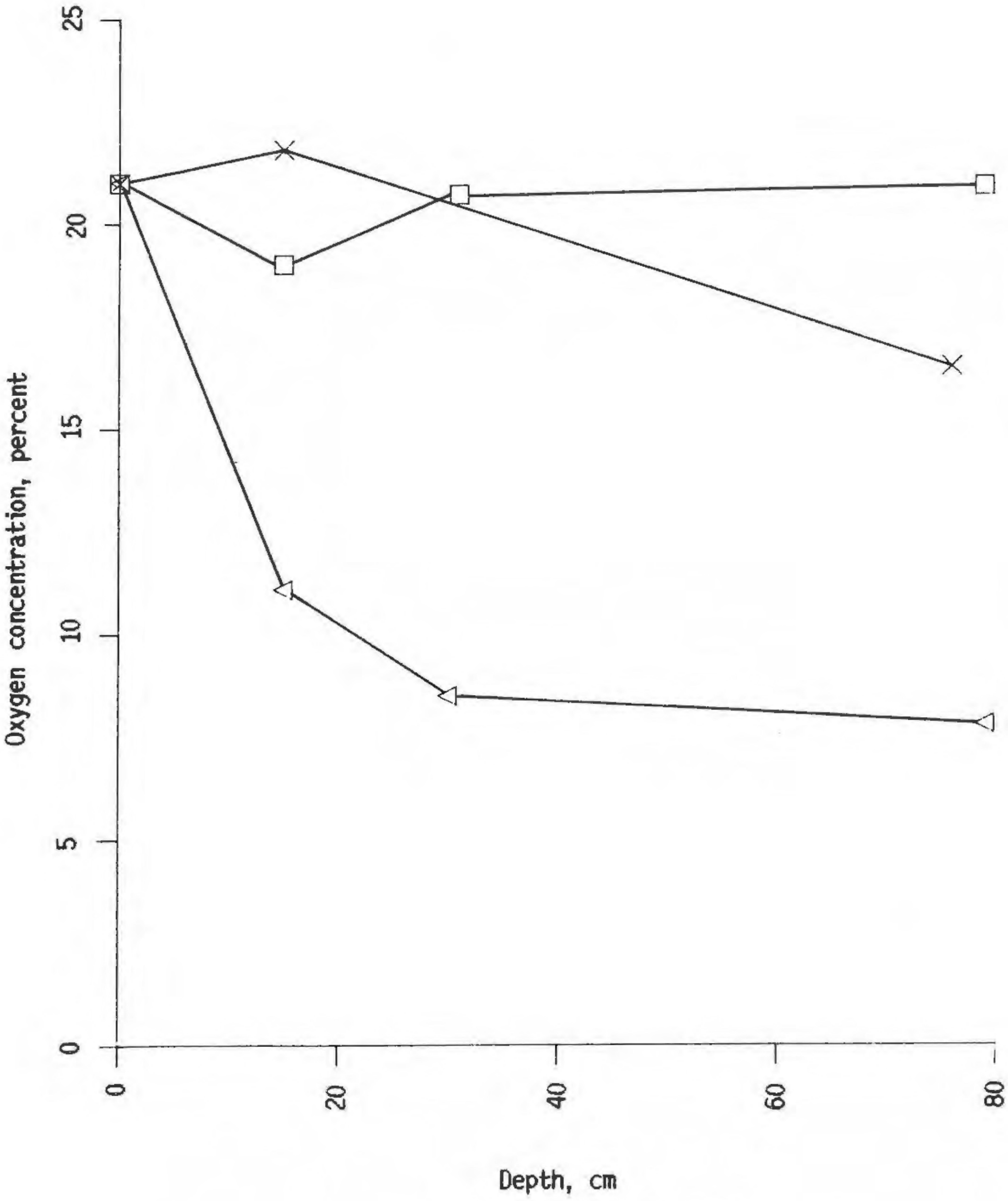

Figure 2. - Winter oxygen profiles in coal refuse at the Morgan County site. Data from January 1983 for sets 2 (△) and 4 (x), from February 1983 for set 3 (□).

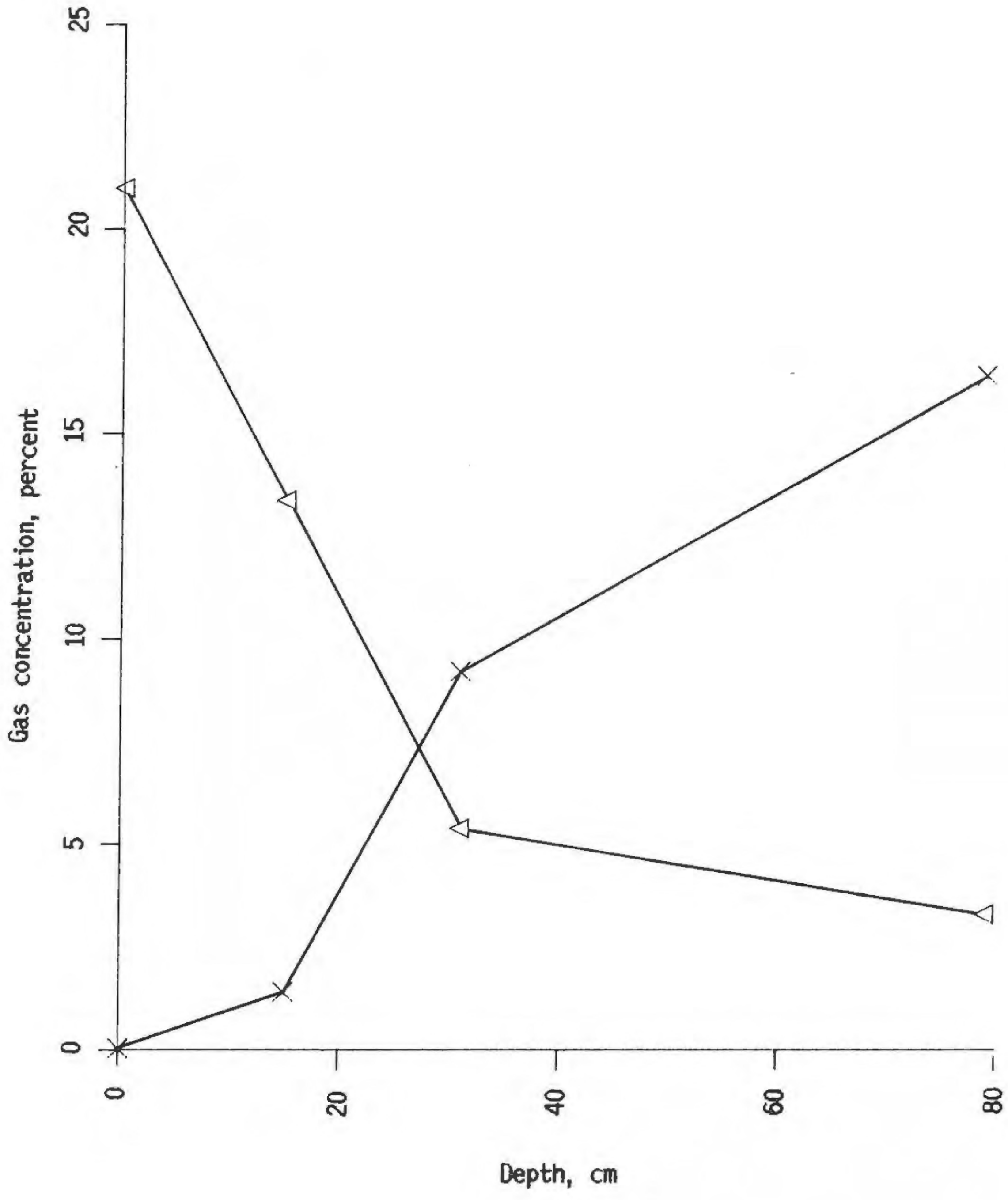

Figure 3. - Oxygen (Δ) and carbon dioxide (x) profiles in set 3 gas probes at the Morgan County site, August 1983.

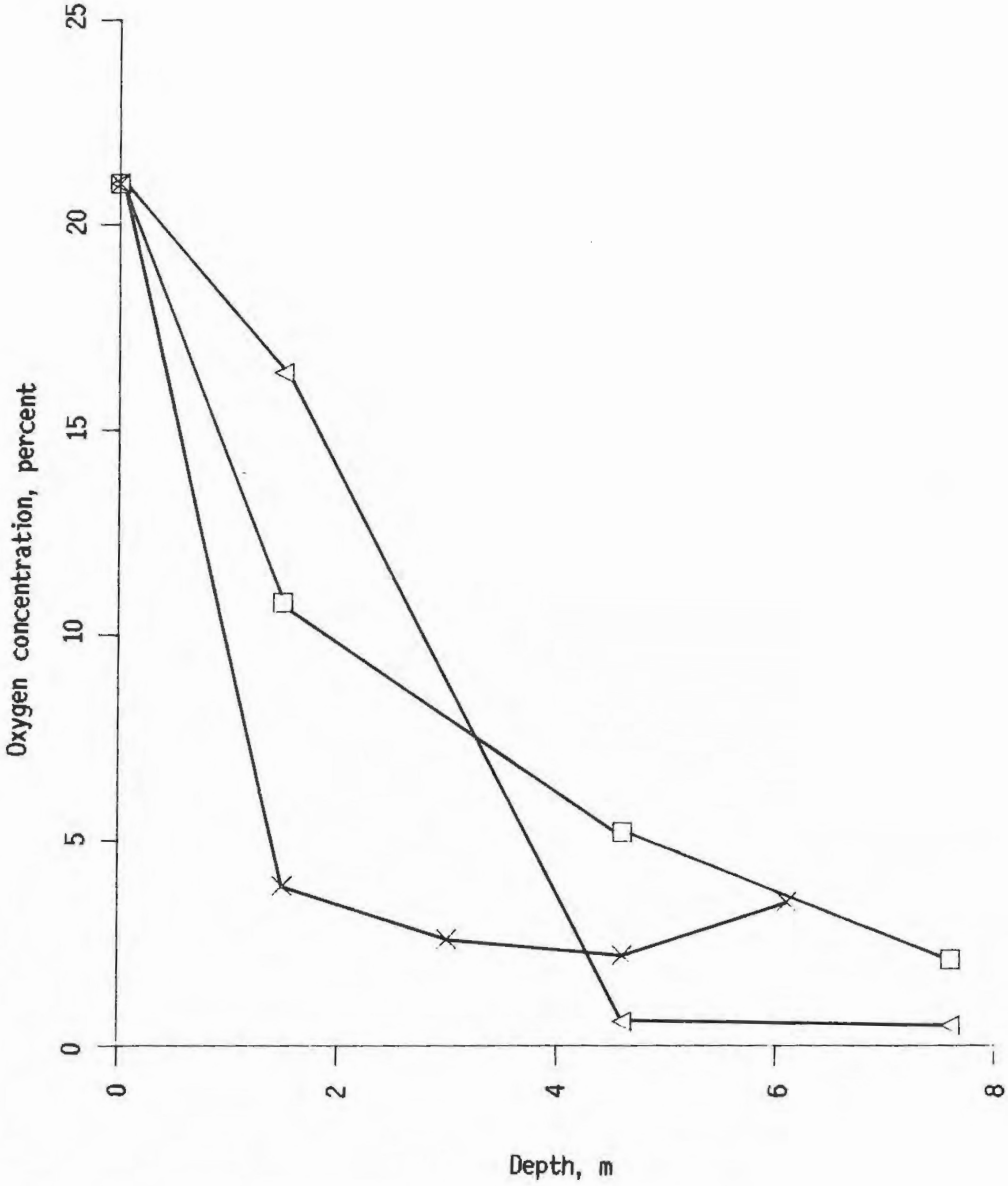

Figure 4. - Typical oxygen profiles for 3 gas samplers in spoil at the Clarion County site. Data from GS 5 (□), GS 7(△) and GS 3(x), July 1983.

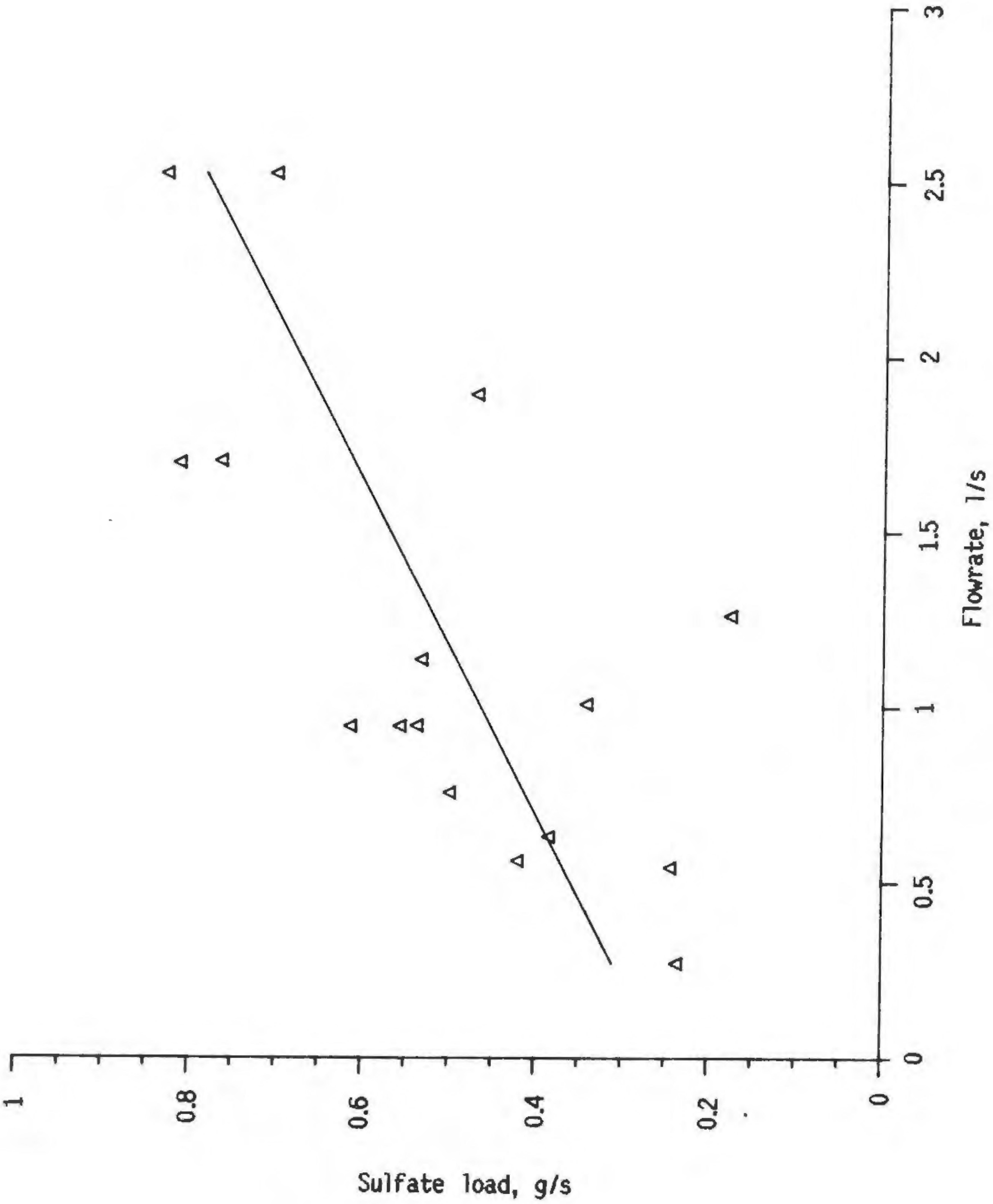

Figure 5. - Contaminant load - flow relationship at the Upshur County site discharge.

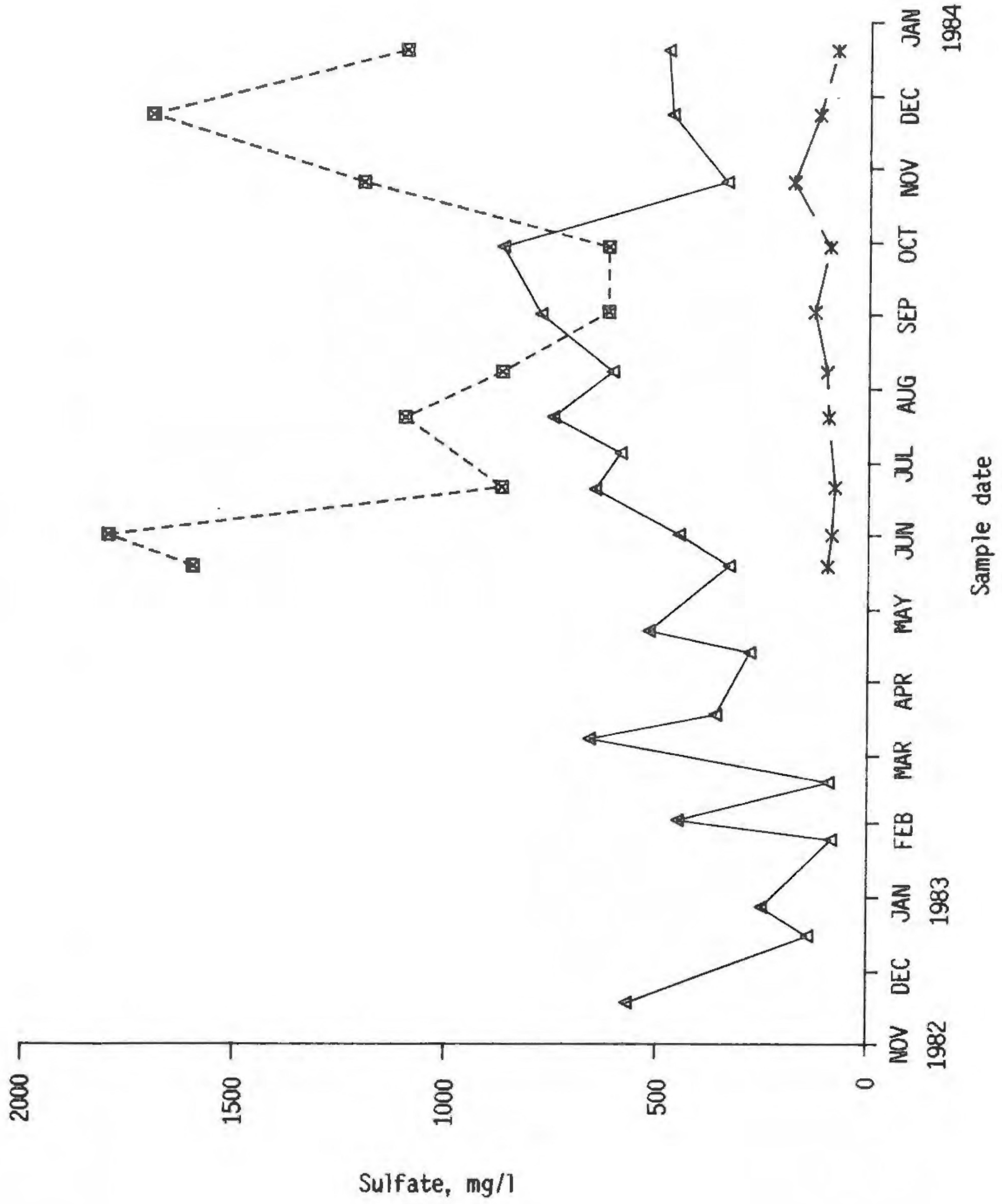

Figure 6. - Sulfate concentrations observed over time at the Upshur County site in monitoring wells 7 (x-—x) and 4 (⊠---⊠) and seep discharge (△—△).

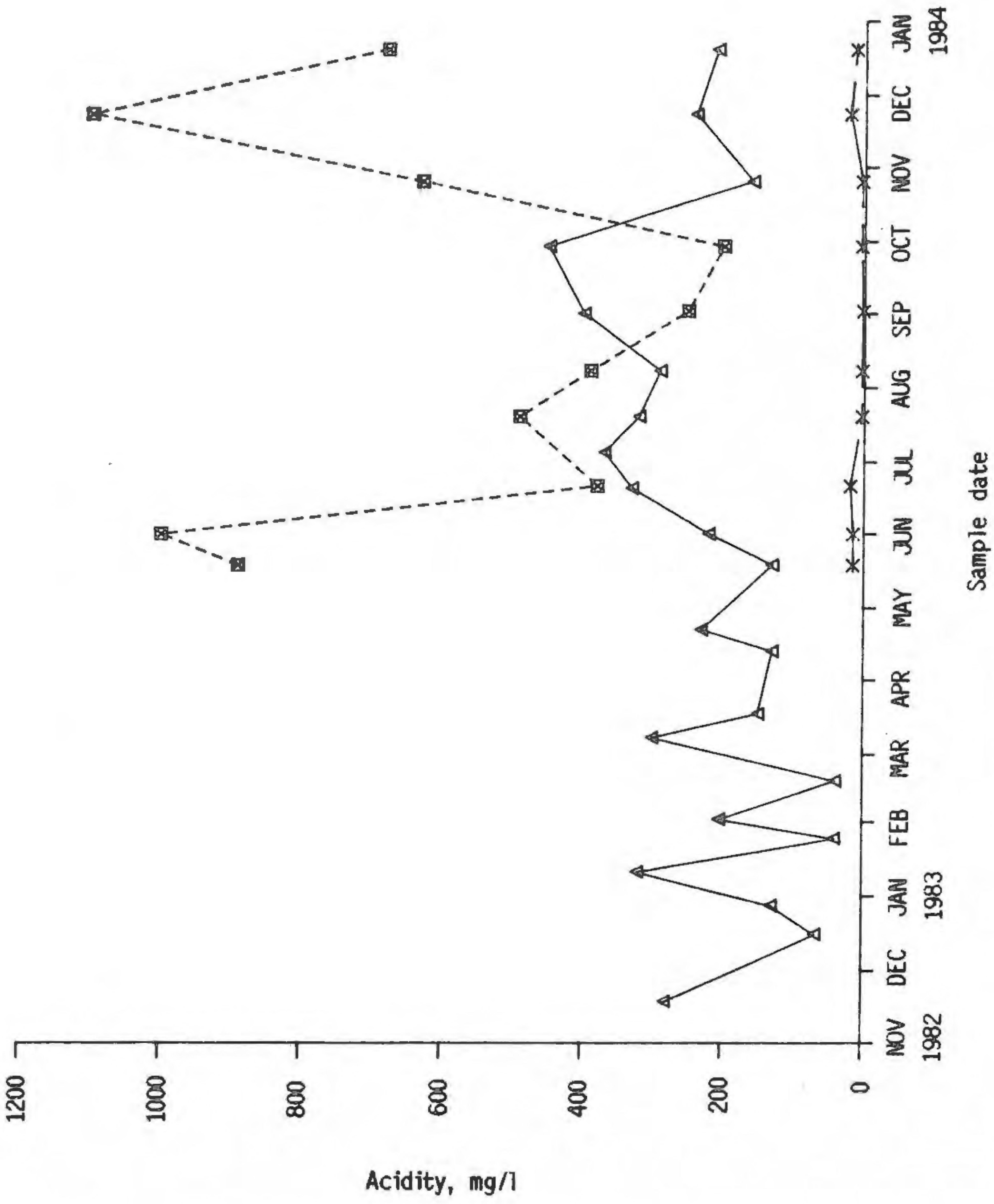

Figure 7. - Acidity levels in monitoring wells 7 (x——x) and 4 (⊠--⊠) and at the seep discharge (△——△) at the Upshur County site.