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Acid Mine Drainage And The Acid Drainage Index

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ACID MINE DRAINAGE AND THE ACID DRAINAGE INDEX

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ACID MINE DRAINAGE AND THE
ACID DRAINAGE INDEX

A Dissertation
Presented to
The School of Graduate Studies
Indiana State University
Terre Haute, Indiana

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

by
Michael S. Talbett
December 1981

APPROVAL SHEET

The dissertation of Michael Talbett, Contribution to the School of Graduate Studies, Indiana State University, Series III, Number 254, under the title Acid Mine Drainage and the Acid Drainage Index is approved as partial fulfillment of the requirements for the Doctor of Philosophy Degree.

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ABSTRACT

Acid drainage is a naturally occurring process that often results from weathering and oxidation of impurities in coal. When coal is exposed through mining, the problem is magnified and it is estimated that some 11,000 miles of streams in the United States are affected by acid mine drainage. As a contribution toward a better understanding of the nature of acid mine drainage, this study evaluates changes in acidity of a small stream that drains areas in which both surface and underground coal mining have occurred.

Thirty-three sample days of field measurements, spread over a period of eight months, at twelve sites on the stream were utilized to measure drainage from two potential acid sources within its drainage basin. These sources were surface runoff from a gob and slurry area associated with a surface coal mine and the constant flow of water from an open air shaft constructed for a now abandoned underground mine. The data collected included stream discharge, stream water pH and related areal measurements. These data were used to evaluate the total amount of pH activity, the amount of pH depression, stream discharge and pH recovery for each sample day.

Data analysis indicated that during the observation period no distinctive seasonal differences occurred in pH or discharge levels during the observation period. Similarly, no systematic relationship was found between the stream pH and discharge. Despite the lack of meaningful correlations between pH and discharge, variations in acidity, as related to discharge, were assessed through the use of a derived Acid Drainage Index (ADI).

The proposed ADI was an empirically derived equation which rated acid drainage conditions in terms of the amount and kind of pH activity and the amount of water in the stream. It utilized the variables pH and discharge to determine how distinct acid drainage conditions could be identified. In this study three types were delineated. These are (1) baseflow period of low flow when the acid load was diluted by available water in the stream and categorized by ADI values between 0 and 19, (2) transition period reflecting moderate ADI values ranging from 20 to 94, and (3) flushout period of highest flow when the amount of acid entering the stream exceeded the ability of the stream to dilute it, and ADI values were above 95.

The ADI provided an easily used numeric value that permitted comparison of acid drainage conditions found in the study area. The organization of ADI values into the groups baseflow, transition, and flushout could be a useful application in other areas where a quantitative comparison of acid drainage conditions in a stream is required.

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Chapter 1

ACID MINE DRAINAGE

Introduction

The pollution of streams by drainage from areas in which coal is found is a naturally occurring process which results largely from pyrite oxidation at both underground and surface sites. Early explorers of the United States recorded that water quality near coal bearing strata was often adversely affected, and when commercial coal mining in the United States began in the early 1600s, acid discharges were associated with mining activity.[1]

Since the early days of mining, the amount of coal extracted in the United States has increased to more than 800 million tons in 1977. By the year 1990 it is expected to be more than 1 billion tons.[2] Accompanying this dramatic increase in coal production has been the number of streams affected by acid drainage. Today acid drainage is a serious problem for there are nearly 11,000 miles of streams that

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[1] H. Evanston, An Account of Pennsylvania: The First Century and a Quarter of the American Coal Industry (Baltimore, Maryland: Waverly Press, 1942), p. 42.

[2] U.S., Department of Interior, Office of Surface Mining and Reclamation and Enforcement, Permanent Regulatory Program Implementing Section 501(b) of the Surface Mining Control and Reclamation Act of 1977 (Washington, D.C.: Government Printing Office, 1979), p. BII-8.

are contaminated by acid water. It has been estimated that nearly 97 percent of those stream miles have been contaminated by acid associated with coal mining.[3]

The Nature of Acid Drainage

Impurities found in situ with coal, such as pyrite and marcasite, undergo weathering and oxidation to produce acid drainage. The amount of acid drainage produced is dependent upon the amount of water, oxygen and pyritic material present, the type of mining operation used to extract the coal, air temperature, and the condition of the pyrite surface area.[4] The water is the medium wherein the acid production takes place and also the vehicle that removes acid from the reaction site.

The sulfur in coal seams is classed as either organic or inorganic. The organic sulfur is derived mainly from the proteins of plants that composed the original vegetal matter. The inorganic sulfur consists of mineral sulfides, sulfates, and free sulfur. Sulfides are most common, as the ores pyrite and marcasite. Both have the same chemical composition (FeS_2) but different crystalline

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[3] U.S., Congress, House, Coal Mining and Water Resources, H.R. 95-218, 95th Cong., 1st sess., 1977, p. 58.

[4] U.S., Department of Interior, Federal Water Pollution Control Administration, Mine Drainage Treatment State of the Art and Research Needs, by R. Hill (Cincinnati, Ohio: Industrial Environmental Research Laboratory, 1968), p. 4.

structures. It is these sulfide ores that oxidize to produce acid when exposed to air and water, with pyrite being the most prevalent ore.

When pyrite is exposed to air and water it undergoes oxidation to produce ferrous sulfate and sulfuric acid as described in the reaction:

$$FeS_2 + 3/2O_2 + H_2O \rightleftharpoons Fe^{+2} + 2SO_4^{-2} + 2H^+$$

Thus, acid water is created and the leaching process exposes new surface to oxidation and further acid formation. Ferrous iron (Fe^{+2}) then undergoes oxygenation to ferric iron (Fe^{+3}) according to the reaction:

$$Fe^{+2} + 1/4O_2 + H^+ \rightleftharpoons Fe^{+3} + 1/2H_2O$$

The ferric iron in turn can hydrolyze to form insoluble ferric hydroxide and still more sulfuric acid as outlined in the reaction:

$$Fe^{+3} + 3H_2O \rightleftharpoons Fe(OH)_{3(s)} + 3H^+$$

These equations provide a description of the chemistry for the oxidation and acid formation process. Water is important to this process because it is the medium in which the chemistry takes place and also the agent for acid removal.

Stream contamination by pyrite material is facilitated by the processes of surface runoff and interflow when water passes over or through areas of coarse coal refuse (gob), underground tunnels, strip mined land, or fine coal refuse (slurry). This acidic water then becomes a component of local stream discharge that can be thought of as being the amount of water available to dilute the acid. Relationships between discharge and acid concentration are complex because of the unequal amount of mined and unmined land in a drainage basin and the varying distribution of localized precipitation throughout the watershed. Consequently, changes in the concentration and extent of acid flow would be expected downstream from an acid source.

Water contaminated by acid drainage is typified by low pH, hardness greater than 250mg/1, suspended solids greater than 250mg/1, and dissolved solids, such as Fe and SO_4, greater than 500mg/1. Low pH increases the solubility of heavy metals. Consequently, acid mine drainage may also have high concentrations of zinc, copper, manganese, calcium, magnesium, and arsenic.[5] These concentrations not only impair biotic activity but also affect water suitability for agricultural, recreational, industrial, and municipal uses.

The pH is a valuable parameter in estimating the quality of a stream since pH reflects the acid concentration of the water. The pH units are measured on a logarithmic scale that ranges from 0, which is extremely acidic, to 14, which is very alkaline. A pH of 6 is 10 times more acidic than a pH of 7. Low pH values in water are known to be harmful to aquatic flora and fauna and are corrosive to metals on contact.

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[5] J. Cairns et al., "The Recovery of Damaged Streams," Association of Southeastern Biologists Bulletin 18 (1971):84.

Acid Producing Sites

It has been estimated that in the United States, 60 percent of acid drainage comes from abandoned rather than current mining.[6] Future estimates may be even higher because federal and state legislation have established minimum levels of acid water discharge only for active mines. Acid drainage from an abandoned mine is a long-term process that continues as long as air and water interact with sulfur bearing materials. This interaction may occur at ground level or beneath the surface in mine openings. Exposed pyritic materials usually found in slag and gob piles are porous, allowing circulation of water and air within them, thus producing acid discharges. Unreclaimed mine sites are, therefore, likely to be significant sites of acid production.

Extracted coal is subjected to a cleaning operation to remove dirt and impurities. The waste material is known as gob, a coarse refuse consisting of coal intermixed with pyrite, clays, shales, and sandstones. A finer textured refuse is created when coal is washed following its separation from the coarse refuse at a tipple site. This finer refuse of coal, dirt, pyrite, and shale mixes with water to create slurry that flows from the tipple to a settling pond. Chemical reactions that take place near the coal refuse surface produce acid. As erosion continually

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[6] U.S., Department of Interior, Surface Mining and Our Environment (Washington, D.C.: Government Printing Office, 1967), p. 21.

exposes new surface material the process continues until the pile is completely eroded.

Abandoned Mine Sites and Waste Disposal

Various techniques may be utilized to reclaim abandoned lands, either singularly or in conjunction with one another. Viable reclamation practices mandate that sites be individually assessed with future land use a major consideration. Possible land use schemes for reclaimed land include wildlife habitat construction, development of agricultural land, the creation of residential, commerical and recreational sites, and refuse disposal areas.

The use of an abandoned mine site for waste disposal is only marginally acceptable because of the threat of ground water and surface pollution. The threat of contamination arises from refuse placed in spoil or coal washings which are permeable and allow leachate movement to occur. In addition, acid drainage from the abundant coal fines on site accelerate the leaching process.

There are numerous studies of both acid drainage and leaching from sanitary landfills.[7] One research approach has been to use modeling to predict responses of the system under various conditions. This kind of work has been done for both acid drainage in streams and sanitary landfills. However, with abandoned coal mine sites

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[7] A survey of the literature dealing with acid drainage and related topics is found in Chapter 2.

being used for sanitary landfills, a study which examines the acid drainage pattern from a site combining these features is valuable.

Research Objectives

The object of the research reported herein was to measure acid mine drainage that entered a stream and the dilution of that acid by stream discharges. A mathematical model was developed which described that behavior.

Stream discharge is dependent upon channel precipitation, surface runoff, interflow, and ground water. Each of these factors contributed toward the amount of water available to dilute acid entering the stream. Therefore, to model the extent of acid drainage downstream from an acid source, data on both pH and stream discharge were necessary.

The study area for this research centered upon Honey Creek, a small stream in Vigo County, Indiana. The drainage basin contained areas of both mined and unmined land. There was an abandoned underground mine site in the drainage basin on which there were gob and slurry areas. This abandoned mine site, known as the Victory Mine, was being used as a sanitary landfill. This particular land use influenced acid drainage effects because gob and slurry material was being used as a covering material for the refuse buried there. The focus of this research was to study the temporal relationships between stream discharge and acid concentration in Honey Creek.

Hypotheses

It was assumed that concentrations and areal extent of acid affected water in Honey Creek varied over time along with changes in discharge. In relation to this attribute two hypotheses were formulated. The first hypothesis was that during the late summer and fall when lowest discharge conditions prevaled, water would be more acidic and acid water would extend farther downstream than during the winter which was a period of colder temperatures and higher discharges.

A second hypothesis concerned the effects of increased discharge on acidity. Increases in discharge would occur after periods of effective precipitation. The increased flow would accelerate the dilution of acid in the water, thus lowering the pH concentration and reducing the extent of acid flow downstream. Both of these hypotheses were tested in this dissertation.

Based on the research objective, a literature survey was undertaken to review studies of acid drainage. This information and analysis of the study area formed the basis of the methodology. Subsequently, a model was formulated that described the pH and discharge data collected. This research added to acid drainage studies in that it related pH directly to discharge levels and created a model to describe acid drainage from an abandoned coal mine site being used as a landfill.

Chapter 2

SURVEY OF THE LITERATURE

Overview

The undesirable effects of acid mine water are widespread and variable in scale, affecting small streams or entire river basins. Consequently, a large body of literature deals with this subject. Published material relating to acid drainage can be organized into broad categories. A comprehensive list of such categories would include the formation of acid water, the effects of acid water on flora and fauna, reclamation techniques to reduce acid concentration, treatment procedures to improve water quality, regional studies of acid drainage, specific descriptive water quality projects being done, coal refuse pile studies, and modeling of acid pollution.

The pertinent categories that related to this study of the pH of acid water from a coal mine/landfill site and stream discharge have been incorporated into this literature review. They were (1) the formation of acid water, (2) coal refuse piles, (3) modeling acid pollution, and (4) studies of sanitary landfills.

The Formation of Acid Water

In a description of the coal formation process, Moore noted that coal was the result of the alteration of vegetal matter that formed peat and then lignite.[8] Further, differences in coal from one place to another resulted from the varying kinds of plants, differing chemical or mechanical conditions in the transformation into coal, or because of changing external conditions during the process. It was therefore possible to examine properties of coal to identify distinguishing traits. Wewerka _et al_ did this for coal from the Illinois Basin and identified 55 trace elements.[9] A series of weathering and leaching experiments were conducted to define the behavior of these elements under various environmental conditions. They showed that it was possible to estimate the probable environmental reactions associated with various coal seams. An extension of this type of work was an attempt by Haynes and Klunstra to evaluate coal seams and spoilbank material with regard to their chemical properties, vegetation, density, and age.[10]

The fact that sulfur is an impurity in coal that affects water quality has been long established. An early description of the acid water process was published in

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[8] Elwood S. Moore, _Coal_, 2d ed. (New York: John Wiley and Sons, 1950), p. 6.

[9] Elwood M. Wewerka et al., _Trace Element Characterization of Coal Wastes_, second annual progress report (Los Alamos, New Mexico: Department of Energy, LA-7360-PA, 1978), p. 33.

[10] R. J. Haynes and W. D. Klunstra, _Some Properties of Coal Spoilbank and Refuse Materials Resulting from Surface Mining Coal_ (Chicago, Illinois: Illinois Institute for Environmental Quality, 1975), pp. 22-4.

1922.[11] Since then the chemistry of acid mine drainage, that could be thought of as discharge of a strong acid into a naturally buffered waterway, has been well understood and documented.[12]

A common indicator of the quality of a stream contaminated by mine acid is pH. It is defined as the minus log of the hydrogen ion concentration or

$$pH = -\log [H^+]$$

The importance of the transfer of hydrogen ions from acids to bases is important to natural water chemistry. It has been suggested by Stumm and Morgan,[13] as well as Hanna <u>et al</u>,[14] that further research using pH as an indicator of acid water is needed to better understand acid mine relationships.

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[11] W. A. Selvig and W. C. Ratliff, "The Nature of Acid Water from Coal Mines and the Determination of Acidity," <u>The Journal of Industrial and Engineering Chemistry</u> (February 1922): 29-43.

[12] For more detailed treatments of the chemical processes involved see C. M. Lau, "Sulfide Oxidation by Ferric Iron in Acidic Aqueous Systems," (Ph.D. dissertation, University of Notre Dame, 1973); and The Ohio State University Research Foundation, <u>Acid Mine Drainage Formation and Abatement</u>, Water Pollution Control Series DAST-42-14010-FPR-04/71, U.S. Environmental Protection Agency, 1971.

[13] Werner Stumm and James Morgan, <u>Aquatic Chemistry</u> (New York: John Wiley and Sons, 1970), p. 4.

[14] George Hanna, Jr. et al., "Acid Mine Drainage Research Potentialities," <u>Journal of the Water Pollution Control Federation</u> 35 (1963): 275-94.

Clark and Hanna[15] have identified variables that affect acid formation rates to be exposed surface area, temperature, water composition, oxygen partial pressure, and pH. A controversial issue among researchers is the importance of bacteria in influencing the rate of chemical reactions in acid production.[16]

Hill noted that secondary reactions of sulfuric acid in mine drainage created characteristics such as low pH, high iron and sulfate concentrations, increased hardness, and significant amounts of aluminum, manganese, calcium, and magnesium.[17] A report by the U.S. Department of the Interior listed other characteristics to be a reddish-yellow color, high turbidity, suspended or dissolved solids, and precipitation of ferric hydroxide (yellow boy).[18] Baker has used this type of information to create four general classes of acid mine drainage (table 1).

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[15] See C. S. Clark, "Oxidation of Coal Mine Pyrite," Journal of the Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers 92, SA2 (1966): 130; Hanna et al., "Acid Mine Drainage," p. 281.

[16] For example, Lau in his dissertation stated that bacteria enhances production but, in a conclusion drawn from a study by The Ohio State University Research Foundation, there was no evidence of significant bacterical pyrite oxidation. See footnote 12 for full references.

[17] U.S., Department of Interior, Mine Drainage Treatment, p. 5.

[18] U.S., Department of Interior, Federal Water Pollution Control Administration, Stream Pollution by Coal Mine Drainage (Cincinnati, Ohio: 1968), p. 13.

TABLE 1

CLASSIFICATION OF MINE DRAINAGE

	Class I	Class II	Class III	Class IV
	Acid Discharge	Partially Oxidized and/or Neutralized	Oxidized and Neutralized and/or Alkaline	Neutralized and not Oxidized
pH	2-4.5	3.5-6.6	6.5-10.5	6.5-8.5
Acidity mg/l $CaCO_3$	1,000-15,000	0-1,000	0	0
Ferrous Iron mg/l	500-10,000	0- 500	0	50-1,000
Ferric Iron mg/l	0	0-1,000	0	0
Aluminum mg/l	0-2,000	0- 20	0	0
Sulfate mg/l	1,000-20,000	500-1,000	500-10,000	500-10,000

SOURCE: Baker, Analysis of Pollution Control Cost, p. 134.[19]

Acid mine water chemistry is complex and involves more than just sulfuric acid production. As a result, there are many chemical treatments of acid water and abatement methods, each having its own particular advantages and disadvantages.[20]

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[19] Michael Baker, Jr., Inc., Analysis of Pollution Control Cost, ARC contract (Appalachian Regional Commission 72-87/RPC-713, 1972), p. 134.

[20] For a list of critiques of methods to prevent acid formation and to reduce acid pollution after it is formed see R. Hill, "The Impacts of Coal Mining on Surface Water and Control Measures Therefore," in Proceedings of the Second U.S.-Polish Symposium: Coal Surface Mining and Power Production in the Face of Environmental Protection Requirements, Castle Ksiaz, Poland: September 1978 (U.S. Environmental Protection Agency EPA-600/7-79-159, 1979).

Coal Refuse Pile Studies

Impurities in coal were undesirable because they increased the ash content of the coal. To permit economic use, a purification and cleaning process was necessary to separate these impurities from the coal. What was left was of little economic value and had to be disposed of.[21] Coalgate *et al* suggested that in strip mines this material could be placed at the bottom of the pit and buried.[22] For underground mines refuse material was placed near the mine site in large mounds called gob piles, or a more preferable term, "coal refuse piles."[23] Coal refuse piles were also found at tipple sites. In a recent study, Waller reported on acid drainage from such a pile and the contamination of water by acid and heavy metals that passed through it.[24] In a description by Thomas, coal was crushed at the tipple site following its separation from coarse refuse that created fine sediments of coal, dirt, pyrite, shale,

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[21] Approved disposal is now required by law, but in the pre-law mining era there were no restrictions.

[22] J. L. Coalgate, D. L. Akers, and R. W. Frum, *Gob Pile Stabilization, Reclamation and Utilization*, *Interim report no. 1, Research and Development Report no. 75* (Office of Coal Research, May 1973), p. 114.

[23] Donald M. Corbett, *Runoff Contributions to Streams from Cast Overburden of Surface Mining for Coal, Pike County, Indiana*, Report of investigations no. 1 (Bloomington, Indiana: Water Resources Research Center, Indiana University, December 1965), p. 7.

[24] W. A. Waller and Associates, *Pollution Control Guidelines for Coal Refuse Piles and Slurry Ponds* (U.S. Environmental Protection Agency EPA-600/7-78-222, 1978), p. 11.

and water.[25] This mixture flowed to a settling pond and, like coal refuse piles, became a source of acid discharge.

In a study of stream pollution from coal refuse pile drainage, Ramaley and Kindig demonstrated that refuse material was entering streams and that increased pollutant levels occurred after periods of increased stream flow.[26] Corbett and Agnew described this condition as a "flushout."[27] It resulted from rains ending periods of low flow and drought. This accelerated flow caused materials to be picked up or washed into the stream from streambeds, mine waste piles, and oxidized materials collected on the banks and in the floodplain.[28]

Corbett pointed out that coal seams which were considered to be major sources of acid, were not large producers when compared with coal refuse piles.[29] His

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[25] Thomas Thomas, An Analysis of Abandoned Coal Mines in West Central Indiana and Suggested Reclamation Techniques (Terre Haute, Indiana: West Central Indiana Economic Development District, Inc., 1978), p. 8.

[26] R. Ramaley and R. Kindig, Stream Pollution from Coal Mine Waste Piles (Indianapolis, Indiana: Indiana Academy of Science, 1969), p. 60.

[27] Donald M. Corbett and Alan F. Agnew, Hydrology of the Busseron Creek Watershed, Indiana, Report of investigations no. 2 (Bloomington, Indiana: Water Resources Research Center, Indiana University, 1968), p. 2.

[28] G. T. Bookman, J. J. Binder, and W. A. Wade, III, "Measurement and Modeling of Storm Water Runoff from Coal Storage Piles and the Impact on Receiving Waters," Proceedings of the Acid Mine Drainage Conference-Coal Conference (Louisville, Kentucky: October 1979), p. 119.

[29] Corbett, Runoff Contributions to Streams, p. 94.

reasoning was that coal waste piles contained more exposed pyritic material that readily oxidized and became available to the receiving stream during the first storm of sufficient intensity.

With regard to streams, Corbett and Agnew concluded that flushouts depended upon the magnitude and intensity of a storm, the length of time since the last flushout, and that old waste piles were a major cause of acid water.[30]

During a rainfall, a coal waste pile, oxygen in the air, and the pyritic material provided an environment favorable to acid formation. According to an Ohio State study, the clays, shales, and sandstones that were found in a waste pile weathered and eroded to expose new surfaces to acid production.[31] This process would continue, if left alone, until the whole coal waste pile was completely eroded.

A study for the Truax-Traer Coal company by Barthauer, Kosowski and Ramsey of a 40-acre coal waste pile found that the reaction zone of a refuse pile was limited to the top 4 inches from the surface exposed to the atmosphere.[32] In noncompacted areas this zone could extend as far as 24 inches.

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[30] Corbett and Agnew, Hydrology, p. 4.

[31] The Ohio State University Research Foundation, Acid Mine Drainage, p. 33.

[32] G. I. Barthauer, Z. V. Kosowski, and J. P. Ramsey, Control of Mine Drainage from Coal Mine Mineral Wastes, Phase I, Water Pollution Control Research Series 14010-DDH-8171, U.S. Environmental Protection Agency, 1971, p. 14.

The Truax-Traer study also reported 54 percent of rainfall appeared immediately as acid runoff from a coal waste pile.[33] The remaining 46 percent infiltrated the pile and reappeared as seepage or evaporated. In a study of storage piles of coal kept at power plants, Cox et al found 73 percent of total runoff was direct runoff and pHs were 2.2 - 3.1.[34] Weeter, in a national survey of storage coal piles kept at power plants, listed that the pHs of 204 samples ranged from 1.5 - 7.6, and 85 percent of the samples exceeded the 6 - 9 pH standard.[35]

Based on his experience with coal oxidation from coal storage piles, Lowthian stated increased pollution can be expected from: (1) coal containing high concentrations of natural moisture, oxygen, and sulfur, (2) increased flow in fluids (e.g. air and water) contacting the coal, (3) alternate wetting and drying of the coal surface, (4) freshly mined or crushed coal, (5) higher coal surface area, (6) higher temperatures, (7) increased pyrite content, and (8) lower coal rank.[36] Since coal refuse piles contain

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[33] Ibid.

[34] D. B. Cox, T. Chu, and R. J. Ruane, Characterization of Coal Pile Drainage (Chattanooga, Tennessee: Tennessee Valley Authority, Division of Environmental Planning TVA-EP-79/13, 1979), p. 14.

[35] D. W. Weeter, "Coal Pile Water Quality Management-Results of a National Survey," Proceedings of the 33rd Indiana Waste Conference, Purdue University (Ann Arbor, Michigan: Ann Arbor Science, 1979), p. 302.

[36] W. E. Lowthian, "Pit and Berm Coal Storage," Proceedings of the 33rd Indiana Waste Conference, Purdue University (Ann Arbor, Michigan: Ann Arbor Science, 1979), p. 532.

higher percentages of unwanted impurities in coal than that which is found at power plants, an even greater pollution load should result.

Coal Waste Piles as a Sanitary Landfill

The use of sanitary landfills for waste disposal is a common practice.[37] In many cases, however, leachates from sanitary landfills were recognized as ground water pollutants.[38]

In a study by Raveh and Avnimelech, average pH values were reported for sanitary landfill leachates under different compaction rates, varying moisture contents, and during different seasons.[39] They found that the lowest pH values occurred during the initial period of waste filling, especially when temperatures were high and the waste well aerated. Similar observations were reported by Johansen and Carlson.[40]

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[37] A. E. Zanoni, "Ground Water Pollution and Sanitary Landfills: A Critical Review," Groundwater 10 (1972): 4.

[38] D. A. Shuster, Leachate Damage Assessment: Case Study of the Fox Valley Solid Waste Disposal Site in Aurora, Illinois (Cincinnati, Ohio: U.S. Environmental Protection Agency EPA/530/SW-514, 1976), p. 17.

[39] A. Raveh and Y. Avnimelech, "Leaching of Pollutants from Sanitary Landfill Models," Journal of the Water Pollution Control Federation 51 (1979): 2705.

[40] O. J. Johansen and D. A. Carlson, "Characterization of Sanitary Landfill Leachates," Water Resources 10 (1976): 1129.

In the United States, municipalities are using abandoned coal strip mines as solid waste disposal sites.[41] However, these sites are often rated as marginal because of their threat to ground and surface water pollution. Coal tailings are moderately permeable, and when refuse is placed in it, leachate movement can occur. The bottoms of coal pits are often of impervious soft shale so movement is lateral. Surface water pollution occurs when moderately permeable spoil is used as a cover material. Not only does this facilitate leaching, but the coal fines generate acid drainage which accelerates the leaching process. A leachate/acid drainage condition is capable of severe environmental damage.

Modeling Acid Pollution

In a discussion of modeling natural water systems, Silva and Harp made the point that natural water systems responded in a variety of ways to inputs and forcing functions.[42] The responses of the water systems could be

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[41] A brief analysis of the suitability of surface mines for waste disposal was given by W. F. Reynolds, Abandoned Strip Mines Studied for Solid Waste Disposal (Redgewood, New Jersey: Public Works Journal Corporation, 1967): 74-5. A more detailed analysis can be found in H. W. Sheffer, Case Studies of Municipal Waste Disposal Systems (Washington, D.C.: U.S. Bureau of Mines Information Circular 8498, 1971).

[42] Homero Silva and Jimmy Harp, The Role of Streams in Pollution, Dilution and Dispersion (Stillwater, Oklahoma: Oklahoma Water Resources Research Institute, Technical Completion Report OWRT-A-083-OKLA, Oklahoma State University, 1978), p. 13.

assessed in spatial and temporal distributions. Modeling was an abstraction of the relationship between the contiguous environment (e.g., rainfall, runoff, surface, and ground water characteristics that determine background water quality) and the variety of man-made effects (e.g., waste water discharge, coal pile runoff, or particular land uses). As such, a model could not incorporate all phenomena but rather abstracted those portions of the physical world that were relevant to the problem under consideration.[43]

O'Loughlin and Bowmer pointed out that when a soluble material was injected into a flowing stream, its eventual fate was determined by the physical processes of diffusion, convection, chemical degradation, absorption, and evaporation.[44] Moreover, after the material was added to a stream it behaved as a one dimensional slug which had a concentration gradient in the direction of flow that could be modeled.

There have been many studies done by engineers to model the concentration gradient. Taylor introduced the dispersion coefficient concept to describe the one dimensional transport process based on cross sectional average

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[43] Ibid., p. 14.

[44] Emmett M. O'Loughlin and Kathleen H. Bowmer, "Dilution Decay of Aquatic Herbicides in Flowing Channels," <u>Journal of Hydrology</u> 26 (1975): 217.

concentrations.[45] Fischer added that before Taylor's dispersion coefficient could apply, a convectional period existed.[46] This convectional period would last from the time the material entered the stream until it became nearly uniform in the stream cross section. The distance downstream to this point was referred to by Beltaos as the mixing length.[47] These ideas were generally accepted, and it was widespread engineering practice to define a dispersion coefficient for all times and distances, and to test it by experimentation.[48] According to Buchanan, in the general dispersion model a contaminant was injected into a stream, and it moved downstream at a certain velocity while undergoing dilution caused by dispersion.[49] The wave of concentration gradually spread as it moved downstream, resulting in decreased peak concentrations.

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[45] G. I. Taylor, "The Dispersion of Matter in Turbulent Flow through a Pipe," Proceedings of the Royal Society of London 223, Series A (1954): 446.

[46] H. B. Fischer, Longitudinal Dispersion in Laboratory and Natural Streams (Pasadena, California: Kneck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Report KH-R-12, 1966), p. 5.

[47] S. Beltaos, "Longitudinal Dispersion in Rivers," Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 106, HY1 (1980): 151.

[48] R. S. McQuivey and T. N. Keefer, "Dispersion-Mississippi River Below Baton Rouge, La.," Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers 102, HY10 (1976): 1426.

[49] T. J. Buchanan, "Time Travel of Soluble Contaminants in Streams," Journal of the Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers 90, SA3 (1964): 2.

However, the use of the dispersion coefficient has shortcomings. Liu and Dieter reported that not only does this method require cumbersome and expensive dilution measurements, but that the dispersion coefficient varied from river to river, from reach to reach in the same river and from discharge to discharge.[50]

Clearly, much work remained to find a model that overcame the shortcomings. The engineering studies mentioned applied to general dispersions in streams and not specifically to acid water.

A variety of studies that incorporated some of the principles described above have been applied specifically to the dispersion of acid mine water in streams. These studies ranged from qualitative attempts to model the behavior of acids in streams to sophisticated mathematical analysis.

Hoehn and Sizemore coupled discharge rates with chemical concentrations to calculate the average daily total added to a stream.[51] However, this study was

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[50] H. Liu and J. Dieter, III, "Predicting Longitudinal Dispersion of Pollutants in Rivers," in _Hydraulics in the Coastal Zone; Proceedings of the 25th Annual Speciality Conference, Texas A and M University, August 1977_ (New York: American Society of Civil Engineers, 1977), p. 136.

[51] R. C. Hoehn and D. R. Sizemore, "Acid Mine Drainage (AMD) and Its Impact on a Small Virginia Stream," _Water Resources Bulletin_ 13 (1977): 153.

criticized by Chadderton because the possibility of dilution effects downstream was discounted.[52]

The relationship between pH and discharge was not clear-cut. Curtis observed an increase in pH activity and flow after mining disturbances in Kentucky.[53] A similar observation was made by Plass in West Virginia, but he reported increases that were not as dramatic.[54] Minear and Tschantz made the related association that in virgin watershed streams there was relatively little variation in pH with season from year to year, while greater ranges were detected in watershed streams disturbed by mining.[55]

They also reported that surface mining disturbance led to an increase in dry weather flow since there was continued streamflow in disturbed areas while undisturbed watersheds ceased streamflow during the late summer. The idea of coal refuse piles as an area for water storage was previously expressed by Corbett.[56]

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[52] R. A. Chadderton, "Discussion-Acid Mine Drainage and Its Impact on a Small Virginia Stream," Water Resources Bulletin 13 (1977): 1286.

[53] W. R. Curtis, "Chemical Changes in Streamflow Following Surface Mining in Eastern Kentucky," Proceedings of the Fourth Symposium on Coal Mine Drainage Research (Pittsburgh, Pa.: Mellon Institute, 1972), p. 214.

[54] W. T. Plass, "Changes in Water Chemistry Resulting from Surface Mining of Coal in Four West Virginia Watersheds," Green Lands (Quarterly of the West Virginia Surface Mining and Reclamation Association) 22 (1976): 45.

[55] Roger A. Minear and Bruce A. Tschantz, "The Effect of Coal Surface Mining on the Water Quality of Mountain Drainage Basin Streams," Water Pollution Control Federation Journal 48 (1976): 2556.

[56] Corbett, Runoff Contributions, p. 47.

In particular, Curtis found alternate wetting and drying periods in late summer led to the highest concentrations of dissolved chemicals in streams.[57] However, in the study by Minear and Tschantz, comparisons of rainfall data and concentration did not reveal a clear association.[58] Gang and Langmuir tried also to relate contaminant concentration with streamflow.[59] They attempted to measure the dilution effects from rainfall runoff in unmined areas and increases in concentration caused by flushouts in mined areas. This relationship was complex and difficult to model because of the dependence on the amount of rainfall and the period between leachings.

In another study relating pH and flow, Jenkins and Carroll found that pH remained relatively constant and independent of flow.[60] In a later and much larger study, again, no universally applicable relationship was found between flow and acidity.[61] Factors that affected acidity

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[57] Curtis, "Chemical Changes," p. 224.

[58] Minear and Tschantz, "Effect of Coal Surface Mining," p. 2565.

[59] M. W. Gang and D. Langmuir, "Controls on Heavy Metals in Surface and Groundwater Affected by Coal Mine Drainage: Clairion River-Redbank Creek Watershed Pennsylvania," in Proceedings of the Fifth Symposium on Coal Mine Drainage Research (Louisville, Kentucky: 1974), p. 80.

[60] Charles R. Jenkins and Henry C. Carroll, "Mine Acid Drainage and Associated Flow Fluctuations." West Virginia Academy of Science Proceedings 41 (1969): 286.

[61] W. A. Sack et al., Modeling of Acid Mine Drainage and Other Pollutants in the Monongahela River Basin under Low Flow Conditions (Morgantown, West Virginia: Civil Engineering Department, West Virginia University, 1976), p. 11.

and discharge relationships were reported to be the presence or absence of alkaline municipal discharges, ground water alkalinity, geological formations in the area, relative proportion of mine flow to stream flow, basin size, and storm frequency. The research that generated these findings was very extensive, using data from over 100 municipalities and 2000 mine-related discharges. The purpose was to form a basis for future water quality management and river planning for West Virginia. The computer programs to model net acidity, total dissolved solids, dissolved oxygen demand, and ultimate oxygen demand were part of the QUAL 2 model developed for the U.S. Environmental Protection Agency.[62]

Another large program for a computer was developed at Argonne National Laboratory for the State of Illinois Water Quality Management Program.[63] Program BASIN can route pollutants through a simulated river system. Yeasted added two subroutines to this program to allow it to simulate the effects of acid mine drainage on the water quality

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[62] Water Resources Engineers, Inc., Computer Program Documentation for the Stream Quality Model QUAL 2, prepared for the U.S. Environmental Protection Agency, May 1973.

[63] H. L. Dyer (Director), State of Illinois Water Quality Management Program, Appendix E, The Water Quality Model QUAL 2, prepared for the U.S. Environmental Protection Agency, May 1973.

of a river system.[64] One of these subroutines allowed the prediction of pH at selected points of a river once alkalinity and CO_2-acidity were known. This could be applied to analyze the effects of mine drainage abatement actions on principal sources of pollution.

The Ohio State University Research Foundation has also developed its own model for mine drainage simulation.[65] The comprehensive model was designed for the optimization of alternative treatment strategies to control mine acid pollution. The model was flexible enough so that "worst" conditions could be simulated in situations expected every 10 or 100 years, or during wet or dry conditions in the hydrologic year.

In summary, there have been numerous attempts to model the behavior of acid mine drainage in streams. At this time, sophisticated computerized models are able to predict the pH of streams, if enough data are available. However, there is no generally agreed upon relationship between pH levels and flow. In large scale simulations it is understandably difficult to relate dilution with distance downstream. Often the accuracy of such models is judged by the overall predictions and not the behavior of separate reach to reach stream segments.

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[64] Joseph G. Yeasted, "Computation of pH Profiles in a Free Flowing Branched River System with Multiple Acid Loads" (M.S. thesis, Carnegie-Mellon University, 1974).

[65] K. S. Schumte et al., Resource Allocation to Optimize Mining Pollution Control (Columbus, Ohio: Ohio State University Research Foundation, 1976).

The research described in this study helped to fill that gap by reporting on the distance component of acid dilution downstream from a source, and how that might change under low-flow conditions of late summer and fall. This has been done by studying the dilution of acid mine water that entered a stream from a sanitary landfill which was also the site of a coal refuse pile. The acid water movement was measured until pH downstream was equal to pH upstream of the source. A description of the study site is contained in Chapter 3.

Chapter 3

IDENTIFICATION OF THE STUDY AREA

Introduction

Additional information about a portion of Honey Creek used as the study area was a prerequisite for an assessment of acid mine drainage. This portion of Honey Creek was chosen as the study area because it was reported in previous studies that seasonal variations in pH and flow did exist downstream from the abandoned Victory coal mine[66] (map 1).

The Victory Mine property is located approximately 6 miles east of Terre Haute and is currently used as a sanitary landfill for Vigo County. The site covers 165 acres on which there is a 15-acre, 18-feet-deep slurry pond that borders Honey Creek on the south. Breaks in the retaining dam allow slurry material to be flushed into the stream. There are gob piles on the property, and gob is being used by the sanitary landfill operation as a cover material.

The flow of water in Honey Creek is sustained primarily by ground water. The ground water, sampled in wells

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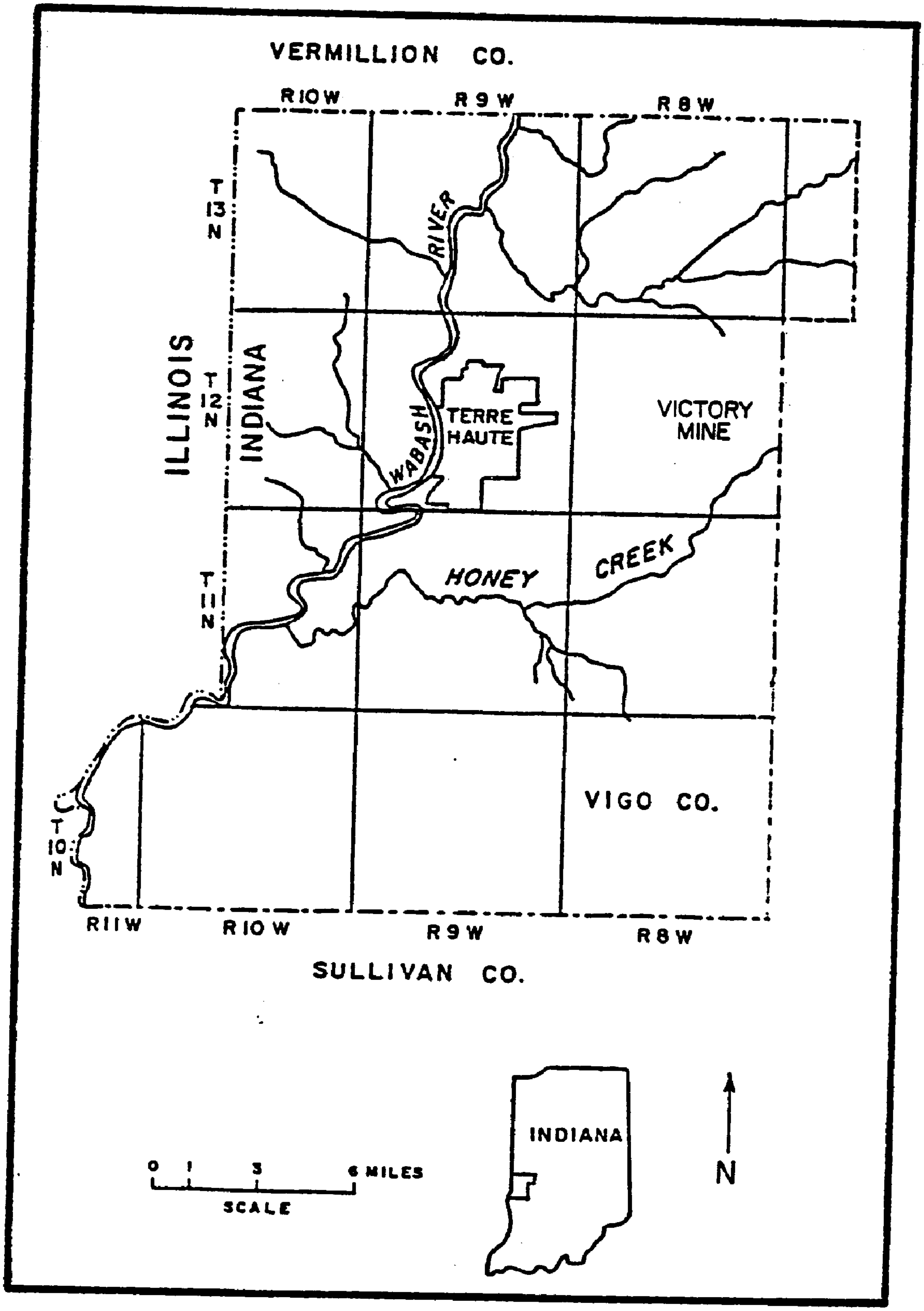
[66] See Thomas, <u>Abandoned Coal Mines</u>, p. 110 and Oytunde Salako, "Seasonal Comparative Analysis of the Pollutants in Honey Creek, Sugar Creek and Coal Creek Tributaries of the Wabash River" (M.A. thesis, Indiana State University, 1980).



Map 1. Location of the study area (after U.S., Department of Interior, Principal Aquifers, p. 3).

found in this area, has been tested and found to have consistent pHs in the 7.1 - 8.9 range.[67] These pH values were measured in water yielded from sand and gravel glacial outwash deposits. Water from these sources helps the stream buffer acid entering it. This ability to neutralize acid meant that following an acid discharge into the stream, pH would be depressed, but that recovery would occur quickly and not far downstream from the point of entry. That behavior was an aid in the data collection because it required fewer sampling stations than would be necessary if the acid contamination extended farther downstream.

Another feature which made this portion of Honey Creek a desirable study area was the presence of two sources of acid mine drainage. In addition to the acid drainage from the Victory Mine site, acid entered Honey Creek farther downstream from an underground source. It was, therefore, possible to measure two sources of acid drainage. The two sources were far enough apart to permit acid from the upstream gob and slurry to be diluted to near pre-acid levels before drainage from the underground source, an air shaft from the abandoned mineworks of the Victory operation, entered the stream.

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[67] U.S., Department of Interior, Geological Survey, Hydrogeology of the Principal Aquifers of Vigo and Clay Counties, Indiana, Bulletin No. 34, by L. Cable, F. Watkins, and T. Robinson (Washington, D.C.: Government Printing Office, 1971), p. 3.

[68] U.S., Department of Interior, Principal Aquifers, p. 24.

Description of the Study Area

Geology. Honey Creek has a drainage basin area of about 89.6 square miles.[69] However, in this study, acid water was measured only along a 4.4 mile segment of Honey Creek that has a drainage area of 18.9 square miles (map 2).

The study area is wholly contained in the Wabash Lowland physiographic province which has an average elevation of about 550 feet. The Wabash Lowland is a plain of low relief underlain by siltstone and shale of Pennsylvanian age. It is bounded on the west by the Wabash River, on the east by the Crawford Upland, and on the north by the glacial deposits of Wisconsin age. There are extensive aggraded valleys and, in places, thick lacustrine, outwash and alluvial sediments.[70] Materials of Pleistocene and Recent age cover most of the area (figure 1). These materials are unconsolidated and include glacial, glacial-fluvial, alluvial, and eolian deposits. The average thickness of the unconsolidated material in the study area is 100 feet and consists of coarse textured sand and gravel. The water bearing sand and gravel make up an important aquifer in Vigo County that is covered by poorly sorted and fine grained Illinoian age tills to a depth of about 45 feet.

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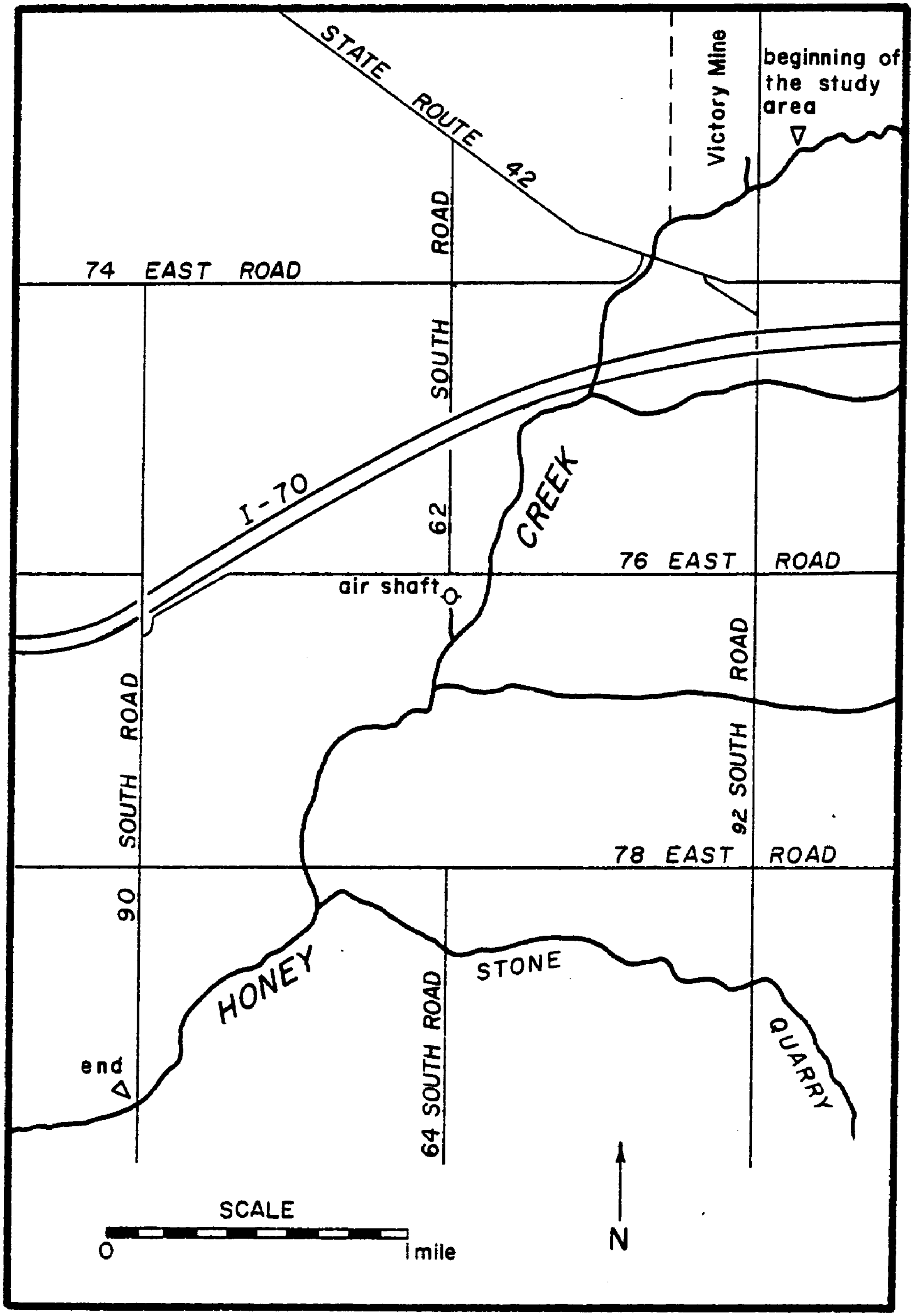
[69] U.S., Department of Interior, Geological Survey, Water Resources Division, Drainage Areas of Indiana Streams, by R. Hoggatt (Washington, D.C.: Government Printing Office, 1975), p. 210.

[70] Alan Frank Schneider, "Physiography," Natural Features of Indiana (Indianapolis, Indiana: Indiana Academy of Science, 1966), p. 48.



Map 2. The study area

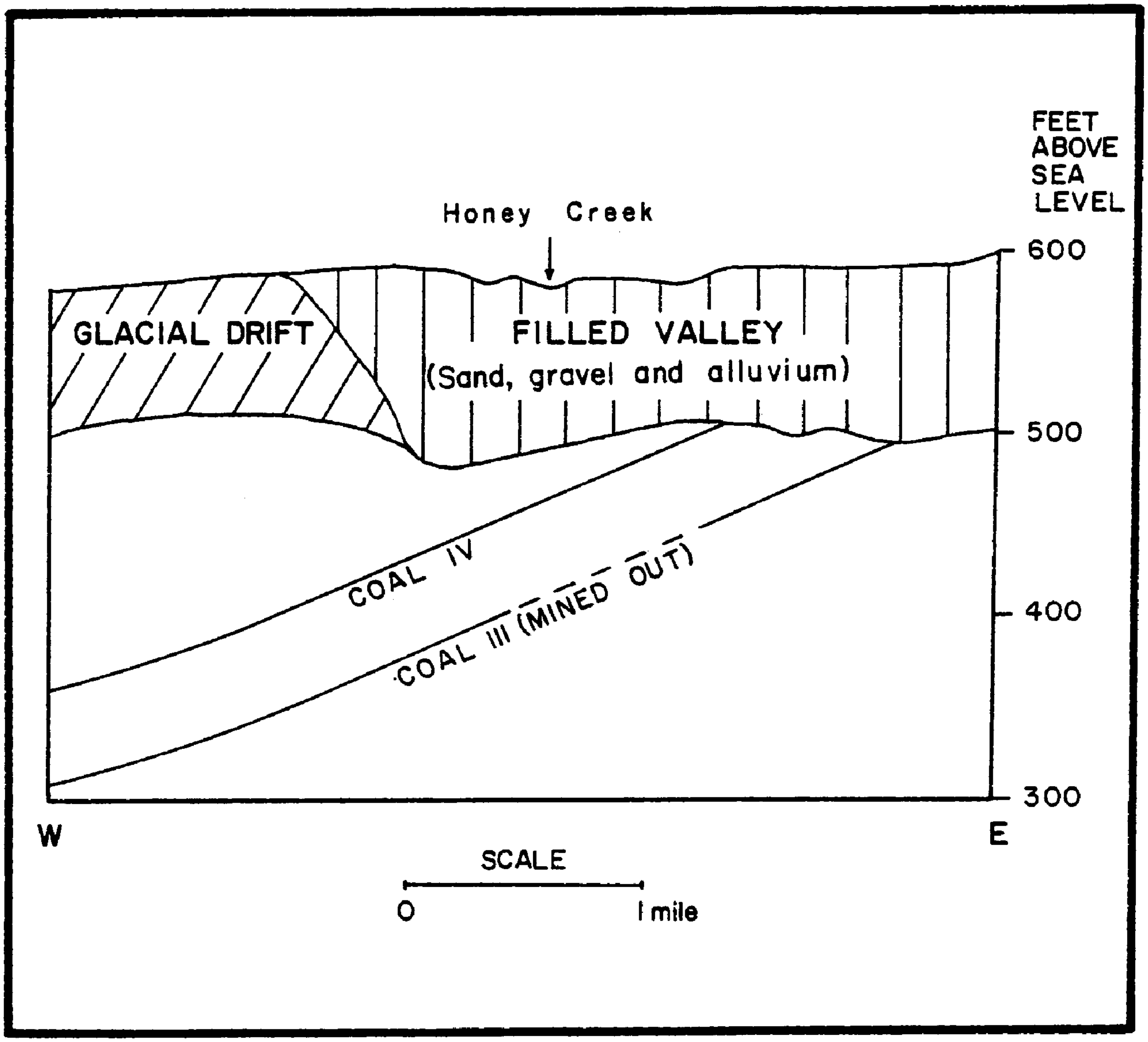


Fig. 1. Cross section of the study area. Modified from Indiana Department of Conservation, Geological Survey, Distribution, Structure and Mined Areas of Coals in Vigo County, Indiana. Preliminary Coal Map No. 1, by C. E. Wier (Bloomington, Indiana: Geological Survey, 1972). The location of the cross section is found on map 3, p. 38.

Underlying the unconsolidated deposits of the study area are carbon bearing rocks of Middle Pennsylvanian age. The uppermost consolidated bedrock layer is the Petersburg Formation. Lying beneath the Petersburg Formation are the Mansfield, Brazil, Staunton and Linton formations. Deposits of coal of Pennsylvanian age that lie in beds that dip 20 to 30 feet per mile to the southwest are found within the formations located in the study area.[71]

The coal mined in the study area is that of Coal III found in the Staunton Formation. Known commonly as the Seelyville Coal, it has an average thickness of 5.9 feet, contains bands of vitrain, is pyritiferous and exhibits cubic cleavage. It is a high sulfur and medium ash coal which required mechanical cleaning for the domestic, steam and electric power uses for which it was marketed (table 2). Coal III was mined in the study area from 1943 to 1954 at the Victory Mine. From this slope mine 6,307,030 tons of coal were extracted.[72]

Coal continues to be mined east of the Honey Creek study area by stripping operations of the Amax Coal Company. Although the land within the study area does not drain

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[71] Indiana Department of Natural Resources, Coal Strip Mines in Indiana, Geological Survey Special Report No. 6 (Bloomington, Indiana: Geological Survey, 1972), p. 3.

[72] U.S., Department of Interior, Geological Survey, Geology and Coal Deposits of the Seelyville Quadrangle, Vigo County, Indiana. Coal Investigations Map C-27, by H. Hutchison (Washington, D.C.: Government Printing Office, 1958).

TABLE 2

ANALYSIS OF COAL III

MOISTURE (Percent)	ASH (Percent)	VOLATILE MATTER (Percent)	FIXED CARBON (Percent)	SULFUR	HEAT VALUE (Btu/lb.)
14.50	8.70	38.91	37.89	3.31	11,187

SOURCE: Hutchison, Coal Investigations Map C-27.

disturbed property, the possibility of pit pumpage from the mining operation into tributaries leading to Honey Creek does exist. Therefore it was necessary to monitor those tributaries during the course of the study.

Hydrogeology. The deposits of Recent age in the study area are mostly floodplain sediments and wind-blown sand. However, they are not important sources of ground water. It is the unconsolidated glacial deposits of Pleistocene age which are the main sources of ground water in the study area. These deposits of glaciofluvial sand and gravel were laid down when the Wabash Valley served as a sluiceway for meltwater from glaciers farther to the north. Wells penetrating this unconsolidated but confined aquifer range from 45 to 100 feet in depth, and the water level in these wells ranges from 20 to 35 feet from the surface. The hydraulic gradient is toward the southwest following the regional dip of the bedrock systems. The water table is found at a depth of 0 to 6 feet below the surface.

The ground water in the study area occurs under confined conditions (map 3). This saturated aquifer of sand and gravel is interbedded with and overlain by till. Water is discharged into the stream by effluent seepage through the overburden where the aquifer is shallow. The average yield of wells in this area is 25 gallons per minute, and the measure of the capacity to transmit water, the field coefficient of permeability, is 550 gallons per day.[73]

The water quality is characterized by excessive iron and high concentrations of bicarbonate and thus is very hard. The high bicarbonate concentration results from the presence of fragmented calcareous material, such as dolomite and limestone, found in the unconsolidated rocks. Calcium and magnesium ions are taken into solution as bicarbonates. Water, primarily from precipitation, passes through the unconsolidated material. Chemical reactions with this bicarbonate water and rock material are the ultimate neutralizers of acid mine drainage and account for the very great buffering capacity of streams in this area.

Soils. The soils in the study area consist of the Genessee-Shoals-Wakeland association (map 4). They are derived from the material of the surrounding loess covered uplands and are found along the floodplain of Honey Creek.

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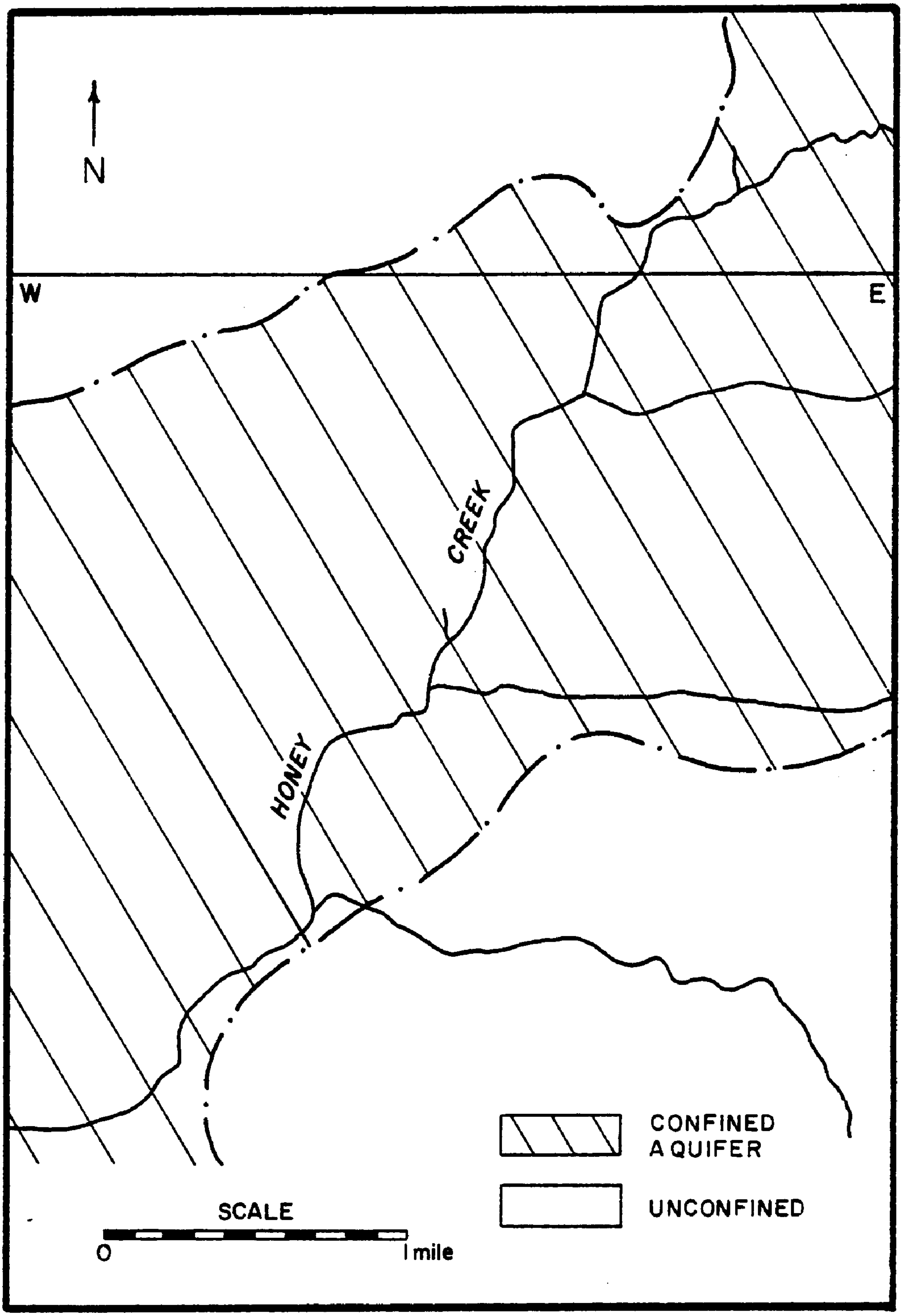
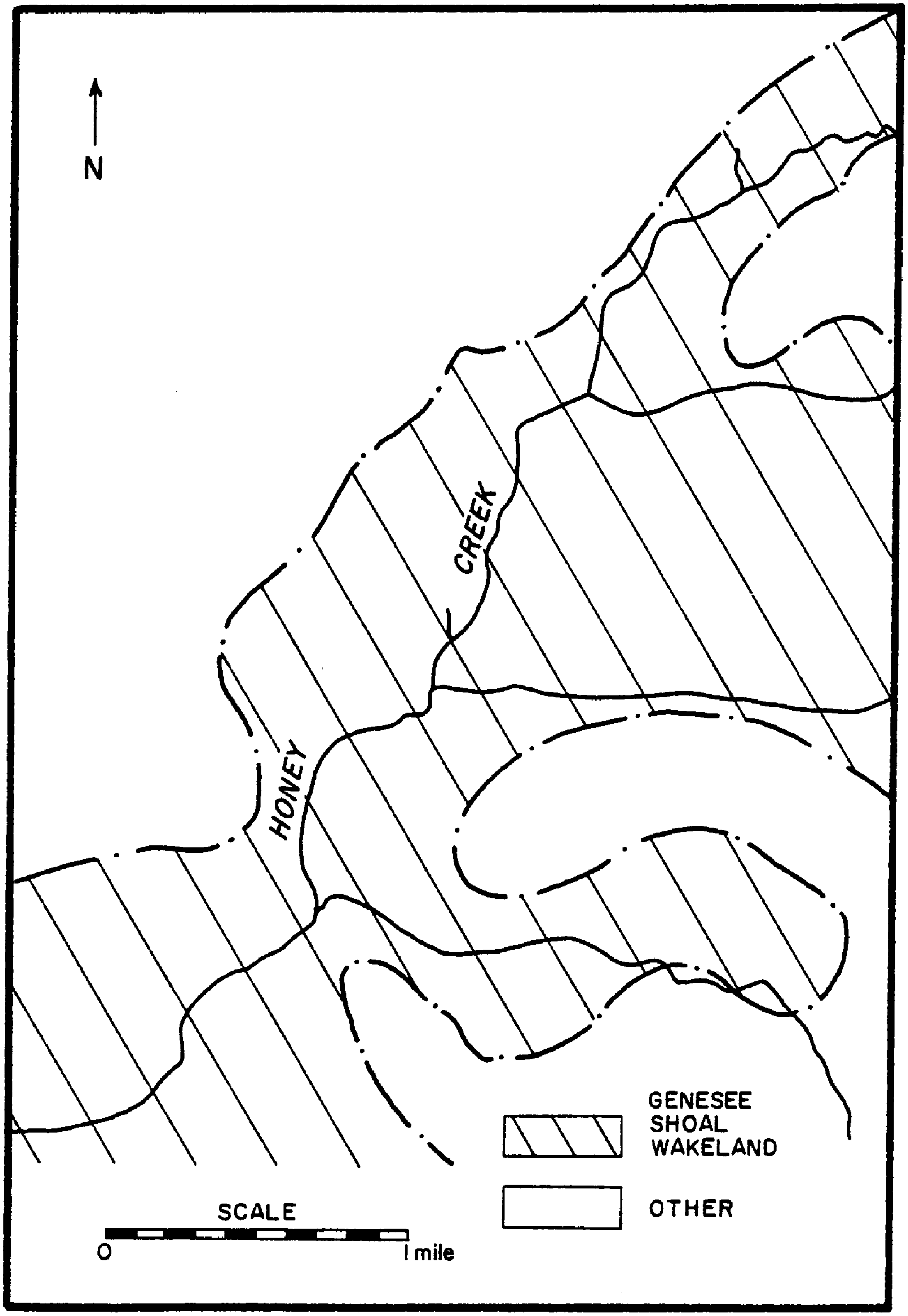
[73] U.S., Department of Interior, Principal Aquifers, p. 31.



Map 3. Boundary of the aquifers in the study area (after U.S., Department of Interior, Principal Aquifers, Plate 5).



Map 4. Soil boundary in the study area (after U.S., Department of Agriculture, Soil Survey).

The native vegetation is mixed hardwoods. All of these soils have high available water capacity and moderate permeability. The pHs in the soil range from being mildly alkaline to medium acidity (table 3).

It has been reported that an effect of flooding an area with acid mine water was to lower the pH of the soil, especially in the upper horizons of the soil.[74] Further, the calcium content and percent base saturation were lowered while cation exchange capacity, iron and aluminum contents increased.[75] However, since the average pH measured in Honey Creek was very close to the pH of the soils in the study area, the stream was not likely to alter the pH of the soil and vice versa.

Soil boring data from the floodplain of Honey Creek identified a silty clay loam surface layer and a subsoil of silt clay. Other borings taken from the floodplain illustrated the variability found in this alluvial deposit (table 4).

Climate. The climate of the study area is humid continental, under the influence of polar-tropical air masses. Passages of fronts and centers of high and low

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[74] R. L. Blevins, H. H. Bailey, and G. E. Ballard, "The Effect of Acid Mine Water on Floodplain Soils in the Western Kentucky Coal Fields," Soil Science 110 (1971): 191-6.

[75] E. J. Crolkosz, L. T. Kardos, and W. F. Beers, "The Effect of Acid Mine Drainage on Two Pennsylvanian Soils," Soil Science 127 (1979): 102-7.

TABLE 3

SOIL pHs FOUND IN THE STUDY AREA

Soil Series	Depth (in.)	pH
Genesee	0 - 9	6.1 - 7.3
	9 - 34	6.6 - 8.4
	34 - 72	7.4 - 8.4
Shoal	0 - 11	6.1 - 7.3
	11 - 53	6.1 - 7.3
	53 - 78	6.5 - 8.4
Wakeland	0 - 8	5.6 - 7.3
	8 - 38	5.6 - 7.3
	38 - 72	5.6 - 7.3

SOURCE: U.S., Department of Agriculture, Soil Survey.

TABLE 4

SOIL BORING DATA FROM THE STUDY AREA

Site	Depth(ft.)	Texture	Gravel(%)	Sand(%)	Silt(%)	Clay(%)
29	0.0 - 0.8	Silt loam	0	14	68	18
	0.8 - 2.5	Silt clay loam	0	9	62	29
	4.6 - 6.0	Clay	0	32	37	31
33 (left)	0.0 - 2.2	Silt clay loam	0	17	58	25
	4.5 - 6.0	Silt clay	0	16	52	32
	8.0 -10.0	Silt clay	0	2	53	45
	20.0 -23.0	Silt clay	0	9	55	36
33 (right)	6.0 - 8.0	Silt loam	1	39	53	7
	8.0 -10.0	Sand	1	87	6	6
	14.0 -16.0	Loam	0	34	47	19
	18.0 -20.0	Clay	0	7	48	45

SOURCE: P. Yeh, Engineering Soils Map of Vigo County, Indiana, No. 15. (Lafayette, Indiana: Joint Highway Research Project, Purdue University, 1971), p. 46.

pressure change the weather frequently. Monthly average normal temperature and precipitation data for Terre Haute support this description.

A local water budget accounted for incoming and outgoing moisture (table 5). It was appropriate to compile a water budget in this case because it provided a means of relating climatic and hydrologic factors in the watershed. Precipitation, evapotranspiration and runoff, which significantly affect discharge, were the principal elements in the budget. The differences between precipitation received and the changing demands for water provided insight into the role of climate and the amount of surplus water available for stream flow. The water budget was compiled using the Thornwaite method, which made use of a number of tables to determine the statistics.[76] Temperature and precipitation values were normal figures for the Terre Haute area. The water holding capacity, corresponding to the type and structure of the soil in the study area, was 250 mm.

Presenting the data from table 5 in graphic form made the seasonal distributions of the statistics stand out (figure 2). The parameters precipitation (P), potential evapotranspiration (PE), and actual evapotranspiration (AE) defined four areas of the diagram. The surplus area represented the time that soil storage (ST) (row 5 in

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[76] C. Thornwaite and J. Mather, eds., "Instructions and Tables for Computing Potential Evaporation and the Water Balance," in <u>Publications in Climatology</u> vol. 10 (Centerton, New Jersey: Drexel Institute of Technology, 1957), pp. 185-311.

TABLE 5

WATER BUDGET
(All Values Except T and I in mm)

Row	J	F	M	A	M	J	J	A	S	O	N	D
1 T[a]	-1.8	-0.1	4.80	11.90	17.30	22.60	24.30	23.40	19.60	13.80	5.60	-0.2
2 I	0.0	0.0	.94	3.72	6.55	9.82	10.95	10.35	7.91	4.65	1.19	0.0
3 Unadj. PE	0.0	0.0	.40	1.50	2.50	3.60	4.00	3.80	3.00	1.90	.60	0.0
4 Adj. PE	0.0	0.0	12.00	50.00	92.00	134.00	151.00	135.00	94.00	55.00	15.00	0.0
5 P	65.0	54.0	81.00	97.00	118.00	115.00	96.00	69.00	80.00	61.00	80.00	61.0
6 P-PE	65.0	54.0	69.00	47.00	26.00	-19.00	-55.00	-66.00	-14.00	6.00	65.00	61.0
7 Acc. Pot. WL						-19.00	-74.00	-140.00	-154.00			
8 ST	315.0	250.0	250.00	250.00	250.00	231.00	185.00	142.00	134.00	140.00	205.00	250.0
9 ΔST	0.0	0.0	0.00	0.00	0.00	-19.00	-46.00	-43.00	-8.00	+6.00	+110.00	+45.0
10 AE	0.0	0.0	12.00	50.00	92.00	134.00	142.00	112.00	88.00	55.00	15.00	0.0
11 D	0.0	0.0	0.00	0.00	0.00	0.00	9.00	23.00	6.00	0.00	0.00	0.0
12 S	0.0	54.0	69.00	47.00	26.00	0.00	0.00	0.00	0.00	0.00	0.00	61.0
13 RO	16.0	35.0	49.00	49.00	38.00	19.00	10.00	5.00	2.00	1.00	1.00	31.0
14 SMRO	0.0	7.0	15.00	21.00	11.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0
15 Tot. RO	16.0	42.0	64.00	70.00	49.00	25.00	12.00	7.00	3.00	1.00	1.00	31.0

[a] Abbreviations: T, mean air temperature; I, heat index; Unadj. PE, unadjusted potential evapotranspiration; PE, potential evapotranspiration; P, precipitation; P-PE, precipitation minus the potential evapotranspiration; Acc. Pot. WL, accumulated potential water loss (accumulated sum of the negative P-PE values); ST, storage; ΔST, change in soil moisture; AE, actual evapotranspiration; D, moisture deficit; S, moisture surplus; RO, water runoff; SMRO, snow melt runoff; Tot. RO, total runoff.

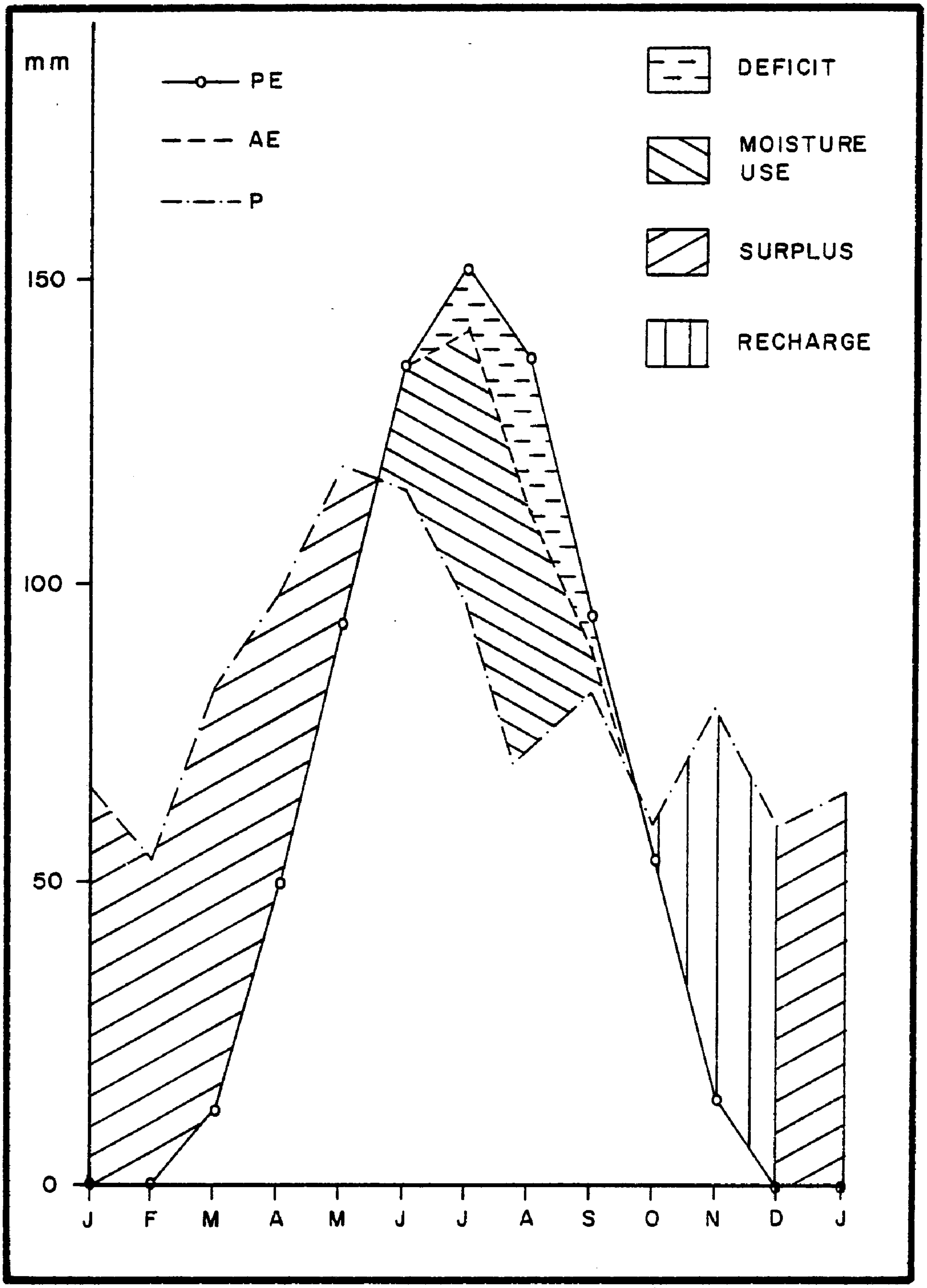

Fig. 2. Water budget for normal data

table 5) was at or above its capacity and P exceeded PE. It was during this period of surplus moisture that runoff (RO) (row 15) was high. This also corresponded with the time of greatest discharge in Honey Creek. The area on the diagram identified as "Deficit" represented that time when PE exceeded P (row 6). During this time the demand for moisture was not met by precipitation, and moisture was extracted from the ground. The low values in row 8 measured this removal. Thus, during July through September, less water was available to contribute to discharge than in previous months. This condition changed during the time identified as moisture recharge. The positive numbers for change in soil storage (ΔST) indicated that even though P was once again greater than PE, moisture was being held in the soil rather than resulting in runoff (line 15). Until the soil storage capacity was reached, less moisture from precipitation was available for discharge as interflow.

The moisture recharge area of the diagram was representative of that time before the soil storage capacity was attained. Thus, available moisture tended to contribute toward soil saturation rather than runoff. After the soil storage capacity was reached, the soil was "full" and additional moisture was considered a surplus. This condition completed the diagram.

Summary

In this chapter, a number of important characteristics about the study area were presented. To interpret the behavior of acid drainage in Honey Creek, the fact that this stream is sustained primarily by ground water and that this ground water is slightly alkaline helps to explain the dilution of acid away from its source.

Chapter 4

RESEARCH DESIGN AND DATA GATHERING

Introduction

In Chapter 2 it was noted that in published literature concerning acid mine drainage, no clear relationship between pH levels and stream discharge has been established. Moreover, little has been written about the distance component of acid dilution downstream from a source of acid drainage. As already stated, the object of this research was to fill this existing gap in the literature by relating pH levels with stream discharge and measuring the extent of acid drainage downstream from a source. The research design followed to assess this problem and the accumulated data are presented in this chapter (figure 3).

Research Design

Figure 3 illustrates the research design and outlines the remaining chapters of this dissertation. Chapter 4 presents the data from the study area which consists of acid mine drainage from two sources. Chapter 5 deals with the analysis of the data which forms the basis for deciding the type of model which would be most appropriate. The model itself is the focus of the 6th chapter and conclusions drawn from this research are covered in Chapter 7.

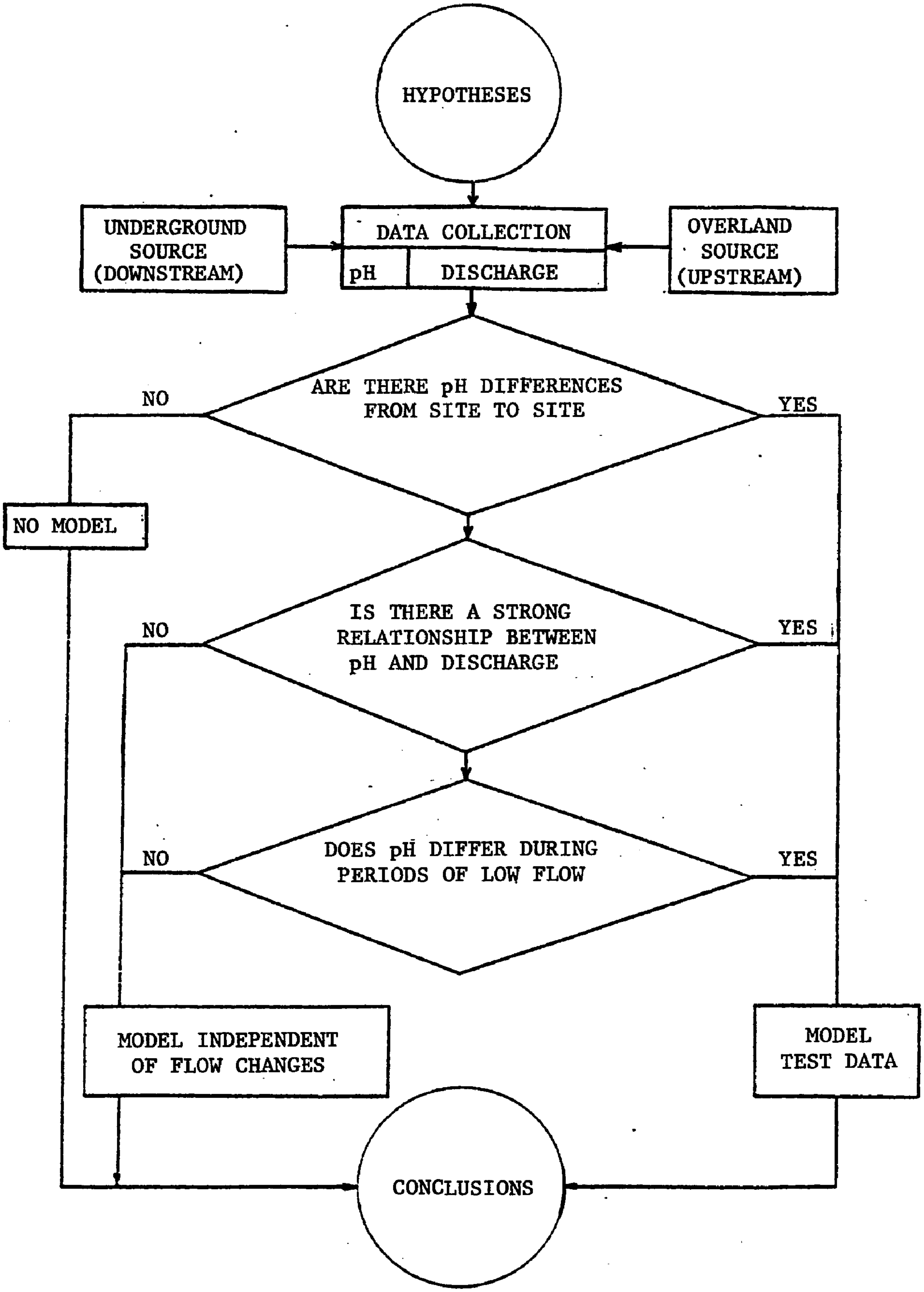

Fig. 3. The research design

Sampling

Ideally, what was desired for this research was a means of continually recording levels of pH, discharge and precipitation along the length of the study area. The only continually recording instrument along that portion of Honey Creek was at the United States Geological Service gauging station.[77] Amax Coal Company has a gauging station in the study area but it operated only sporadically. Hulman Field Airport is located three miles to the west of Honey Creek and it was hoped that Flight Services could provide the needed precipitation data. However, data were not available from any of these sources. Other means of data collection had to be employed.

To collect hydrologic data, a repetitive synoptic sampling approach was adopted. Sampling of the streams was not done on a regular schedule (i.e., every Wednesday at 1:00), but at various times during conditions of interest (after periods of drought, precipitation, etc.). The sampling period was from July 1980 to February 1981, which included the period of low flow in Honey Creek. Precipitation data were obtained from the nearest continually recording rain gauge which was located on the Indiana State University campus, 6.5 miles to the west.[78]

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[77] This station was constructed in the fall and was not operational until October 1980.

[78] Precipitation data will appear in Chapter 5.

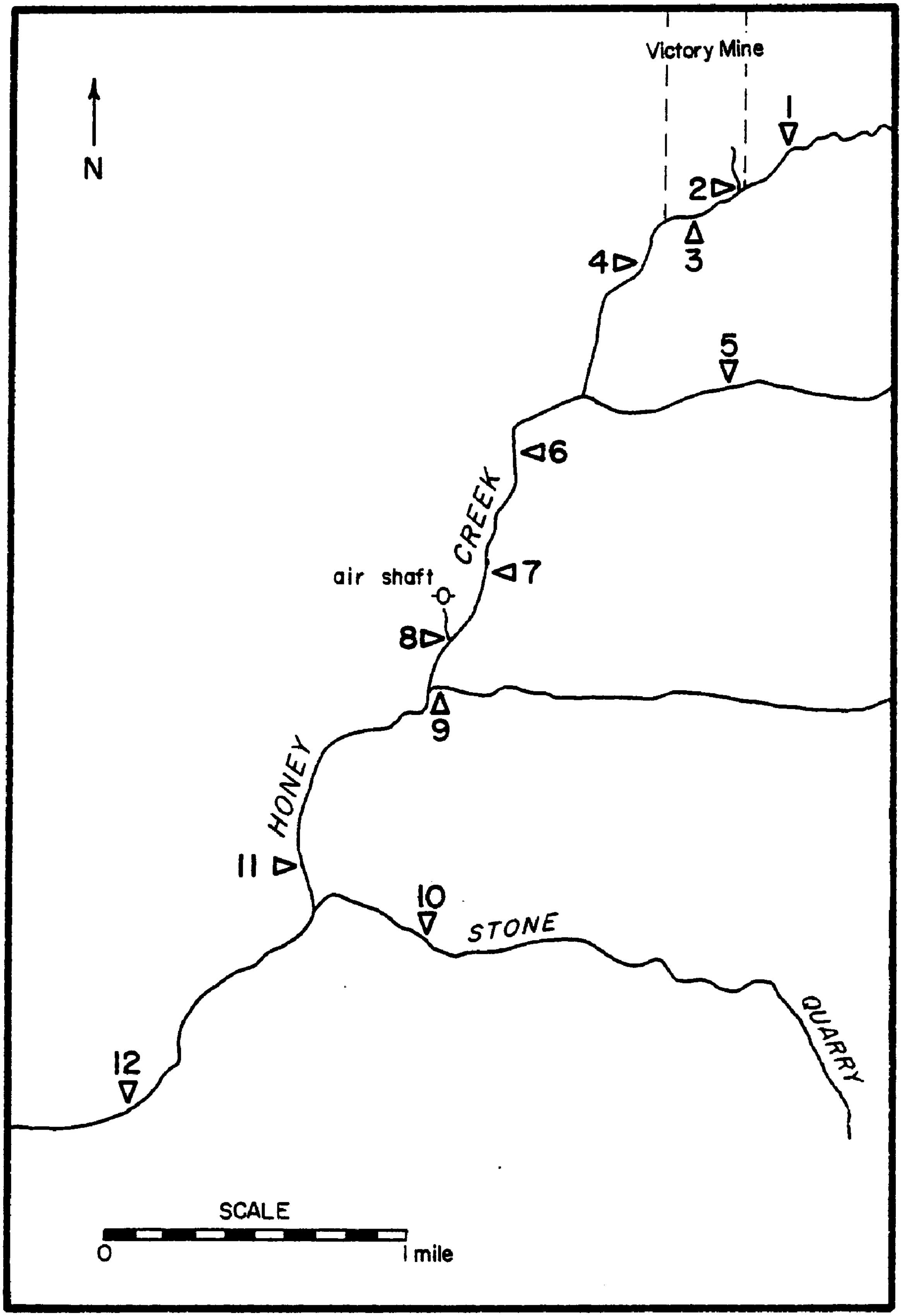
Disharge measurements were made by using a Kahlsico Price Pattern current meter having a rating of .25 to 8.0 fps (feet per second). A Hack digital pH and temperature meter, having an accuracy range of ±.01 and 1.0°C respectively, were used for the acid concentration measurements. Both of these instruments had the advantage of being portable so that measurements could be made instantaneously in the study area.

The time required to monitor the entire five-mile length of the Honey Creek study area and the tributaries on each sampling day was prohibitively long. It was impractical to sample the entire length of the study area each day so a systematic approach was adopted. A series of twelve stations were established where the actual water sampling took place. Thus, the sampling procedure was actually two-fold, occurring in both the temporal and spatial dimensions.

Location of the Sampling Sites

To test the research hypothesis, it was necessary to first collect enough data over a period of time that would be representative of conditions in the study area. To accomplish that, a network of sampling sites was identified along Honey Creek and its tributaries where pH and stream discharge measurements were taken (map 5).

The decisions regarding the placement of these sites were dependent upon a proper location in order to



Map 5. Location of the sample sites

detect changes in concentration and enable one person to make all of the measurements on each sampling day. Another limiting factor was access to the creek. In some places dense vegetation or restrictive property boundaries made it difficult to approach Honey Creek.

Site 1 on map 5 was located upstream from the acid drainage emerging from the Victory Mine landfill property. This enabled pH levels to be established prior to any acid contamination from the landfill. The initial volume of water could also be ascertained. The pH level measured at this point became the standard against which downstream levels would be compared (table 6). When a downstream pH reading equaled or exceeded the pH of site 1, then acid dilution was assumed to be complete.

Site 2 was located at the first encounter with a tributary draining the Victory Mine landfill. This small tributary collects runoff from a five-acre gob area which forms the southeast portion of the Victory Mine property. Discharge from this source ranged from periods of no flow at all to a maximum of 1.65 cfs (cubic feet per second). The fluctuations were due to the amount and intensity of precipitation, plus the length of time since the last precipitation. Although discharge was periodic, the water was consistently very acidic, having a pH range of 1.12 to 3.50.

The third site was located 0.2 miles away from site 2 that allowed any mixing of discharge from that site

TABLE 1

DISCHARGE[a] AND pH MEASUREMENTS TAKEN AT THE SAMPLING SITES, 1980-81

NO.	DATE	SITE 1		SITE 2		SITE 3		SITE 4		SITE 5		SITE 6		SITE 7		SITE 8		SITE 9		SITE 10		SITE 11		SITE 12	
		pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE	pH	DISCHARGE
1	7/20	7.50	.630	nf	0	6.50	.636	6.40	-	7.40	.616	6.90	1.380	7.20	1.415	6.24	.439	7.35	.453	7.38	.565	7.30	2.380	7.20	3.026
2	7/22	8.01	1.648	1.25	.411	7.48	2.313	6.68	-	7.98	1.361	7.36	2.885	7.40	2.973	6.22	.526	7.13	1.413	6.91	1.034	6.78	6.344	7.06	8.862
3	8/03	8.20	.396	nf	0	7.72	.409	7.17	-	8.07	.320	7.81	.715	8.07	.805	6.34	.421	7.65	.349	7.64	.391	7.74	3.493	8.04	4.535
4	8/11	8.24	.641	1.89	.315	7.74	.920	6.81	-	8.16	.574	7.38	1.783	7.90	2.145	6.74	.459	7.74	.505	7.79	.556	7.53	3.121	7.85	5.456
5	8/13	8.19	.541	1.61	.239	7.62	.589	6.94	-	8.19	.493	7.49	1.575	7.94	1.873	6.68	.441	7.75	.346	7.85	.412	7.71	3.195	8.00	3.982
6	8/15	8.15	5.314	3.50	.551	7.66	5.963	6.21	-	8.29	4.838	6.93	11.367	7.26	12.254	6.69	.769	6.79	2.621	7.06	4.357	6.80	18.075	7.22	23.330
7	8/24	7.82	.553	nf	0	7.40	.541	6.70	-	8.15	.497	7.83	1.014	8.02	1.206	6.41	.512	7.89	1.033	7.78	3.021	7.70	3.917	7.91	5.435
8	8/31	7.79	.529	1.82	.254	7.41	.837	7.10	-	7.99	.428	7.56	1.132	7.92	1.352	6.27	.475	7.69	.324	7.52	.453	7.55	3.013	7.92	4.378
9	9/02	7.63	2.534	2.48	.615	6.91	2.897	5.97	-	7.75	2.201	6.63	4.824	7.05	5.701	6.57	1.026	6.91	2.212	6.51	2.823	6.43	10.886	6.72	14.864
10	9/10	7.67	.506	1.60	.234	6.85	.770	6.56	-	7.72	.418	7.02	1.485	7.36	1.725	6.12	.469	7.50	.359	7.36	.388	7.21	3.405	7.48	4.116
11	9/14	7.86	.424	nf	0	7.19	.418	6.69	-	7.76	.315	7.36	.783	7.77	.942	6.73	.385	7.62	.243	7.47	.328	7.72	1.955	7.82	2.774
12	9/17	8.07	7.941	1.83	.728	7.57	9.011	6.47	-	8.10	6.368	6.82	16.728	7.06	17.341	6.81	.637	6.58	4.351	6.75	4.809	6.73	28.719	6.89	44.591
13	9/28	7.98	.477	nf	0	7.72	.496	6.96	-	8.48	.417	8.03	.864	8.35	.914	6.35	.503	7.87	.375	7.58	1.836	8.01	3.973	8.36	6.460
14	10/06	8.13	.462	nf	0	7.77	.471	7.38	-	8.16	.345	7.75	.818	8.12	.916	6.75	.407	7.85	.394	7.72	.473	7.38	3.188	7.77	4.701
15	10/09	7.86	.546	nf	0	7.46	.576	7.00	-	7.99	.481	7.61	.980	8.20	1.603	6.79	.437	7.67	.374	7.69	.382	7.95	3.822	8.20	4.448
16	10/14	7.87	.555	nf	0	7.45	.587	7.13	-	7.78	.411	7.48	.811	8.08	.929	6.94	.396	7.44	.366	7.70	.392	7.61	2.427	8.18	3.121
17	10/20	8.00	.518	1.46	.150	7.60	.682	7.17	-	8.18	.486	7.63	1.364	8.02	1.682	6.50	.461	7.50	.326	7.75	.332	7.91	3.026	8.02	4.067
18	10/28	7.96	1.284	2.23	.293	7.23	1.734	6.92	-	7.79	1.093	7.37	3.721	7.55	4.003	6.46	.628	6.97	.645	7.10	.781	7.19	7.605	7.26	10.267
19	11/04	8.03	.588	nf	0	7.11	.609	7.12	-	7.80	.412	7.53	1.423	7.70	1.592	6.40	.457	7.38	.356	7.59	.420	7.29	3.532	8.07	4.240
20	11/09	8.14	.655	nf	0	7.61	.713	7.43	-	7.84	.506	7.48	1.271	7.86	1.417	6.54	.431	7.45	.457	7.83	.536	7.59	3.284	8.19	3.420
21	11/18	8.15	.717	1.53	.152	7.85	.786	7.55	-	7.68	.611	7.66	1.231	7.86	1.418	6.64	.413	7.51	.312	7.64	.463	7.79	3.025	8.20	3.880
22	11/23	8.23	.978	2.90	.198	7.80	1.203	7.29	-	8.03	.881	7.54	3.069	8.18	3.399	6.69	.430	7.60	.630	7.73	.636	7.80	4.615	8.33	5.509
23	11/30	7.89	.877	1.34	.117	5.88	1.029	6.39	-	7.98	.794	7.50	2.823	7.73	2.904	6.83	.426	7.66	.422	7.69	.516	7.64	3.926	7.78	4.621
24	12/07	7.95	.579	2.15	.106	6.86	.715	6.70	-	8.06	.462	7.59	1.988	7.93	2.092	6.36	.385	7.83	.352	7.50	.445	7.52	3.981	7.88	4.845
25	12/11	7.97	.680	1.65	.129	6.38	.952	6.50	-	8.36	.519	7.48	1.856	7.78	1.990	6.45	.437	7.85	.381	7.69	.570	7.70	2.972	7.91	3.946
26	12/15	7.76	.411	1.77	.113	6.42	.563	6.57	-	8.04	.349	7.21	1.109	7.74	1.296	6.41	.456	7.85	.341	7.78	.443	7.72	2.901	7.87	3.805
27	1/05	7.50	Frozen	nf	0	7.23	Frozen	7.03	-	7.83	Frozen	7.31	Frozen	7.63	Frozen	6.48	.478	7.96	Frozen	7.48	Frozen	7.29	Frozen	7.68	Frozen
28	1/13	7.34	"	nf	0	7.15	"	7.17	-	7.76	"	7.20	"	7.42	"	6.89	.401	7.80	"	7.33	"	7.39	"	7.52	"
29	1/20	7.31	"	nf	0	6.92	"	6.93	-	7.66	"	7.27	"	7.49	"	6.50	.454	7.71	"	7.25	"	7.13	"	7.35	"
30	1/25	7.09	"	nf	0	6.99	"	6.57	-	7.48	"	7.08	"	7.33	"	6.29	.460	7.59	"	7.22	"	6.91	"	7.49	"
31	2/01	6.92	"	2.28	0	6.65	"	6.50	-	7.43	"	6.93	"	7.30	"	6.53	.417	7.50	"	7.09	"	7.05	"	7.30	"
32	2/11	7.01	"	1.12	0	6.73	"	6.45	-	7.37	"	7.06	"	7.45	"	6.50	.410	7.09	"	7.20	"	6.97	"	7.34	"
33	2/22	8.02	2.690	3.58	.651	7.57	3.018	7.34	-	7.96	3.473	7.73	4.315	7.96	4.943	6.70	.716	7.76	2.264	7.83	2.672	7.54	11.712	7.81	15.722

[a] Discharge measurements in cfs (cubic feet per second).

to take place. This third location was situated upstream of the 15-acre, 18-feet-deep slurry pond that forms the southwestern portion of the Victory Mine.

At the fourth site water drained off the slurry pond would be diffused and the hydrogen ion concentration would reach equilibrium in the stream. Thus, at this point in Honey Creek, all the drainage from the landfill site was measured. Although site 4 was an appropriate location for pH measurements, discharge readings taken here were not reliable. Coal fines eroded from the slurry area were being moved along the streambed which thus appeared black. The thickness of this loose material was nearly six inches deep and the coal fines would quickly clog the wheel of the current meter. These conditions hampered discharge readings.

The fifth site was located on an unnamed tributary entering Honey Creek from the east. The water in this stream does not receive acid drainage from the Victory Mine property. It also differs from Honey Creek because fish have been observed. In the modeling procedure the impact of this tributary on pH dilution of Honey Creek had to be determined.

Site 6 was the least accessible. Although it was the next downstream site on Honey Creek from site 4, the sedimentation problem was not as severe and discharge measurements could be taken.

The next sampling site was located 0.5 miles downstream from site 6. Site 7 provided the last pH measurements solely from the effects of acid discharge from the Victory Mine property. Site 7 served a dual role. It marked the end of the upstream portion of the study area and the beginning of the downstream portion. Upstream, the effects of the runoff of the Victory Mine were measured. Downstream from point 7 another source of acid drainage is introduced into Honey Creek. It is drainage from an underground opening. For modeling purposes site 7 served a function similar to that of site 1. It set the initial levels of pH and discharge in Honey Creek with which downstream readings were compared.

The 8th site was at the end of a 0.2-mile-long tributary that carried acid water into Honey Creek. The location of this source of drainage was identified on the Coal Investigation Map C-27 as a coal test well.[79] However, it appeared more likely to be an abandoned air shaft leading from a collasped opening of one of the original tunnels of the Victory Mine. At this site it was possible to measure the amount of water and its pH level before it entered Honey Creek. Unlike site 2, which carried the overland acid runoff from the Victory Mine, site 8 did not have much fluctuation in flow and pH values were not as low.

Site 9 was located on a second unnamed tributary draining into Honey Creek from the east. The discharge and

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[79] U.S., Department of Interior, Seelyville Quadrangle.

pH of this water were also necessary statistics to include in the modeling of Honey Creek. This tributary at times carried water that was collected at a strip mine operation and thus the pH and discharge varied, depending on its release from a holding pond created by the mining operation.

The tenth site was on Stone Quarry, one of the tributaries in the study area draining to the east. The data collected here were similar to those collected at site 9.

At site 11, discharge from both the underground source and the tributary measured at site 9 were included in Honey Creek. Stone Quarry enters Honey Creek below site 11 and its effect would contribute to the readings taken at site 12, the final station. When the water in Honey Creek passed site 12 it appeared to approximate the pH level of site 7, the starting point for the downstream portion of the study area which contained the underground source of acid drainage.

Goals of the Analysis

The data in Table 6 represented the downstream behavior of a stream receiving varying amounts of acid drainage and discharge loads from its tributaries. To evaluate the research hypothesis a model was prepared that related pH and discharge levels to a distance factor.

However, before modeling was done it was necessary to examine the data to see if there were differences between sampling points along Honey Creek and/or differences between sampling dates. Without these differences there would be no need to proceed any further. If there were differences in pH between sampling sites then it would be indicated that a changing downstream gradient in pH did exist. It was these changes downstream that the model was designed to predict. It was hypothesized that a pattern of changes in the extent of that pH gradient would be present, corresponding to the amount of water in the stream. Therefore, it had to be determined if sampling dates during periods of lower flow, dry periods and late summer and fall, differed from periods of higher flow.

Another prerequisite to modeling was a further examination of the relationship between pH levels and discharge. Since water is both the conveyor of acid drainage to the stream and the agent for dilution, it would be useful to know the effects of different amounts of discharge on pH levels. The strength of the relationships between discharge and pH in this situation had to be measured.

The above considerations were analyzed and the results are presented in the next chapter.

Chapter 5

DATA PRESENTATION

Introduction

The pH and discharge measurements made at each study site were presented in table 6. In this chapter those data are analyzed for patterns or trends in the behavior of acid drainage in Honey Creek. Analysis of the data concerned three questions. (1) Were there differences in pH among sampling sites? (2) Did the pH of the stream change during low flow conditions? (3) Was there a strong relationship between pH and discharge?

The answers to the above questions determined which paths were to be followed in the research design diagrammed in figure 3. If no differences in pH were found among the sampling sites, then there would be little indication from the data that any extensive downstream lowering of pH was caused by acid drainage from either source of acid in the study area. Accordingly, a model of pH behavior downstream of an acid source could not be formulated using these data.

In addition to pH data, the presence or absence of a pattern in discharge measurements affected the modeling procedure. If there were only small changes in discharge during the sampling period or if pH and discharge did not seem to be related, then a model independent of flow changes would be appropriate.

pH Measurements

After the pH measurements for each sampling site were graphically analyzed, patterns became apparent. When all of the sampling data for one site were plotted against time a pH profile could be constructed. Comparing the pH profiles two similarities were observed--that the shapes of the profiles resembled one another and that if one profile was displayed along with the next downstream profile there was little overlap. When all of the pH profiles were examined, four groups of sample sites could be identified--(1) depression-sites 1, 3, and 4 where pH was decreasing in a downstream direction, (2) recovery-sites 6, 7, 11, and 12 where pH was increasing in a downstream direction, (3) acid source-sites 2 and 8, and (4) tributary-sites 5, 9, and 10.

Depression. Sample sites 1, 3, and 4 make up the depression group (figure 4). Site 1 represents the initial pH levels or the background condition for the study area. Between sites 1 and 3 there is an acid source, and the gap on the graph separating profiles 1 and 3 indicates that a lowering of pH has occurred. At site 4 pH was recorded to be, on the average, even lower than at site 3. However, during the sampling period this average relationship did not always exist. On November 30, meltwater was present from the first major winter storm of the season which left a three-inch-deep snowcover over the study area. Jefferies, Cox, and Dillon reported that a depression in pH was observed in snow-melt runoff in Ontario, but in that case,

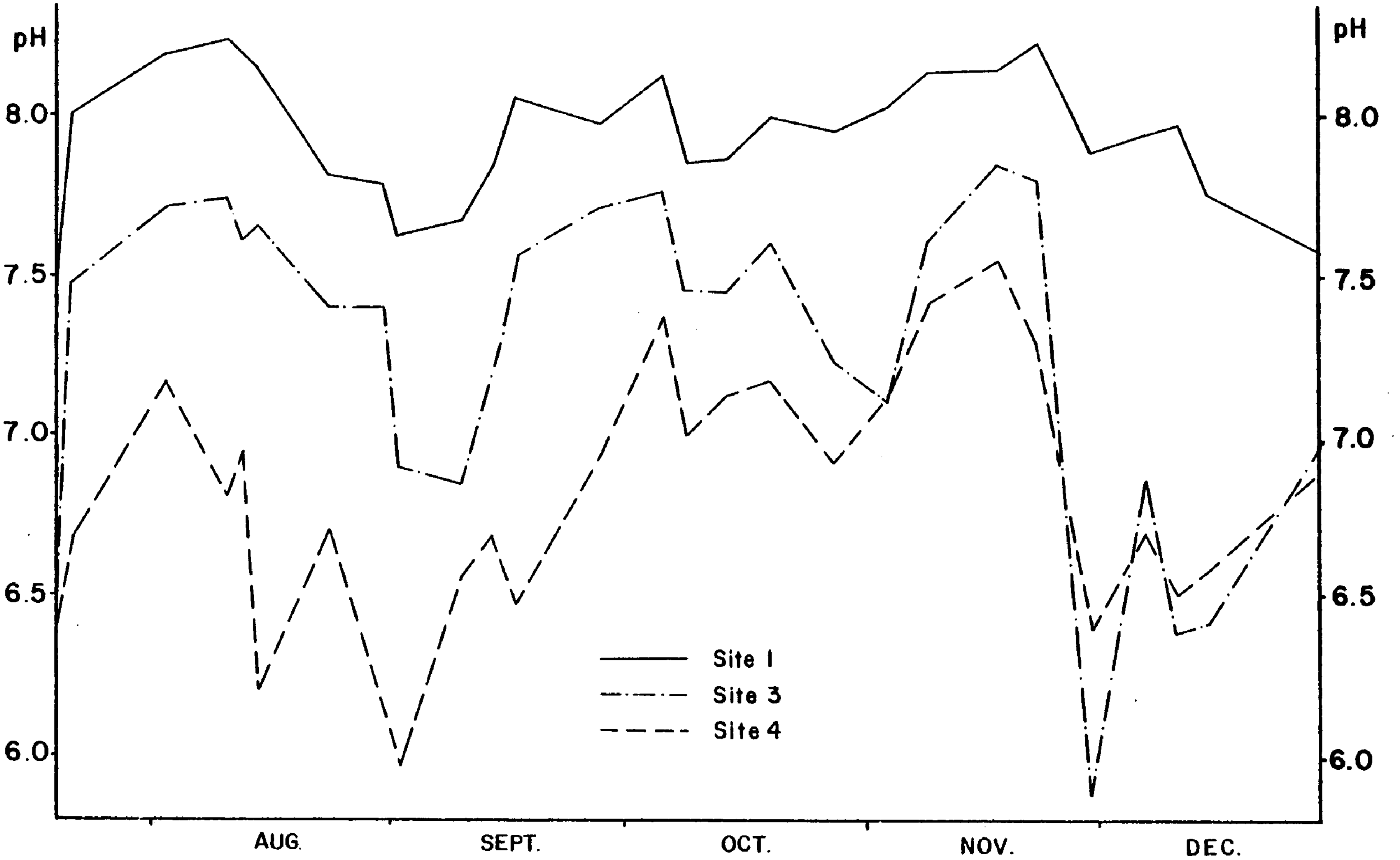

Fig. 4. The depression group

the pH of the snowpack that had accumulated was 4.0 - 4.5.[80] The snowfall of 28, 29 November was measured to have a pH range of 7.01 - 7.42 so the resulting depression in pH of the stream was probably not due to the precipitation itself, but rather the capacity of meltwater to act as a remover of acid. The snowfall at this time occurred before the ground was frozen for the season and the snow fell on relatively warm ground. During the melting process the upper layers of the gob area became saturated with moisture from the snowmelt and this runoff carried acid with it into Honey Creek. That was the same process which takes place during rainfall runoff. However, one difference might have been that snowmelt provided a steady supply of moisture at the surface to encourage both acid formation and removal. As long as there was melting snow to keep the upper portions of the gob moist, a favorable environment for continued acid production existed. Runoff from precipitation removes acid that has accumulated at the surface so that there is an initial depression. But once it stops raining the source of moisture at the surface begins to dry and acid production is slowed.

Overall the depression group illustrated the lowering of pH levels in the stream after acid drainage had been introduced. Downstream the acid began to become

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[80] D. Jefferies, C. Cox, and P. Dillon, "Depression of pH in Lakes and Streams in Central Ontario During Snowmelt," Journal of the Fisheries Research Board of Canada 36 (1979): 640-6.

diluted to the point that pH would no longer decrease. The addition of more non-acidic water then began to raise the pH in the stream as the dilution process continued. This condition was representative of the second group of pH profiles, the recovery.

Recovery. The pH profiles of sites 6, 7, 11, and 12 made up the recovery group. In appearance the recovery group did not seem to differ from those of the depression group, but there was a reversal in the relative positions of the curves. In the depression group, pH was decreasing in a downstream direction, whereas pH increased in the downstream direction in the recovery group.

Sites 6 and 7 (figure 5) were displayed separately from sites 11 and 12 (figure 6) because two recoveries were being represented. The recovery from the overland source of acid drainage began after site 4 since pH levels at the next downstream site were higher. The pH profile for site 7 was very similar to the profile for site 1 which indicated that pre-acid levels had been reached, hence recovery was near completion.

The second recovery occurred after the introduction of acid from the underground source. By the time water in the stream reached site 12 the pre-acid levels of sites 1 and 7 were once again approximated. On the basis of pH, another group of related pH profiles was identified which represented water that was nearly at pre-acid levels.

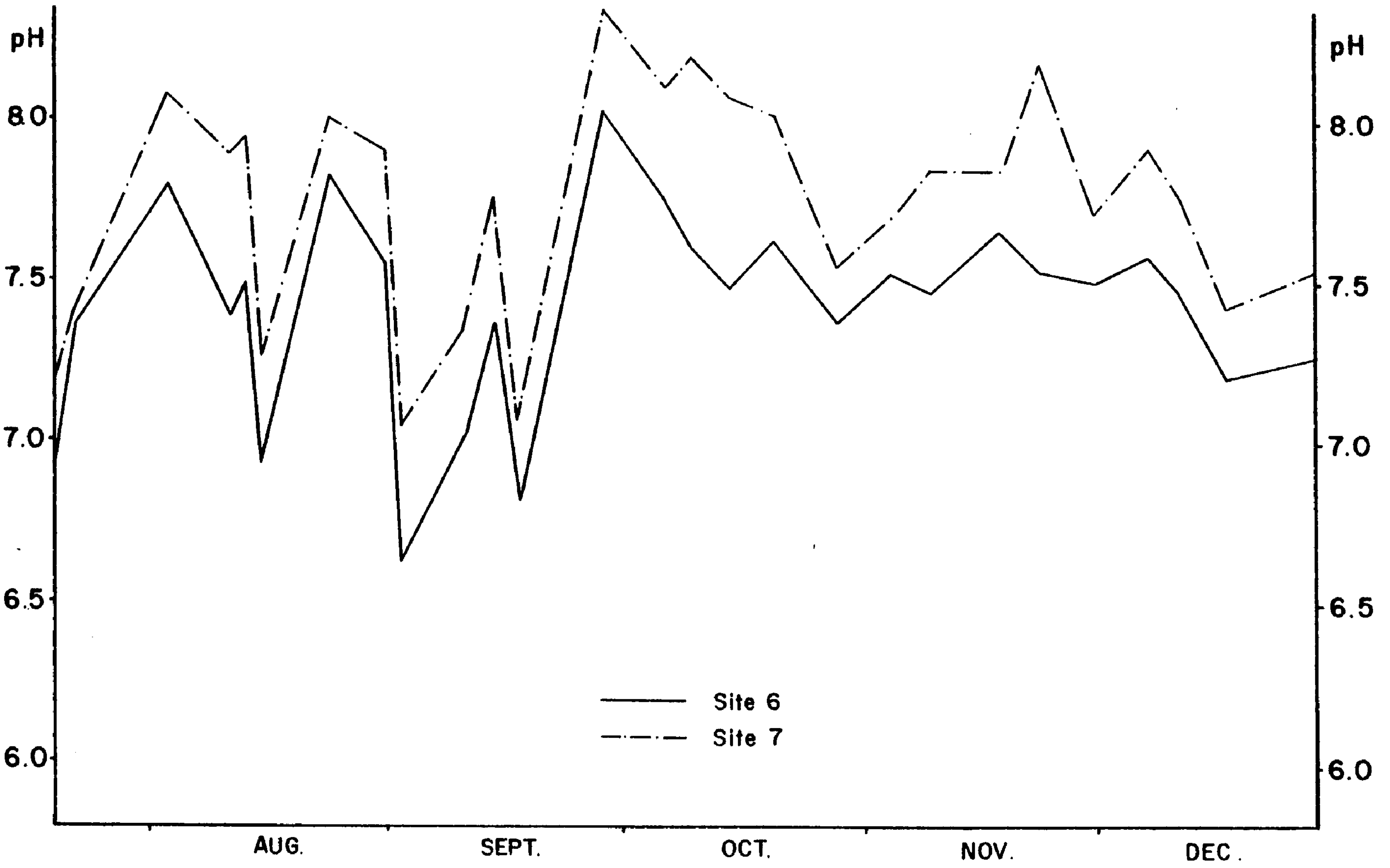

Fig. 5. The recovery group for the upstream sites

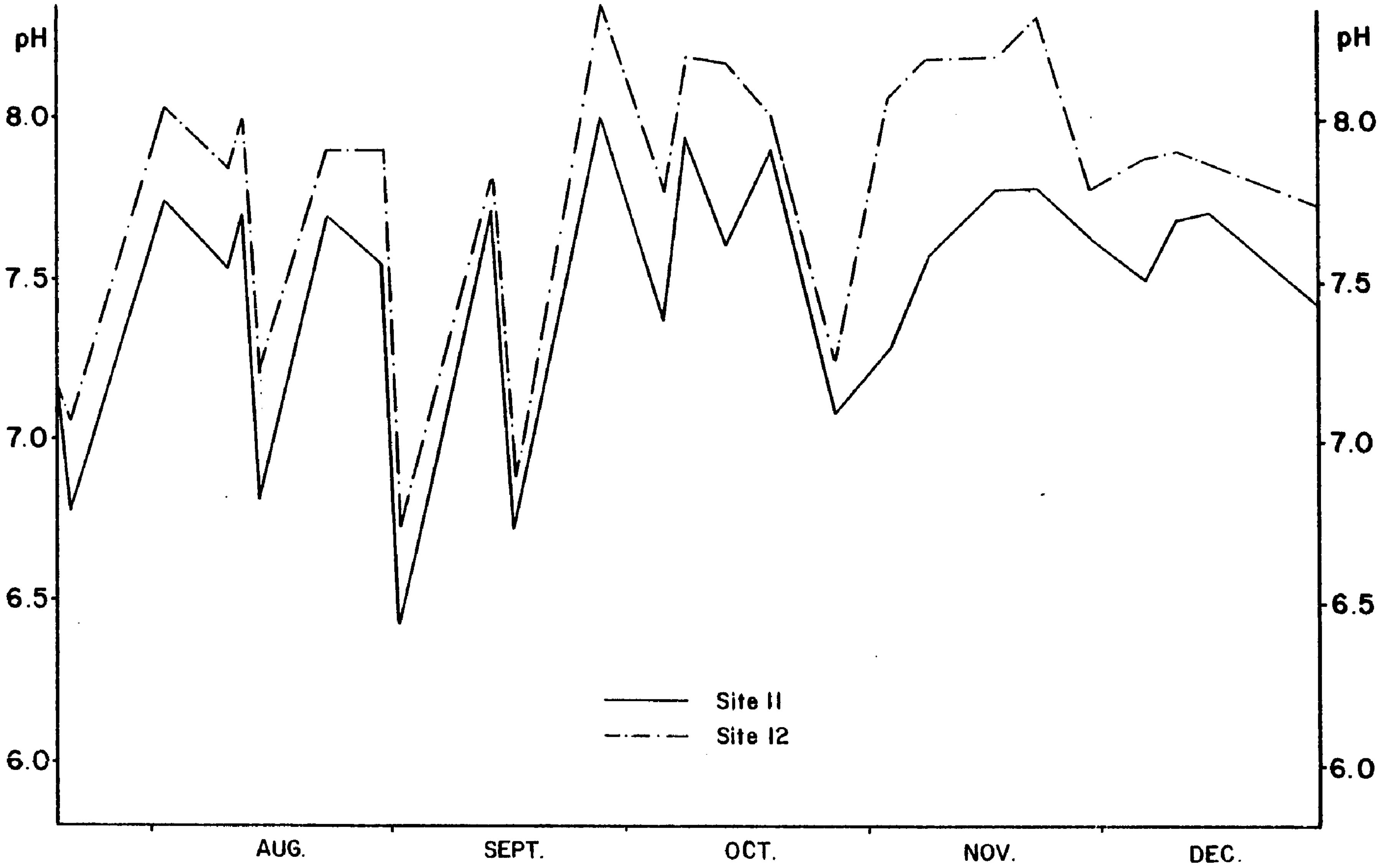

Fig. 6. The recovery group for the downstream sites

Sites 1, 7, and 12 would have been members of that group, and if their respective pH profiles were plotted together, much overlap among them would exist.

Acid sources. The acid mine drainage from overland and underground sources was measured at sites 2 and 8. These two pH profiles were markedly different from those of the other groups because the average pH was much lower (figure 7). The pH profile for site 2 also differed in that the curve was a broken line which had fewer points plotted on it. That is because tributary flow at site 2 was interrupted by dry periods at which time there was no water present in the tributary. Hence no pH measurements could be made there. The solid portions of the curve connect consecutive sampling days with flow, and dots were used to connect a sample day with flow but had a dry day either before or after it.

Site 8 was a continuous source of acid and also differed from site 2 because of higher pH values. In addition the range of pH values for site 8 was much less than the range of pH values for site 2.

Tributaries. The remaining sites, 5, 9, and 10, made up the tributary group (figure 8) for they represented three tributaries that entered Honey Creek from the east. The pH profile for site 5 was more like that of site 1, and the profiles for sites 9 and 10 resembled the profiles

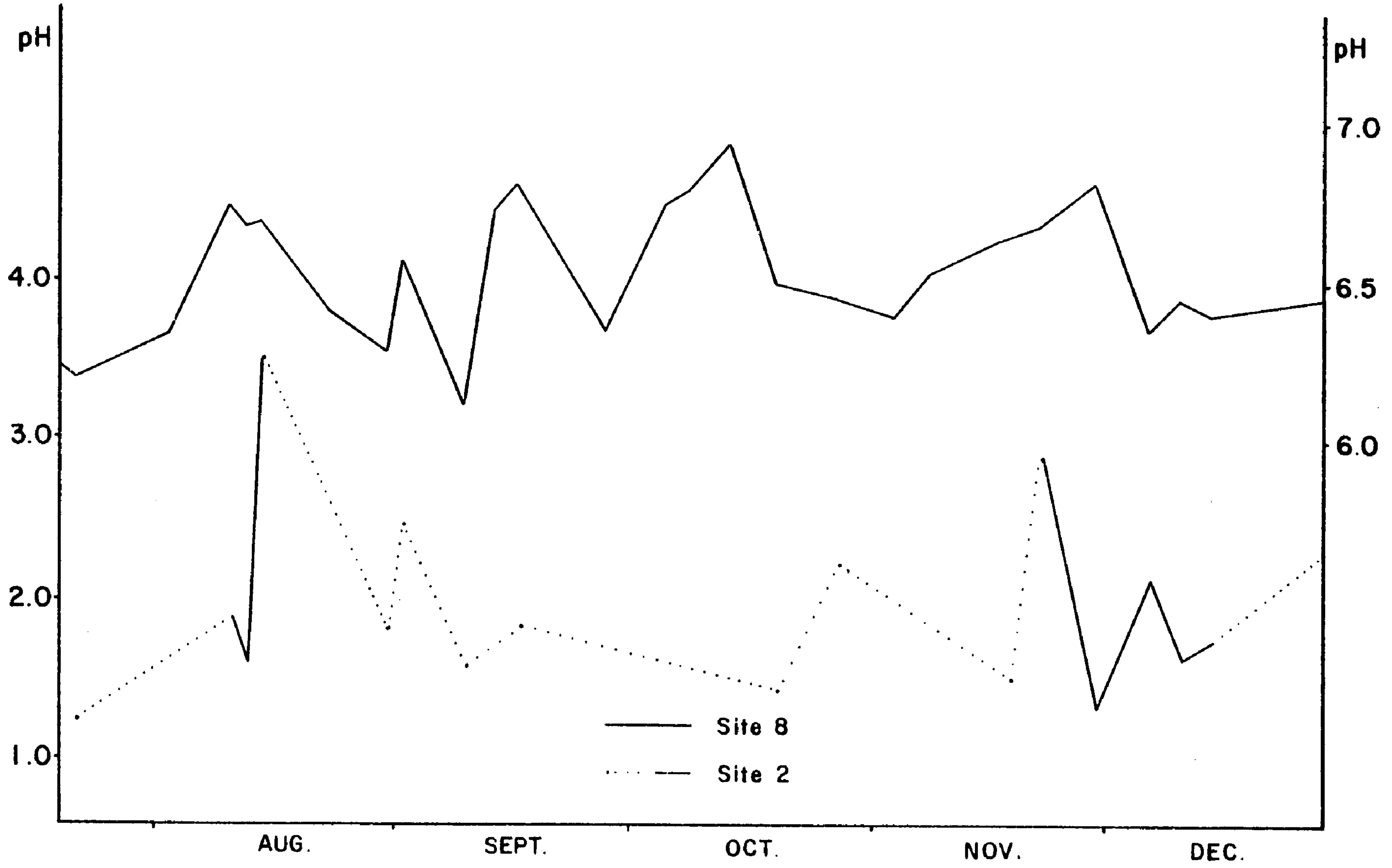

Fig. 7. The profiles for the acid sites

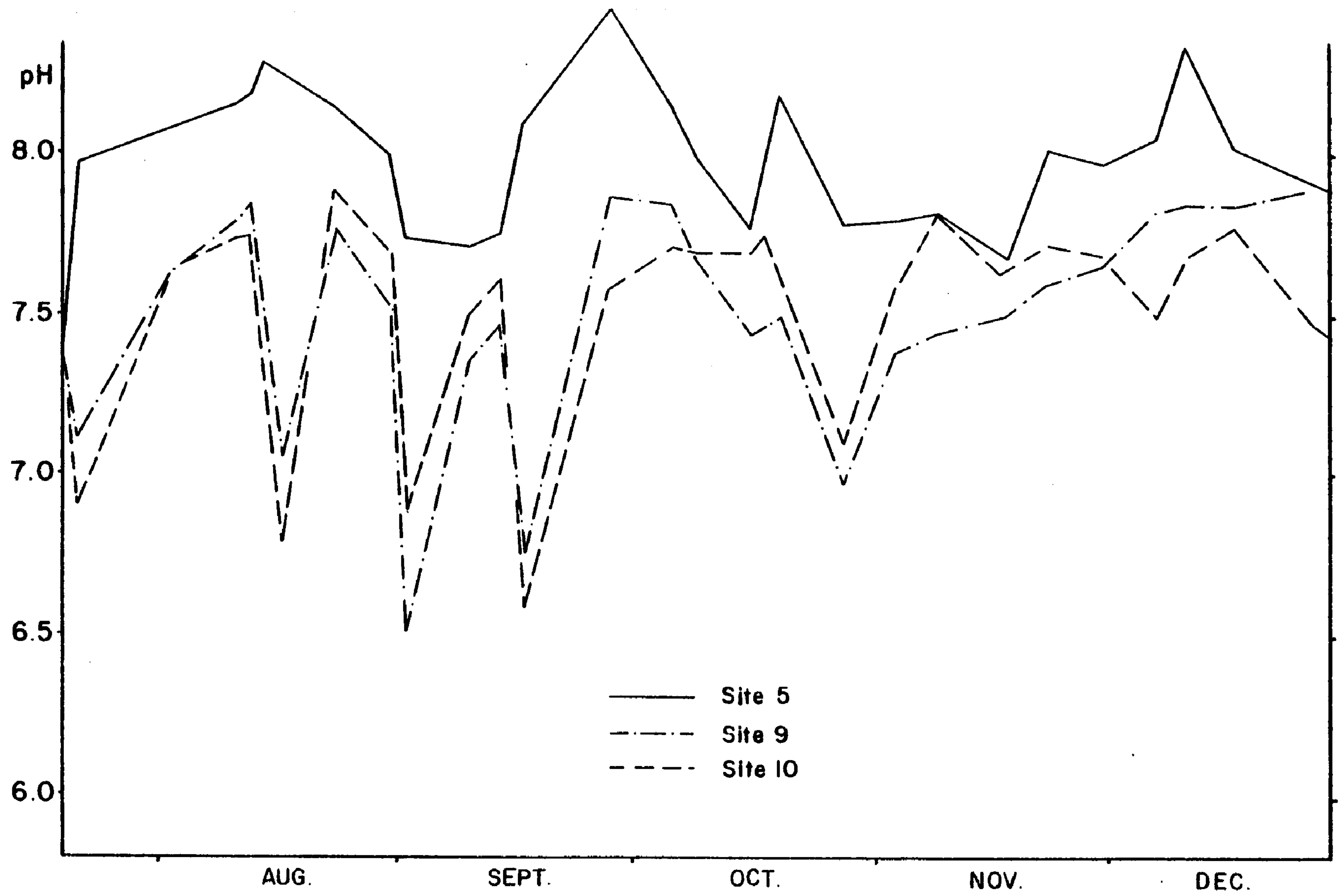

Fig. 8. The profiles for the tributary group

for 11 and 12. The explanation for this difference in pH between sites 5, 9, and 10 involved a depression of pH values for sites 9 and 10. The tributary at site 5 did not have such a depression. The depressions in the tributaries at sites 9 and 10 were caused by pit pumpage of acid water from the strip mine operations east of the study area which flows into these tributaries. Acid water which entered Honey Creek from these tributaries affected the stream and the pH profiles at sites 11 and 12 reflect the impact this addition had.

The pH profiles of the four groups displayed some interesting similarities and differences which, so far, have been treated in a qualitative manner. The next step was to assign statistical significance to these curves.

Site Differences in pH

In some of the pH profiles there were overlaps among the curves and in others there were gaps between curves. A method to determine whether there were statistical differences between the mean values of the pH measurements was desirable. If there were statistical differences in the mean pH from one site to another, a gradient could be assumed to have existed during the study period. The t-test was appropriate in this situation because the population distribution did not grossly depart from normal and there was homogeneity of variance. Table 7 contains the results of this test performed on selected sites.

TABLE 7

DIFFERENCES IN pH AMONG SITES

Group	Site (Mean)	vs.	Site (Mean)	Result*
Depression	1 (7.82)		3 (7.22)	different
	3 (7.22)		4 (6.87)	different
	7 (7.71)		11 (7.41)	different
Recovery	6 (7.37)		7 (7.71)	different
	11 (7.41)		12 (7.71)	different
	1 (7.82)		7 (7.71)	no difference
	7 (7.71)		12 (7.71)	no difference
	1 (7.82)		12 (7.71)	no difference
Tributaries	5 (7.91)		1 (7.82)	no difference
	1 or 5		9 or 10	different
	9 (7.52)		10 (7.46)	no difference

*Significant at the .01 level.

In the depression group there was a significant lowering of pH in Honey Creek after acid from sites 2 and 8 entered the stream. This depression continued downstream from both sources. The pH continued to drop significantly between sites 3 and 4 and sites 11 and 12. The tests for significance also supported the earlier statement about the recovery groups having an average increase in pH between sites 6 and 7, from the overland acid load, and sites 11 and 12, from the underground acid source. In addition, table 7 also indicated that there were no differences in average acid levels between sites 1 and 7 or sites 7 and 12. Moreover, there were no statistically significant differences between average pH levels at the beginning of the study area or at the end. These facts gave support to the idea that acid drainage from the overland source was diluted to pre-acid levels before acid drainage from the underground source was encountered. In turn, acid drainage from the underground source was diluted to pre-acid levels before it left the study area.

The significance tests for the tributary group also supported the initial observations. Sites 1 and 5 were not found to be different and neither were sites 9 and 10. Yet, when site 1 was compared with site 9 or 10, and site 5 was compared with site 9 or 10, there were differences.

Thus far, differences in pH had only been established from site to site. If there were patterns in variation within the sites, then this would have been an important consideration and might suggest a seasonal variation. An appropriate statistical test to determine if there was a change in pH values within the sites was a One-Way Analysis of Variance. To perform this test the data had to be separated into treatment groups. The desired place for this separation was between the low flow conditions of late summer and fall and the higher flow conditions of winter.

Seasonal Differences in pH and Discharge

The analysis of variance technique used in this case divided the observations in the experimental data into two treatment groups, the low flow of summer and the higher flow of winter. The division between these two conditions occurred in October when precipitation levels normally exceed actual evapotranspiration levels (see figure 2). Sample numbers 1-17 made up the theoretical low flow treatment group and samples 18-33 comprised the theoretical higher flow group.

The results of the analysis of variance (table 8) performed on pH levels from both treatment groups indicated that there were no statistical seasonal differences between their variances when compared with the population variance. Similarly, when discharge levels were compared, no statistical seasonal differences could be identified (table 9). These results were not altogether surprising because during the sampling period below normal precipitation levels were recorded (table 10 and figure 9). This meant that discharge levels did not significantly change from the low flow state during the sampling period.

TABLE 8

ANALYSIS OF VARIANCE RESULTS FOR SEASONALITY OF pH LEVELS

Site	1	3	4	5	6	7	8	9	10	11	12
F Value	3.680	6.069	0.801	4.515	0.0	.293	.002	1.212	0.240	.003	.426
Result*	no	no	no	no	no	no	no	no	no	no	no

* Significant at the .01 level.

TABLE 9

ANALYSIS OF VARIANCE RESULTS FOR SEASONALITY IN DISCHARGE LEVELS

Site	1	3	5	6	7	8	9	10	11	12
F Value	.491	.162	.252	.179	.275	.426	.722	.659	.365	.587
Result*	no	no	no	no	no	no	no	no	no	no

*Significant at the .01 level.

TABLE 10

MONTHLY PRECIPITATION DATA

	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec
Normal	2.56	2.11	3.20	3.81	4.65	4.51	3.77	2.70	3.16	2.38	3.13	2.41
1980	2.87	1.30	3.38	2.44	2.36	4.01	2.16	3.77	3.42	2.04	1.49	.70

Relationship Between pH and Discharge

If there was a systematic relationship between pH and discharge levels it would be possible to estimate one variable from knowledge of the other. A regression analysis would determine to what degree these two variables were related. The pH and discharge measurements, with pH being the independent variable, were used in the regression analysis done for each site (table 11).

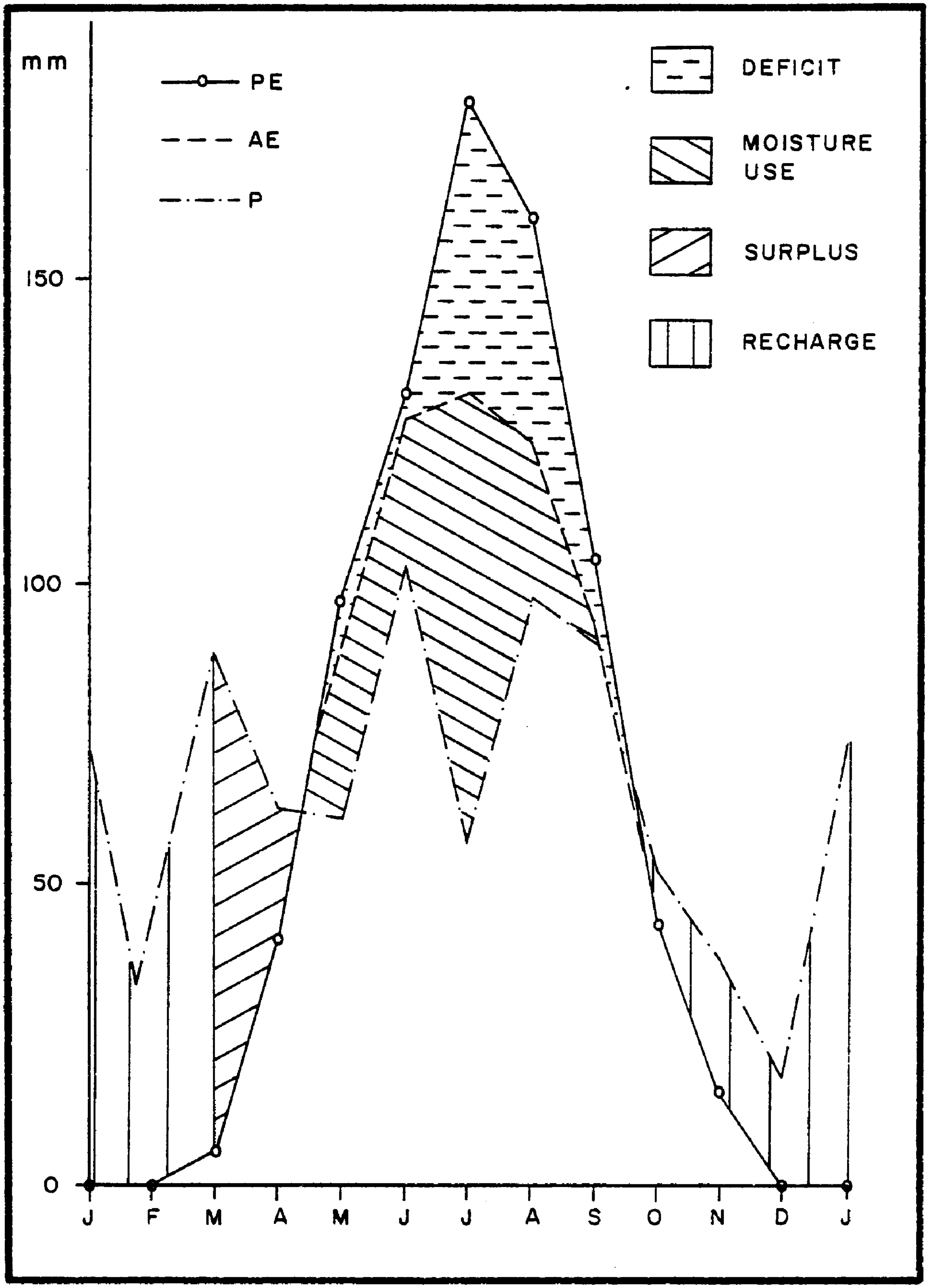

Fig. 9. Water balance for 1980

TABLE 11

RESULTS OF REGRESSION ANALYSIS FOR pH AND DISCHARGE

Site	1	3	5	6	7	8	9	10	11	12
r	.151	.151	.142	.566	.608	.031	.726	.550	.648	.600
r^2x100	2.280	2.280	2.020	32.040	36.970	.100	52.710	30.250	41.990	36.000

The results from table 11 indicated that there were no strong systematic relationships between pH and discharge. Based on just a knowledge of discharge, a prediction of pH was possible which might be better than a random guess. The closer the absolute value of r was to 1, the more accurate would be the prediction of pH based on discharge information. The "r^2 x 100" term value for each site in table 11 was interpreted as a percentage of how much was known to make a perfect correlation of pH from discharge. In this case, the best prediction of pH from discharge information would be made at site 9 where 52.7% of the variance in pH was predictable.

Still, 47.3% of the variance remained unexplained. Other sites exhibited greater unexplained variances. These low correlations between pH and discharge variables did not mean that there was a random association between them but, that a linear regression model was a poor fit to these data. The absence of a strong linear relationship meant that a modeling procedure based on pH and discharge alone would not be very powerful in terms of prediction.

Summary

The results of the analysis established that there were significant differences in pH from site to site which could be organized into depression, recovery, tributary or acid source groups. The relationship among the sites within each group was consistent during the sampling period. That meant the separation of pH profiles for each site was preserved, even though the profiles themselves were erratic. Regardless of whether the pH of one site was above or below the sites surrounding it, the shapes of the curves resembled each other. This indicated that a gradient in pH did exist in Honey Creek.

The analysis also indicated that the values for pH and discharge did not significantly differ during the study period. This lack of seasonality in flow and pH meant that only one condition was being observed in the study area, that of low flow.

The lack of a strong correlation between pH and discharge did not mean that there were no associations between those two variables but that the relationship was not linear or systematic. Changes in pH with discharge did occur but not always in the same way. On some sampling days pH would be relatively high corresponding to high levels of discharge. Other days, low pH values would be accompanied by high discharge levels. Likewise, changes in pH would occur when discharge levels were low.

The possible causes for the apparent lack of a more regular association between pH and discharge might lie in the distribution of and amount of precipitation. Perhaps the relationship between pH and discharge should not have been expected to be regular since both the length of time between precipitation events and the amount varied. Relating precipitation variables to the behavior of pH and discharge in Honey Creek is the subject of the next chapter.

Chapter 6

THE ACID DRAINAGE INDEX

Introduction

In the last chapter the fact that a consistent pH gradient did exist in Honey Creek was established. However, the pH levels of this gradient fluctuated in time in such a way that graphically the pH profiles maintained relative separation between sites. The extent of these fluctuations was shown by the peaks and valleys of the pH profile shapes (figures 4 - 8) which differ markedly from a smooth line. These changing pH levels were thought to be related to changes in discharge, but no regular linear association was found between those two variables. In this chapter pH and discharge were further examined to determine how they were related which would explain acid drainage behavior in Honey Creek in a meaningful way.

Hypotheses Evaluations

Based on the data collected for this study the first hypothesis, that there would be a seasonal difference in pH levels at sampling points, had to be rejected. This rejection was related to the below normal precipitation received in the area which was therefore responsible for smaller seasonal variations in discharge than would normally be expected. Thus, low flow conditions prevailed during the entire sampling period and a seasonal dilution of acid with higher discharge levels was not observed. The rejection of the hypothesis, in this case, should not imply that increases in pH do not occur with higher discharge, but that during the fall and winter of 1980 that response did not occur.

The second hypothesis, that increases in discharge following precipitation events would tend to increase dilution, was also rejected. The basis for this rejection was the unsystematic relationship that existed between pH and discharge. Regular changes between those two variables were not observed. This rejection, unlike that for the first hypothesis, was not due to an anomalous condition but rather to the complex nature of the relationships between pH and discharge. A means of relating pH and discharge is presented in this chapter.

Impact of Precipitation

The effects of precipitation on the behavior of acid mine drainage provided a means to relate pH and discharge levels in streams. Precipitation had a direct effect on stream discharge by creating surface runoff, interflow, and channel precipitation which combined to increase discharge after the requirements of evaporation, transpiration, and soil moisture recharge had been met. The response of pH levels in the stream to precipitation was not predictable.

The pH of a stream was affected by acid mine drainage when acid in solution or acid forming material in suspension entered the stream. This acid drainage most commonly reached the stream channel as surface runoff that could not have been retained as ground storage with the result that storm runoff contributed varying amounts of acid and acid forming materials to the stream. This phenomenon drastically affected the quality of water in a receiving stream. That condition was referred to by Corbett and Agnew as a "flushout." A brief synopsis of their work is included here to illustrate how precipitation, acid load, and discharge interacted to cause lower pH levels.

Flushouts occur from the following three sources which can be directly related to precipitation. These are first, the erosion of gob and slurry areas; second, oxidized acid forming materials which have collected on the bands and in the floodplain since the last storm of consequence; and third, the agitation of acid forming materials which have settled out on the streambed.[81]

Corbett and Agnew also concluded that increased acid concentrations caused by flushouts were of short duration and were greatest when runoff first reached the receiving stream.[82] In a case where there was only one peak discharge, the pH would be expected to drop with the

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[81] Corbett and Agnew, Busseron Creek, p. 134.

[82] Ibid., p. 149.

advent of runoff entering the stream. Thereafter pH should begin to rise once the available acid material was washed away or enough dilution water was present. If the intensity and duration of precipitation varied during a storm, the number of peak discharges and possibly the number of flushouts would increase.

The precipitation-discharge-pH relationship was further complicated by factors which affected the ratio of acid to dilution water in runoff. Such factors were the magnitude and intensity of the storm, the length of time since the last flushout, the ratio of mined area to unmined area, and the ease of storm runoff passage.[83] Therefore, it was not known at which point dilution waters entering a receiving stream would begin to reduce acid concentrations resulting from acid mine drainage.

Observed pH and Discharge Relationships

An outgrowth of the discussion of the flushouts was the organization of discharge and pH characteristics into three groups. These groups represented different aspects of the flushout process and were identified as baseflow, flushout, and transition groups. The following selected examples were chosen to illustrate the pH and discharge conditions for these groups.

Baseflow, 20 July. The first sampling day of the study period occurred at the end of a long very dry period.

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[83] Ibid., p. 155.

In the 22 days prior to 20 July, only 0.19 in. of precipitation was recorded. The discharge in the stream at this time corresponded to 3 cfs at site 12 which was one of the lowest discharges recorded at that site during the study period. During this drought condition the flow of Honey Creek on this day dropped from 7.5 cfs at site 1 to 6.4 cfs at site 4. It was not until the tributary flow at site 5 entered the stream that pH began to approach pre-acid levels. At site 7 there was enough water in the stream to dilute the acid load entering the stream from the Victory Mine property. Farther downstream, the acid discharge from site 8 was adequately diluted and the pH at site 12 equalled that of site 7.

The condition of the stream on 20 July and the levels of pH and discharge display what could be categorized as being that of baseflow or equilibrium behavior. Under conditions of baseflow behavior there was no surface runoff to contribute to discharge or carry acid into the stream. The primary acid sources at this time would be seepage from the gob and slurry areas of the Victory Mine[84] and the nearly constant pH and discharge drainage from the air shaft. Compared on an ordinal scale with other categories of pH and discharge conditions to follow, discharge levels were lowest at this time and the amount of acid production

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[84] Areas disturbed by mining which are not compacted have been reported to be significant storers of moisture available for streamflow during drought conditions.

was less. However, the proportion of acid load to available dilution water was what affected the pH value of the stream. Because there was less water available in the stream than at other times to dilute any acid entering it, even a small amount of acid could alter pH.

Flushout, 17 September. The 12th sampling day occurred on 17 September. Only 3 hours had passed since precipitation, which amounted to 1.44 in. over a 24-hour period, had ceased. On this day the highest discharge measurements of the sampling period were made. The discharge rate was 44.6 cfs at site 12 which was 37.2 cfs higher than the average flow of 7.4 cfs for this site. Accompanying this large increase in discharge was an increase in the acid load. As a result, the pH at site 7 was a full pH unit lower than site 1. By itself, this lowering of pH did not seem very great but it existed even in the presence of a significant contribution of dilution water, having a pH of 8.1, from the tributary at site 5. Farther downstream the pH continued to be low in spite of the large volume of water present. The two tributaries, sites 9 and 10, which usually add dilution water to Honey Creek, were also experiencing a flushout and on this day helped to suppress pH.

The condition of the stream on 17 September, with respect to pH and discharge, exhibits what could be called flushout behavior. Following the heavy rainfall, surface runoff carried acid in solution and acid-forming materials into the stream and pH levels were lowered in spite of the increased flow. In addition to the acid entering the stream from the gob and slurry areas, the oxidized acid-forming materials, which had collected on the floodplain and the streambanks, were also responsible for this lowering of pH, especially in that portion of Honey Creek between sites 7 and 12. When the flushout conditions on this day were compared with those of the baseflow or transition group, discharge levels were highest and overall pH levels were their lowest.

Transition, 28 September. The samples on this day were taken 20 hours after a 0.48 in. rainfall. Peak discharges had already been reached and the flow was returning to baseflow levels. Tributary flow measured at site 2 had a pH of 2.2 and the overall effect on the upstream portion of Honey Creek was a 0.4 reduction in pH. This was not as severe a reduction as was caused by flushouts but was greater than that experienced by baseflow at these discharge levels.

Members of the transition group represented those conditions having a particular combination of pH and discharge levels that made them different from the baseflow group but not the same as the flushout group. A sample day was eligible to be included in this group if discharge levels were increased, either as a result of precipitation which was insufficient in amount to cause a flushout, or if enough time had passed since the end of the rain that peak discharge levels had already been reached and runoff was waning. With respect to these conditions, less acid was moved into the stream than during a flushout and dilution of this acid was expected.

Acid drainage in the study area ultimately was derived from two sources, the Victory Mine property and the airshaft. Downstream from those sources acid drainage conditions were found to be different. On the same sampling day the upstream portion of Honey Creek might be a member of the baseflow group and the downstream portion might belong to the transition group. In fact, the upstream and downstream groups had no members in common on any of the sample days in the transition group. The basis for determining how the groups were identified, or how it was possible to compare and contrast the behavior of the two acid sources, is the subject of the next section.

The Acid Drainage Index

The changes in pH experienced by Honey Creek downstream from acid sources were due to many complex relationships in the environment and the stream. Using the pH and discharge data collected for this study, it was possible to determine how these variables interacted to produce certain acid conditions previously identified as baseflow, flushout, and transition.

The acid drainage index (ADI) is an empirically derived equation which rates acid drainage conditions in terms of the amount of pH acitivity and the amount of water in the stream. The form of the equation is

$$ADI = \left(\frac{\frac{d_{pH}}{\Sigma\Delta_{pH}}}{(\frac{\Delta Q}{D})} \text{ X } \sqrt{\bar{d}_{pH}} \right) \text{ X } 100$$

in which:

d_{pH}	is the amount of pH depression measured downstream from an acid source,
$\Sigma\Delta_{pH}$	is the cumulative amount of pH change in the stream,
ΔQ	is the increase in discharge in the stream,
D	is the distance from the first to the last sample site, and
$\bar{d}_{pH}$	is the difference in pH between the first and last sampling point (if the difference is 0 or a negative number the value of d_{pH} is arbitrarily set at .01).

The ADI equation utilized the variables pH and discharge to determine how they interacted to create certain acid drainage conditions. The ADI provided a way to compare acid drainage conditions and a means of quantitatively describing how they were created.

The components of the ADI were arranged in such a way that sampling conditions in the stream on one day could be compared with conditions on another day in a consistent manner. The terms of the equation and how they interacted with each other provided a quantitative means of describing acid mine drainage conditions.

An advantage gained by using the ADI equation was that it could be applied to the entire stream or, in this case, to individual reaches in a stream. This flexibility enabled the behavior of acid drainage downstream from the two acid sources in Honey Creek to be compared.

The term ^{d}pH was a measure of the amount of pH depression in a stream segment. It represented the difference between the pH at the beginning of a stream segment and the lowest pH value in that stream segment, excluding the tributary sample sites.

The terms ΔQ and D were treated together because they were evaluated first. When the increase in discharge, from the first sample site to the last sample site, of the stream segment under consideration was divided by the distance separating those two points, a flow gradient (FG) was created. The distance parameter was important to compare stream discharge for segments of different length for it normalized the discharge values. The flow gradient was actually a rate of change for an entire stream segment and represented more than just one sample site.

The term $\Sigma\Delta_{pH}$ was like the flow gradient in that it described the entire stream segment rather than just one sample site. It was the summation of changes in the absolute values of pH from site to site along Honey Creek, excluding the tributaries. After the introduction of acid discharge, the stream underwent pH depression and recovery and this term incorporated all of that activity. When $^{\Sigma\Delta}$pH was divided by FG, an estimate of pH activity was expressed as a rate of change for the entire stream segment. At this point the variables pH and discharge were being considered together in the ADI equation, but other considerations were necessary to make the relationships clear.

Dividing the result from the $^{\Sigma\Delta}$pH and FG relationship into ^{d}pH created an estimate of the amount of pH depression that took place in the stream with respect to the total amount of pH change and discharge level. To this, the dilution effect was added.

The term $^{\bar{d}}$pH was a measure of the effectiveness of the stream in recovering from the acid depression. If the difference between the first and last sample site was 0 or if the pH at the last site was greater than at the first site, then recovery was assumed to have taken place and the value .01 was assigned to $^{\bar{d}}$pH. Taking the square root of this value before multiplying it to the already evaluated terms ^{d}pH, $^{\Sigma\Delta}$pH, and FG kept the index in a form which when multiplied by 100 avoided the use of decimals.

Discussion of the ADI

The calculated ADI values were measures of the acid drainage conditions in Honey Creek on particular sample days. ADI values were calculated for the upper portion of Honey Creek (sites 1, 3, 4, 6, and 7) which received acid drainage from the gob and slurry area (table 12). The lower portion (sites 7, 11, and 12) received acid drainage from the underground air shaft and the ADI values for this situation were also included (table 13).

The higher the ADI the greater the amount of acid depression and the less able the stream was to recover. This meant that low pH levels extended farther downstream before they were diluted to pre-acid discharge levels than on days with a lower ADI. On days with low ADI, acid drainage was able to be diluted and subsequently the difference between pre-acid drainage water and post-acid drainage was small.

Conditions that promoted high ADI values were those when the amount of acid drainage which entered the stream exceeded the ability of the stream to dilute that acid load. Such conditions prevailed during flushout conditions. During this occurrence, the increase in stream discharge was accompanied by increases in the acid load. This increased acid load resulted from acidic material left from the last flushout and newly formed acid that was carried into the stream by surface runoff. The amount of this increase depended on the length of time since the last flushout and the magnitude and intensity of the storm that produced runoff.

The proportion of acid load to discharge was an important relationship in the ADI equation. Downstream from the Victory Mine property discharge levels were

TABLE 12

ADI VALUES FROM SITES 1, 3, 4, 6, AND 7

Sample No.	d_{pH1}	$\Sigma\Delta_{pH_1}$	FG_1*	$\bar{d}_{pH1}$	ADI_1
1	1.10	1.90	.407	.30	13
2	1.33	2.05	.688	.61	35
3	1.03	1.93	.212	.13	4
4	1.43	2.42	.781	.34	27
5	1.25	2.25	.691	.25	19
6	1.94	2.99	3.605	.89	221
7	1.12	2.44	.339	.01	2
8	.69	1.51	.427	.01	2
9	1.66	2.74	1.645	.58	76
10	1.11	1.91	.633	.65	30
11	1.20	2.25	.269	.09	4
12	1.60	2.19	4.880	1.01	360
13	1.02	2.41	.227	.01	1
14	.75	1.49	.227	.01	1
15	.86	2.06	.549	.01	2
16	.74	1.69	.194	.01	1
17	.83	1.68	.604	.01	3
18	.94	1.67	1.412	.41	51
19	.92	1.51	.521	.33	18
20	.71	1.14	.395	.28	13
21	.60	.91	.364	.29	13
22	.94	1.83	1.257	.05	14
23	2.01	3.86	1.052	.16	22
24	1.25	2.48	.785	.02	6
25	1.47	3.03	.680	.19	14
26	1.34	2.66	.459	.02	3
33	.68	1.30	1.170	.06	15

*$FG_1 = \dfrac{\Delta Q_1}{D_1}$

TABLE 13

ADI VALUES FROM SITES 7, 11, AND 12

Sample No.	d_{pH2}	$\Sigma\Delta pH_2$	FG_2*	$\bar{d}_{pH2}$	ADI_2
1	.01	.20	.657	.01	0
2	.62	.90	2.403	.36	99
3	.33	.63	1.522	.03	14
4	.37	.69	1.352	.05	16
5	.23	.52	.860	.06	4
6	.46	.88	4.520	.04	47
7	.32	.53	1.726	.11	35
8	.37	.74	1.235	.01	6
9	.62	.91	3.740	.33	146
10	.15	.42	.975	.12	12
11	.05	.15	.747	.01	2
12	.33	.49	11.122	.17	309
13	.34	.69	2.263	.01	11
14	.74	1.13	1.544	.45	68
15	.25	.50	1.161	.01	5
16	.47	1.04	.894	.01	4
17	.11	.72	.973	.01	1
18	.36	.43	2.556	.29	115
19	.41	.59	1.080	.01	7
20	.27	.87	.817	.01	2
21	.07	.48	1.004	.01	1
22	.38	.91	.861	.01	4
23	.09	.23	.700	.01	3
24	.43	.77	1.123	.05	14
25	.08	.29	.798	.01	2
26	.02	.17	1.024	.01	1
33	.34	.69	4.399	.05	48

$$*FG_2 = \frac{\Delta Q_2}{D_2}$$

relatively low and the addition of acid drainage had a greater impact on lowering pH than it did in the area near the air shaft. Downstream from the air shaft there was more water available to dilute acid so the amount of pH depression was less than near the gob area. Yet, the existence of a depression in spite of higher discharge levels indicated that an acid load was still present. This acid drainage condition was different from the condition described near the gob. Using the ADI equation, both acid conditions could be compared.

The ADI equation made it possible to segregate individual sample days into one of three groups identified previously as baseflow, transition or flushout. The ADI values from tables 12 and 13 were plotted along with pH to improve separation between points (figures 10 and 11).

The group which had the highest ADI values was flushout. This group consisted of those sample days when pH recovery following depression did not occur. During flushout conditions the amount of acidic material washed into the stream increased and discharge levels were their highest.

Discharge weighted heavily in the ADI equation, especially for the flushout group. The relatively larger discharge amounts resulted in large FG values. When FGs were divided into total pH activity for the stream segment (${}^{\Sigma\Delta}$pH) and those results divided into the depression terms (^{d}pH), larger numbers were yielded than if FGs had been smaller. The recovery terms (${}^{\bar{d}}\mathrm{pH}$), that indicated the differences in pH from start to finish, were also greater during flushout conditions. After they were included, the ADI equation was complete and the values were highest.

The flushout group had the most readily recognized set of acid mine drainage conditions. The remaining groups, transition and baseflow, were not as easily distinguished. Variations in observed pH and discharge made it difficult to establish criteria for those two groups.

However, the ADI equation used variations in discharge and pH to make distinctions. Rather than rely solely on either one, the ADI equation used the numerous combinations of pH and discharge conditions to determine to which group a sample day would belong.

The impact of larger FG values on ADI in identifying flushout conditions was mentioned. In distinguishing between transition and baseflow, the sensitivity of the ADI to the term ${}^{\bar{d}}\mathrm{pH}$ became apparent. For example, on table 12 sample numbers 18 and 22 had similar values for all terms except ${}^{\bar{d}}\mathrm{pH}$ and they belonged to different groups (figure 10). In table 13 sample numbers 3 and 7 displayed similar traits (figure 11).

Baseflow group members had the lowest ADI values. In the extreme case, the lowest ADI value was found on table 13, sample number 1 where there was little total pH activity (${}^{\Sigma\Delta}\mathrm{pH}$), low flow (FG), a small depression (${}^{d}\mathrm{pH}$), and a small difference in pH between sites 7 and 12 (${}^{\bar{d}}\mathrm{pH}$).

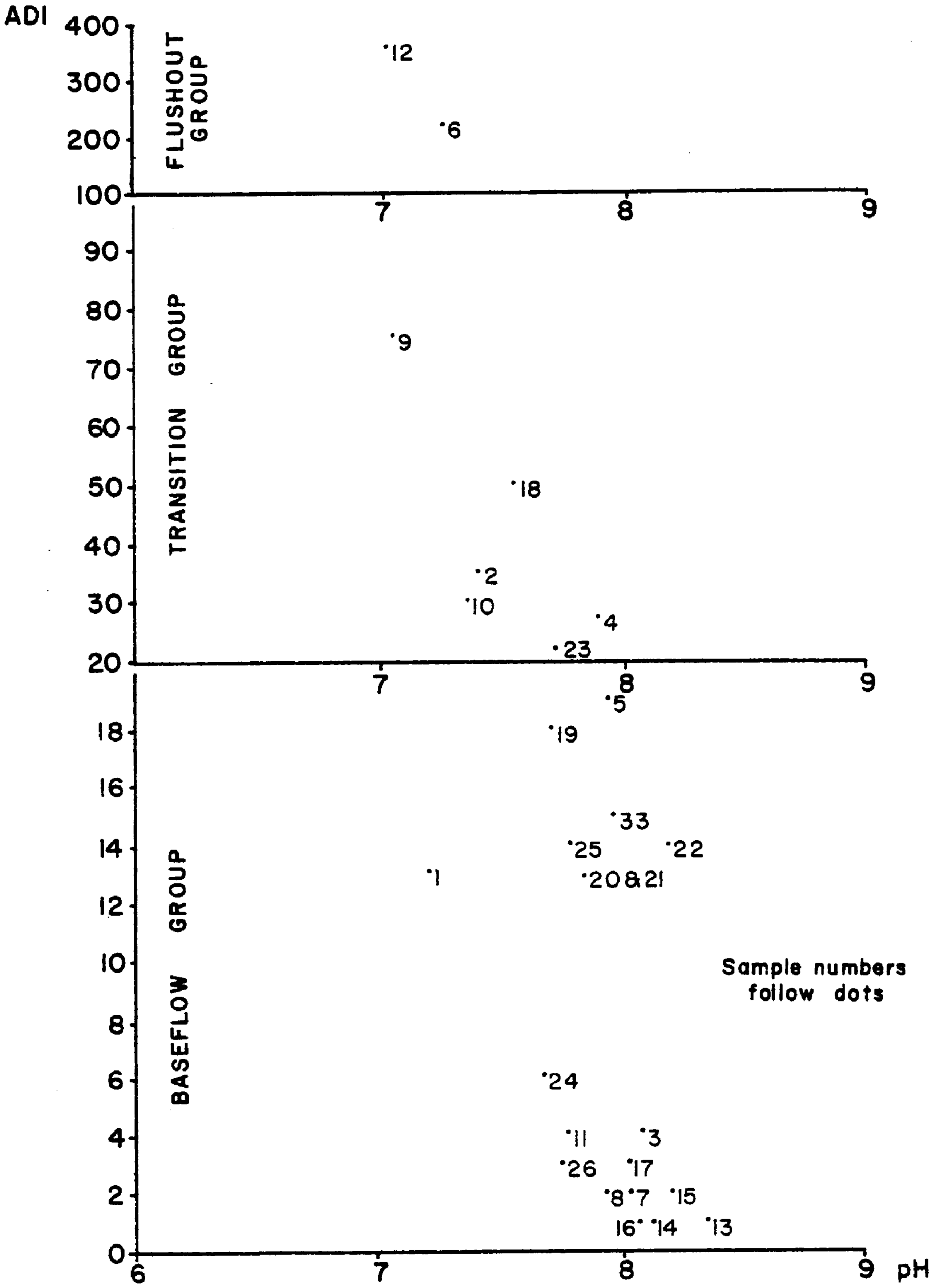

Fig. 10. ADI values for sites 1, 3, 4, 6, and 7

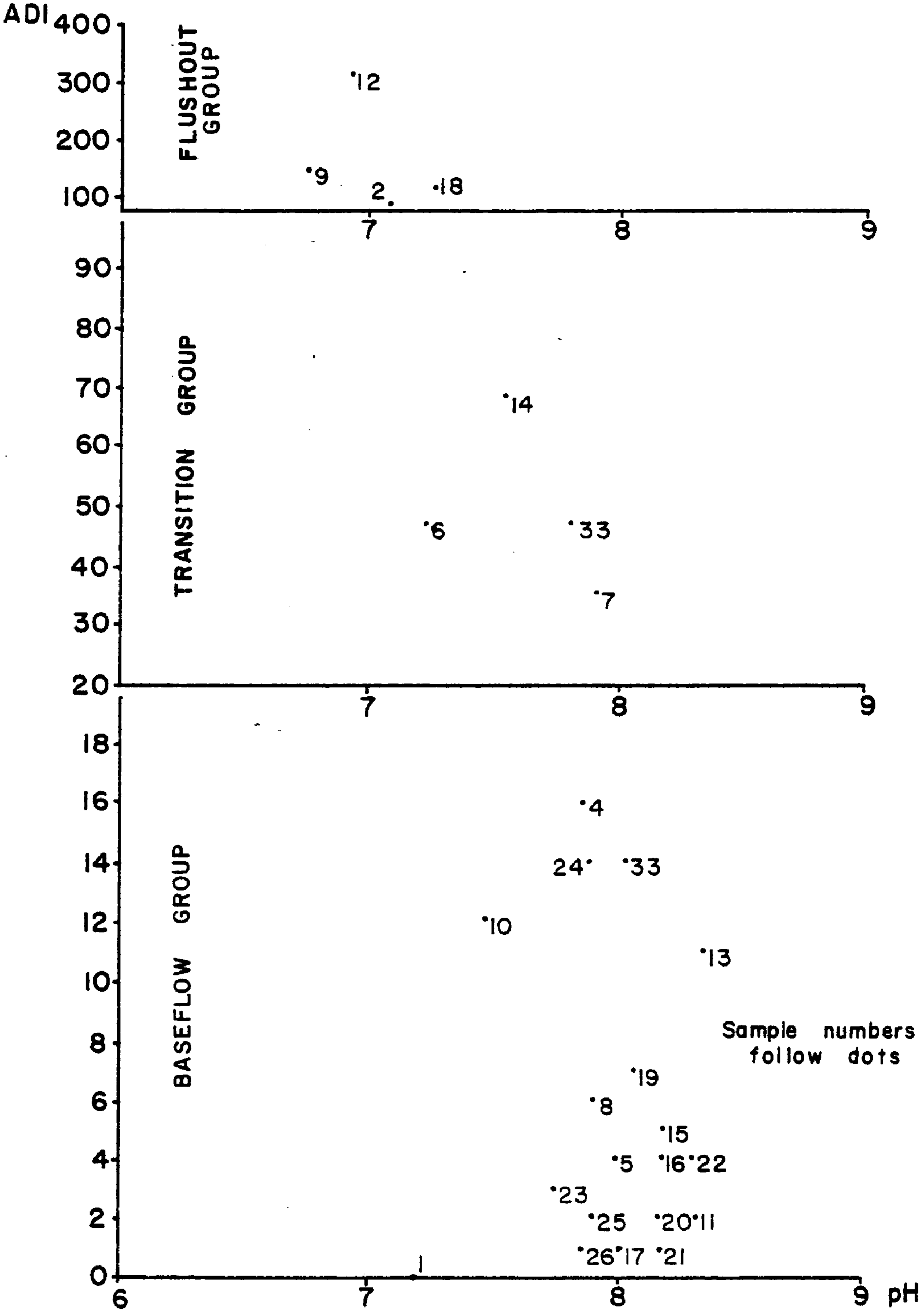

Fig. 11. ADI values for sites 7, 11, and 12

Overall, the most common characteristics of baseflow were the presence of lower than average FG and $^{\bar{d}}$pH values.

The transition group was the most difficult to identify (figures 10 and 11). At the upper end of the ADI scale it was separated from the flushout group by a break in the values. At the lower end of the ADI scale the break was not as large. The position occupied by the transition group on the ADI scale reflected the moderate values for the terms of the equation.

The use of the ADI made it possible to organize the sample dates into three groups which represented different conditions in Honey Creek. Errors in measurement for any of the variables that make up the ADI would affect their index values. Table 14 contains ADI values from the transition group found in figure 10 and recalculated ADI values with an error margin of ±10% assigned to the variables. It was found that for this group of ADI values changing any one variable by ±10% would not cause the ADI to change enough to enter either the flushout or baseflow group. The smaller the original ADI, the less it is affected by changes in the variables. For example, sample 9 had the largest original ADI in table 14 and the largest changes in the recalculated values. Sample 4 had the lowest original ADI and the smallest changes. This relationship is consistent with the fact that with higher ADIs, as in the transition and flushout groups, the larger the natural break in the ADI values separating those two groups.

TABLE 14

RECALCULATED ADI VALUES

Sample No.	2	4	9	10	18
d_{pH}	38	29	84	32	56
	31	24	68	27	46
$\Sigma\Delta_{pH}$	32	24	69	27	46
	39	30	85	33	57
FG	38	30	83	33	56
	31	24	68	27	46
$\bar{d}_{pH}$	36	28	80	31	53
	33	26	72	28	48
Original ADI	35	27	76	31	51

Chapter 7

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Acid mine drainage can be a significant water quality problem in coal producing areas, especially where there are old abandoned mines. This study contributed to the understanding of acid mine drainage by reporting on the changes in pH caused by the addition of acid and the subsequent dilution of that acid in a small stream.

This study was unique when compared with other acid mine drainage studies partly because it was an intensive study of a small stream, less than five miles long. This was a much smaller distance than most studies which invariably concern drainage basins of larger rivers and streams. Although it was a small scale study, the entire process of acid drainage and dilution was observed. Thus, this study represented a closer look at individual acid sources rather than aggregate effects of many sources in a drainage network.

Another unique factor of this study was the magnitude of the pH levels observed. In previous studies the pH levels were much lower than the levels reported here. Except for the pH levels at site 2 the other measurements were all above federal minimum pH standards. This was not significant because it was not the object of this study to identify a hazardous site but to measure the effects on pH of acid mine drainage entering a stream. In this study a means of quantitatively assessing flushouts and comparing the effects of acid mine drainage from two different sources was created.

The focus of this study was on dilution of acid mine drainage. Thus, of primary interest was the relationship between pH and stream discharge. It was hypothesized that increases in discharge, either seasonally or following precipitation, would be accompanied by higher pH values in the stream.

Thirty-three days of field measurements within a network of twelve sampling sites were made from July 1980 through February 1981. This network included two acid mine drainage sources, the surface runoff from a gob area and the constant flow of acid water from an open air shaft.

The collected data and the analysis of that data supported five conclusions. These conclusions were derived from the evaluation of the two research hypotheses and the use of the proposed acid drainage index.

Conclusions

Seasonality. There was no statistical difference between the discharge rates of the summer/early fall sample days and the winter days. Thus, the hypothesis that there would be a difference in pH levels in the stream because of seasonal change in discharge levels was rejected. In the rejection of this hypothesis the possibility of committing a Type I Error should be considered. Although it was true that the data did not reflect a seasonal difference, there is the possibility that such a seasonal difference might exist in other years.

Preliminary discharge and pH data, collected from Honey Creek sites during February and April, indicated that at this time discharge levels were higher than during the summer. Although this data set contained only one-third as many sample days, the pH levels measured did not differ from the low flow levels. This finding was similar to that found in a report by Jenkins and Carroll which stated that pH in streams affected by mining remains relatively constant and independent of flow.[85]

Short term increases in discharge. Short term increases in discharge occurred following precipitation events. Although changes in pH levels were observed with changes in discharge, analysis of the data revealed no clear linear association between those two variables. Thus, the second hypothesis, that short term increases in discharge following precipitation resulted in dilution and high pH levels, was rejected.

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[85] Jenkins and Carroll, "Acid Drainage," p. 286.

Insight into the behavior of acid mine drainage and discharges following precipitation events was gained from the discussion of the flushout phenomenon by Corbett and Agnew. Their descriptions of events had numerous examples of actual stream data for illustration but their discussion of the subject was a qualitative one.

In this study an attempt was made to quantify the relationship between discharge and pH, and it resulted in the formation of an acid drainage index. The remaining conclusions were derived from the use of that equation.

Categories of acid mine drainage. The sampling design for this study was intended to be representative of conditions in Honey Creek throughout the sampling period. As such, the data on pH and discharge included days when conditions seemed to be stable with respect to pH and discharge and days when there were changes. Upon examination of the entire data set, a situation suggesting dynamic equilibrium conditions seemed to exist. Further analysis, which used the empirical acid drainage index, enabled baseflow conditions and deviations from baseflow conditions to be quantitatively identified. In all, three groupings were used to describe acid behavior in the stream--baseflow, transition, and flushout.

The baseflow or equilibrium conditions existed on those days when there were only slight differences in pH between sites upstream of an acid source and those downstream.

This condition usually existed in the period between precipitation events when surface runoff was not present. In effect, this condition became the standard for equilibrium conditions against which increases in discharge and changes in pH were compared.

Transition conditions differed from baseflow conditions in that stable conditions did not exist. Either increased discharge, greater pH depressions, or a combination of both of those factors upset the balance in the stream and recovery from pH depression was not as complete as it was for baseflow.

Flushout conditions represented the biggest deviation from baseflow conditions. Following the heaviest rainfalls during the study period both acid load and discharge levels increased the most. The amount of these increases and in what proportion they occurred determined the acid drainage index value.

Differences between acid sources. The acid drainage index enabled conditions in the stream to be assessed with respect to their source of acid. In this study two sources of acid existed in Honey Creek: the surface runoff from gob found in the upstream portion (sites 1, 3, 4, 6, and 7) and the flow from the air shaft in the downstream portion of the study area (sites 7, 11, and 12). It was found that there were differences in the acid drainage behavior downstream from each of these sources.

The difference picked up by the acid drainage index was in the recovery downstream from each acid source. Downstream of the gob area pH levels were depressed more than they were downstream of the air shaft. Recovery of pH levels took place in both instances but there was more dilution water available at sites 7, 11, and 12 than between 1 and 7. Thus, there was seemingly less of an acid load present downstream of the air shaft and more water to dilute it.

Flushout intensities. The amount and intensity of precipitation varied throughout the sampling period. Consequently, the flushout process following each storm affected the stream in a varied fashion. Some storms were more able than others to wash acid material into the stream.

The acid drainage index made it possible to consistently compare discharge and pH conditions. The acid drainage index acts as a scale upon which flushout conditions can be measured and compared. Although there were not enough data to determine at which levels discharge and pH conditions combined to quantitatively create flushouts, the possibility of establishing threshold values exists.

Recommendations

Further investigations using the acid drainage index would permit more to be learned about acid mine drainage. One research approach would be to focus on thresholding. Using the acid drainage index and data collected from continuously recording pH meters and stream gauges, accurate threshold values for the three groups of baseflow, transition, and flushout could be established.

Another avenue for additional research is to expand the acid drainage index to include precipitation data directly. To better understand the flushout phenomenon, more information is needed about the effects on acid drainage from varying amounts of precipitation and from varying lengths of time between storms. Coupling a system of rain gauges with pH and discharge measuring instruments in a small drainage area like Honey Creek would provide data which might uncover a clear relationship between amounts of precipitation received and changes in the stream. Modifying the acid drainage index to include this type of information would make it a better model of acid mine drainage conditions.

The acid mine drainage index has practical applications, especially in long range forecasting. Using the acid drainage index to measure the intensities of flushouts, flushout frequencies can be computed. Much like the probability tables created for flood stages of rivers and streams, once a large enough data base was created for a place, probabilities for flushouts of certain magnitudes can be computed for a river or stream.

In its present form the acid drainage index is a coarse estimator of fluctuating acid mine drainage conditions in a stream. Its main contribution to the existing knowledge of acid mine drainage is that it begins to quantitatively describe the processes involved.

APPENDIXES

APPENDIX A

SAMPLE ADI CALCULATION

Sample no. 1, table 12
July 20, 1980

dpH = Total amount of pH depression for stream segments of sites along Honey Creek (tributaries excluded).

(site 1 - site 3) + (site 3 - site 4)
(7.50 - 6.50) + (6.50 - 6.40) = <u>1.10</u>

ΣΔpH = Total amount of pH activity of sites along Honey Creek (absolute values).

(site 1 - site 3) + (site 3 - site 4) +
(site 4 - site 6) + (site 6 - site 7)

(7.50 - 6.50) + (6.50 - 6.40) +
(6.40 - 6.90) + (6.90 - 7.20) = <u>1.90</u>

Q = Difference in discharge between sites 1 and 7.

1.415 - .630 = <u>.785</u>

D = Distance from site 1 to site 7.

<u>1.925</u>

$\bar{d}$pH = Difference in pH between sites 1 and 7.

7.50 - 7.20 = <u>.30</u>

FG = Q ÷ D

.785 ÷ 1.925 = <u>.407</u>

$$\text{ADI} = \left(\frac{\frac{1.10}{1.90}}{.407} \text{ X } \sqrt{.30} \right) \text{ X } 100 = 13$$

APPENDIX B

DIMENSIONAL ANALYSIS OF THE ADI

The ADI can be modified so as to be dimensionless by raising the term pH to the 3/2 power and multiplying the equation by two new terms, Q1 and D1. However, these modifications tend to make the ADI seem more complicated than it was originally presented. If a dimensionless ADI is desired, the form given below can be used where D1 is the average width of the stream and Q1 is the average discharge of the stream.

$$\left(\frac{\dfrac{d_{pH}}{(\Sigma \Delta pH)^{3/2}}}{\dfrac{Q}{D}} \times \sqrt{d_{pH}} \times \frac{D1}{Q1} \right)$$

The proof that this equation is dimensionless is also given.

$$\left(\frac{\dfrac{d_{pH}}{(\Sigma \Delta pH)^{3/2}}}{\dfrac{Q}{D}} \times \sqrt{d_{pH}} \times \frac{D1}{Q1} \right)$$

$$\left(\frac{\dfrac{d_{pH}}{(\Sigma \Delta pH)(\Sigma \Delta pH)^{1/2}}}{\dfrac{Q}{D}} \times \sqrt{d_{pH}} \times \frac{D1}{Q1} \right)$$

$$\left(\frac{\dfrac{d_{pH}}{\Sigma \Delta pH}}{\dfrac{Q}{D}} \times \frac{\sqrt{d_{pH}}}{\sqrt{\Sigma \Delta pH}} \times \frac{D1}{Q1} \right)$$

$$\frac{Q}{D} \times \frac{Q1}{D1} = \frac{ft^3/sec}{ft} \times \frac{ft}{ft^3/sec}$$

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