2005

Water quality changes of underground mines in northern West Virginia

Jennifer Demchak
West Virginia University

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Recommended Citation

Demchak, Jennifer, "Water quality changes of underground mines in northern West Virginia" (2005).
Graduate Theses, Dissertations, and Problem Reports. 2260.
<https://researchrepository.wvu.edu/etd/2260>

This Dissertation is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Dissertation in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Dissertation has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

WATER QUALITY CHANGES OF UNDERGROUND MINES IN NORTHERN WEST VIRGINIA

Jennifer Demchak

Submitted to the Davis College of Agriculture, Forestry, and Consumer Sciences

At West Virginia University

In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

In

Agricultural Sciences

Jeffrey Skousen, Ph.D., Chair

Louis McDonald, Ph.D.

John Sencindiver, Ph.D

Joe Donovan, Ph.D

Paul Ziemkiewicz, Ph.D.

Division of Plant and Soil Sciences

Morgantown, West Virginia

2005

ABSTRACT

Water quality changes of underground mines in Northern West Virginia

Jennifer Demchak

Acid mine drainage (AMD) is a serious problem from both abandoned surface and underground mines, and about 10,000 km of streams have been impacted by AMD in the northeastern U.S. (Pennsylvania, Maryland, Ohio, and West Virginia). Streams in the region have shown improvement over time and this improvement has been partly attributed to reclamation of mined sites and natural attenuation of AMD impacts. This study was initiated to determine the water quality changes from underground mines over time in northern West Virginia. In order to compare chemistry data across years and seasons with varying flow, relationships between discharge rates and acidity values were assessed. Results indicate that water quality from the majority of abandoned, above drainage underground mines did significantly improve over time, some exponentially and some linearly. The amount of improvement varied with coal seams. Graphs plotting flow and precipitation showed the highest flows generally in the spring and low flows in the fall. Acidity concentrations from two underground mines did not change significantly with varying discharge rates, which neither supports previous ideas of a flushing or dilution of acid salts from the mine. One mine, T&T, showed a slight trend of highest acidity values at high flows, while Omega showed highest acidity at low flows. Additional long term data sets with frequent flow and acidity data will be necessary to confirm these results.

EXECUTIVE SUMMARY

Acid mine drainage (AMD) is a serious problem from both abandoned surface and underground mines, and about 10,000 km of streams have been impacted by AMD in the northeastern U.S. (Pennsylvania, Maryland, Ohio, and West Virginia). Streams in the region have shown improvement over time and this improvement has been partly attributed to reclamation of mined sites and natural attenuation of AMD impacts. Therefore, this study was initiated to determine the water quality changes from underground mines over time in northern West Virginia. Water quality data were collected from 44 underground mines that were sampled in 1999 and 2000, and compared to data collected during 1968 and 1980. There were significant water quality differences between years and coal seam, but disturbance had no effect. While pH was not significantly improved, average total acidity declined 79% between 1968 and 2000 in the Pittsburgh mines and 56% in the Upper Freeport mines. Iron decreased an average of 80% across all sites, while sulfate decreased between 50 and 75%. Twenty of the 44 sites had water quality information in 1980, which served as a midpoint to assess the rate of decline of acidity and metal concentrations. Five of the 20 sites showed an apparent exponential rate of decline in acidity and iron, while 10 of the 20 sites showed a more linear decline. Drainage from five Upper Freeport sites increased in acidity and iron. Above drainage underground mines are not as predictable in water quality improvement as surface mines and below-drainage mines. In total, the drainage from 34 of 44 above drainage sites showed significant improvement in acidity over time. Ten discharges showed no improvement and three got much worse.

Two above drainage underground mines, Omega and T&T, which had daily flows and frequent analysis of water chemistry, were used to test the effect of flow on acidity concentrations. Both are located near Morgantown, WV and were mined for Upper Freeport coal. They do, however, vary in size, topography, and overburden depth.

Graphs plotting precipitation and flow show the highest flows generally occurring in the spring, with low flows in the fall. The time graphs showed no clear acidity trends with flow. Flow category had no significance on acidity values at T&T, but in general the highest flows generally had the highest acidity values. Graphical analysis showed a slight trend for increased flow to increase acidity ($R^2 = 0.92$). At Omega, the individual flow category term was not

significant, but the interaction of flow category with season was significant. This resulted in significantly higher acidity values at low flows at this site.

Significant differences were seen in acidity across years at both sites with acidity concentrations gradually declining over time. Analysis of flow and acidity data from these two mines gave hardly any relationship between flow rates and acidity concentrations. While two ideas have existed about flow rate on discharge acidity concentration from above drainage underground mines (flushing versus dilution), neither idea was supported by this analysis. Additional long term data sets with frequent flow and acidity data will be necessary to confirm these results.

ACKNOWLEDGEMENTS

I would like to first thank my major advisor Dr. Jeff Skousen for his encouragement of independent thinking, along with the support and guidance to produce a dissertation of practical importance and implication. I would like to thank my advisory committee of Dr. Louis McDonald, Dr. John Sencindiver, Dr. Joe Donovan, and Dr. Paul Ziemkiewicz for their thoughtful insight and expertise during this project. In addition, I want to thank Jason Stewart for his willingness to always lend a hand and most importantly, his friendship.

Furthermore, I would like to thank my parents for their love and support throughout my life. They instilled in me a belief in myself that anything was possible. I would like to thank my husband Sean for his love, friendship, and endless support (both emotionally and technically). I would also like to extend a sincere thanks to my fellow graduate students and staff for your friendship, guidance, and willingness to help along the way.

TABLE OF CONTENTS

<i>ABSTRACT</i>	<i>ii</i>
<i>EXECUTIVE SUMMARY</i>	<i>iii</i>
<i>ACKNOWLEDGEMENTS</i>	<i>v</i>
<i>TABLE OF CONTENTS</i>	<i>vi</i>
List of Figures	ix
List of Tables	x
<i>CHAPTER 1: INTRODUCTION</i>	<i>1</i>
Objectives	2
<i>CHAPTER 2: LITERATURE REVIEW</i>	<i>3</i>
AMD History	3
AMD Formation and Effects on Aquatic Ecosystems	4
Types of Underground Mines	5
AMD Treatment Methods	8
Longevity	10
Flow Rate Effects on Acidity Concentrations	13
Literature Cited	15
<i>CHAPTER 3: LONGEVITY OF ACID DISCHARGES FROM UNDERGROUND MINES LYING ABOVE THE REGIONAL WATER TABLE</i>	<i>20</i>
Introduction	20
Materials and Methods	27
1968 Study	28
1999-2000 Study	28
Statistical Analysis	29
Results and Discussion	30
Flow and Concentration Differences within a Year	30

Comparisons between 1968 and 2000	31
Comparisons among 1968, 1980, and 1999-2000	32
Effects of Disturbance, Mine Size, and Time Since Closure	33
Conclusions	35
Acknowledgments	36
Literature Cited	36
<i>CHAPTER 4: FLOW EFFECTS ON ACIDITY AT TWO MINE SITES IN WV: OMEGA AND T&T</i>	<i>51</i>
Introduction	51
Methods and Materials	54
T&T	54
Omega	54
Sampling	55
Measured vs. Calculated Acidity	55
Statistical Analysis	56
Results and Discussion	56
Precipitation Effects on Flow Rate	56
Acidity Values Plotted Over Time	57
Year, Seasonal and Monthly Flow Effects on Acidity	58
Daily Flow Effects on Acidity	60
Conclusion	61
Literature Cited	62
<i>CHAPTER 5: DISSERTATION SUMMARY</i>	<i>76</i>
<i>APPENDICES</i>	
Appendix A: Location Maps of Underground Mines	
Area Summary	A-1
Area 1	A-2
Area 1 (on topo)	A-3
Area 2	A-4
Area 2 (on topo)	A-5
Area 3	A-6
Area 3 (on topo)	A-7

Area 4 _____	A-8
Area 4 (on topo) _____	A-9
List of sampling points _____	A-10

Appendix B: Site Descriptions for Underground Mines

Site Descriptions for Underground Mines _____	B-1
Stream Information and Study Area _____	B-9
Coal Beds _____	B-11
Historical and Additional Data _____	B-12

Appendix C: Water Quality Results for Underground Mines in 1968, 1980, and 1999-2000

Appendix D: ANOVA Results for Precipitation, Flow and Acidity Models for T&T and Omega

T&T ANOVA RESULTS	D-1
Model : Flow Category * Year	D-1
Model: Flow Category * Year* Season	D-3
Model: Average Flow * Year	D-6
Model: Average Flow * Year * Season	D-8
Model: Average Flow * Month.....	D-10
Model: Flow Category * Average Precipitation	D-12
Model: Average Flow * Average Precipitation	D-13
Omega ANOVA Results	D-14
Model: Flow Category * Year	D-14
Model: Flow category * Year * Season	D-16
Model: Average Flow * Year	D-20
Model: Average Flow * Year * Season	D-21
Model: Average flow * Month	D-24
Model: Average Precipitation * Flow Category	D-26
Model: Average Flow * Average Precipitation	D-27

List of Figures

Figure 3-1. Below drainage vs. Above drainage.....	45
Figure 3-2. Average values for flow, acidity, iron, and pH across years and months for the T&T data set.	46
Figure 3-3. Cumulative frequency 1968 vs. 2000.....	47
Figure 3-4. Pittsburgh acidity & iron over years.....	48
Figure 3-5. Changes in acidity for Upper Freeport sites	49
Figure 3-6. Changes in iron for Upper Freeport sites	50
Figure 4-1: Regression analysis of the measured and calculated acidity at the T&T mine site.	70
Figure 4-2: Regression analysis of the measured and calculated acidity at the Omega mine site.	70
Figure 4-3: Daily flow and precipitation at the T&T mine site from 10 Nov 1995 to 31 Dec 2003.....	71
Figure 4-4: Daily flow and precipitation at the Omega mine site from 1 Feb 2000 through 31 Dec 2003.....	71
Figure 4-5: Acidity concentrations and flow plotted over time at the T&T mine site using monthly averages.....	72
Figure 4-6: Regression analysis of flow and acidity concentration at the T&T mine site.	72
Figure 4-7: Acidity concentrations and flow plotted over time at the Omega mine site using monthly averages.	73
Figure 4-8: Regression analysis of flow and acidity concentration at the Omega mine site.....	73
Figure 4-9: Acidity concentration from 1995 through 2003 years at the T&T mine site.....	74
Figure 4-10: Acidity concentration over seasons at the T&T mine site.....	74
Figure 4-11: Acidity concentrations over months (January to December) at the T&T mine site.	74
Figure 4-12: Acidity concentrations over flow categories (Low, Mid, and High) with a trend line and regression shown at the T&T mine site.	74
Figure 4-13: Acidity concentration from 1995 through 2003 years at the Omega mine site.	75
Figure 4-14: Acidity concentration over seasons at the Omega mine site.	75
Figure 4-15: Acidity concentrations over months (January to December) at the T&T mine site.	75
Figure 4-16: Acidity concentrations over flow categories (Low, Mid, and High) at the Omega mine site.	75

List of Tables

Table 3-1. Discharge and Mine Overview	41
Table 3-2. Analysis of variance results and model fits for T&T water quality data for 1996 to 2001.....	42
Table 3-3. Correlation coefficients between water quality parameters for the T&T underground mine site.....	42
Table 3-4. Characterization of T&T flows and concentrations (1996 to 2001) across all months (January to December) and during low-flow sampling times (June to September).	43
Table 3-5. Average values for 1968 and 1999-2000 water quality data (two dates) from Pittsburgh and Upper Freeport underground mines.	43
Table 3-6. Average water quality value from Pittsburgh and Upper Freeport underground mines	44
Table 4-1: Characterization of T&T flows and acidity (1996 to 2003) using Tukey analysis.....	64
Table 4-2: Analysis of variance results and model fits for T&T water quality data for 1996 to 2003.	64
Table 4-3: Characterization of Omega flows and acidity (2000 to 2003) using summary statistics and Tukey analysis.....	65
Table 4-4: Analysis of variance results and model fits for Omega water quality data for 2000 to 2003.....	65
Table 4-5: Description of data categories for T&T and Omega using flow categories.....	65
Table 4-6. Average flow & acidity for T&T by category	66
Table 4-7. Average flow & acidity for Omega by category.....	66
Table 4-8: Flow rates and acidity amounts at the T&T mine by rainfall event.....	67
Table 4-9: Flow rates and acidity amounts at the Omega mine following dry periods of no rain along with high rainfall events.	69

CHAPTER 1: INTRODUCTION

Surface mining has disturbed approximately 1.8 million ha (4.4 million ac) in the Appalachian Region since 1930 (Barnhisel et al. 2000, Paone et al. 1978, Zeleznik and Skousen 1996). No estimates have been made on the areal extent of underground mining in this region. The West Virginia Department of Environmental Protection (WVDEP) estimates that in West Virginia alone about 610,000 ha (1.5 million ac) have been mined by underground methods, while about 276,000 ha (682,000 ac) have been surface mined in the state (Bennett 1991).

Acid mine drainage (AMD) is a serious problem from both abandoned surface and underground mines. According to the Environmental Protection Agency (1995) approximately 10,000 km of streams have been affected by AMD in the northeastern U.S. (Pennsylvania, Maryland, Ohio, and West Virginia). Mines abandoned prior to 1977 generate more than 90% of the AMD in streams and rivers in the region with the majority of this acid drainage coming from underground mines. Acid drainage from abandoned deep mines is problematic and hard to correct because the mines are partially caved and flooded, thereby restricting access, and reliable mine maps are often not available for study.

Many of these acid discharges exist with no responsible parties to treat them and when abandoned they become the responsibility of the state or federal government. Simple and inexpensive treatment approaches are being sought as well as a better understanding of the natural amelioration and reclamation processes that occur to improve water quality over time (Kleinmann et al. 1981). Much work has been done on selection, design, and effectiveness of AMD treatment methods, both active and passive (Hyman and Watzlaf 1995, Hedin et al. 1994). However, changes in water quality over time from surface and underground mines are not as well documented because long-term datasets are not available. In order to determine appropriate remediation strategies, it is critical to determine methods to predict the longevity of these acid discharges.

It has been estimated that acidic water discharges from surface mines for 10-20 years, then gradually decreases as the acid producing salts are leached (Meek 1996). Estimates of acid drainage from underground mines are much more difficult to predict. For underground mines in the U.K. estimates of 10-100 years have been made (Younger 1997). In West Virginia underground mining began in 1742 and continues to the present. Many of today's discharging

mines were present and abandoned long before the Surface Mining Control and Reclamation Act of 1977 placed regulations and responsibility of mine drainage on the operator; prior to this date, few documents exist relating to the water quality from surface or underground coal mines.

Understanding the history of these mines is vital in determining longevity. Determining water chemistry is the primary step, but research into the size of the mine, years in operation, coal bed mined and pyrite content, coal recovery rate, type of mining, techniques of abandonment, up dip vs. down dip status, roof caving amount and rate, water infiltration rate, water flow through the mined out area, roof cave-in barriers, water impoundment, oxygen content and flux should also be considered. Such information is difficult to locate and relate to a particular mine. The old mines, as stated, are not well documented, but a few mines have sufficient historical data to estimate the longevity of the acid discharge.

Objectives

1. Determine the water quality changes over time from underground mines in northern West Virginia.
2. Assess the relationship between discharge rates and acidity emanating from underground mines.

CHAPTER 2: LITERATURE REVIEW

AMD History

Acid mine drainage (AMD) is one of the most serious problems facing the watersheds of Appalachia today, affecting over 16,090 km (10,000 miles) of streams (U.S. Environmental Protection Agency 1995). Coal was first mined in the U.S. in Richmond, Virginia in 1750. Coal mining was performed by small operators using only picks and shovels on surface coal outcrops where little soil cover occurred. During the 1800s, the demand for coal increased forcing the development of underground mines. The USDA Soil Conservation Service (1976) estimated that surface mining by 1975 had disturbed about 243,000 ha (600,000 acres) of land. No estimate has been made of the km of underground tunnels where coal had been removed by underground mining.

The detrimental effects of mine drainage were evident soon after coal was first discovered and excavated. The study of AMD-creating processes began in 1910 and research into treatment using lime and soda ash as neutralizing agents began soon after (Gleason and Russell 1987). The first intensive effort to control AMD was made by the U.S. Public Health Service in the 1930s, where they reduced drainage from underground mines using mine seals (Bennett 1991). In 1947, the role of microorganisms in AMD formation and treatment was established when iron and sulfur oxidizing bacteria were isolated from AMD producing sites (Gleason and Russell 1987). This research led to an understanding of the factors involved in mine drainage formation, which in turn allowed for precautionary measures to be taken when extracting coal. Several states, including Pennsylvania and West Virginia, had regulations governing surface mine reclamation and allowable discharge water quality in the 1950s. With the passage of the Surface Mining Control and Reclamation Act (SMCRA) in 1977, all coal mines came under Federal regulation and had to meet standard effluent criteria. Effluent standards for pH, total suspended solids, Fe, and Mn were established and monitoring of water discharge points from mines was required. The effects of discharged water on receiving streams also had to be evaluated.

In 1966 a large scale regional survey occurred in Appalachia by Biesecker and George (1966). They traveled through nine states from Pennsylvania to Alabama and showed that water quality in 200 of 318 streams was below drinking water standards. Lorenz and Stephan (1969)

looked at stream water quality as affected by deep mines in Pennsylvania, Ohio, Maryland, West Virginia, Kentucky, Tennessee, and Alabama. They determined that the quality of mine water depends on the thickness and type of overburden. A study by Renton and Hidalgo (1975) showed through artificial leaching that no correlation existed between abundance of pyrite and the amount of acid produced. Rauch et al. (1984) studied the effects of surface mining on ground water quality in northern Preston County, West Virginia. They showed that peak contamination by sulfate and iron in groundwater wells occurred 2 to 4 years after mining ceased, then improvement began.

AMD Formation and Effects on Aquatic Ecosystems

AMD is formed when overburden or coal containing pyrite is exposed to oxygen and water during underground and surface coal mining. When neutralizing compounds are absent in the overburden, water draining from surface and deep mines can become acidic and contaminated with high concentrations of dissolved Fe, Mn, Al, and SO_4 (Edenborn et al. 1993). Metal concentrations in AMD vary and depend upon the disturbed soil and mineral rock composition from which the drainage developed. The type of drainage is highly correlated to the amount and type of pyrite present and the degree of physical weathering that has occurred. Mine drainage may be either net acidic or net alkaline. Net acidic drainage lacks adequate buffering capacity and net alkaline drainage contains net neutralizing potential, generally as HCO_3^- , to accept proton acidity (Robb and Robinson 1995). The oxidation of iron sulfides (FeS_2) creates the high concentration of iron, sulfate, and proton acidity in the water, but the sulfuric acid dissolves other nearby minerals causing high concentrations of aluminum, additional iron, manganese, and other elements.

AMD from surface and underground mines pollutes surrounding receiving streams with acid and metals, thereby destroying aquatic and streambed habitat. The first noted effects of AMD are red-yellow precipitates of iron hydroxide in streambeds and the toxic effects of acid and metals on fish and other aquatic flora and fauna in receiving streams (Paine 1987). As iron-laden AMD reaches a surface stream, the usually higher quality stream neutralizes some of the acidity causing a rise in water pH. When the pH rises above 3.5, Fe^{3+} in the water forms $\text{Fe}(\text{OH})_3$, which then precipitates and coats stream bottoms. The iron precipitate is commonly called “yellow-boy.” AMD has numerous effects on the stream including sediment and solid deposition and

coating, oxygen removal, acidification, depletion of neutralizing capacity, and a decrease in light penetration, which in turn affects photosynthesis and the clarity of the water. The “yellow-boy” solid precipitate smothers out stream bottom dwelling insects, thereby, decreasing food resources for fish (Robb and Robinson 1995). A direct toxic effect of dissolved Fe and Al may also occur reducing the diversity of fauna within the streams (Jarvis and Younger 1997). AMD is also devastating to public-use water supplies, recreation, and agriculture and industrial use. Other metal oxides can also precipitate and may fill in spaces between rocks, depleting organism habitat (Robb and Robinson 1995). $\text{Al}(\text{OH})_3$ appears as a white solid, while MnO_2 appears as a black coating on sediments.

In the eastern U.S., abandoned mines generate more than 90% of the AMD in streams and rivers and most of the drainage stems from underground mines (U.S. Environmental Protection Agency 1995). Drainage quality from underground mines depends on the relative proportion of acid producing and acid consuming minerals (pyrites and carbonates respectively in the coal and surrounding geologic material, and less on the total overburden chemistry (Skousen et al. 2002).

On surface mines, AMD can discharge from overburden material that has been blasted apart and moved to reach the coal, thereby exposing pyritic material. The porosity and hydraulic conductivity of the materials in a surface mine backfill are greater than those of consolidated rock overburden that existed prior to mining, and changes in water flow paths are evident (Caruccio 1968). Water tends to flow through more permeable acid sandstones than calcareous shales. The water continues downward until it encounters a barrier, the coal pavement or other compacted or slowly permeable layer. Water emanating from a surface mine backfill will reflect only the chemistry of the rock types encountered, and probably not the overall chemistry of the entire overburden (Ziemkiewicz and Skousen 1992).

Types of Underground Mines

Underground mining will continue for years to come because 70% of the coal in the U.S. is attainable only by underground mining (Meyers 1981). Different mining methods were and are used for coal removal depending on the depth of the overburden covering the coal bed and depending on the position of the coal in relation to the land surface. Drift mines are most typical at sites where the coal outcrops at the surface and remains horizontal to the land surface. Drift mines were the most common underground mine before advances in technology allowed access

to deeper coal. Another underground mining method is a slope mine. Slope mines are used where there is some overburden above the coal and an incline tunnel is needed. The coal is then removed and brought to the surface on a conveyor belt. A further development was shaft mines. These are used on coal beds covered by thick overburden, which need vertical shafts to enter the mine (Meyers 1981). Today's underground mining includes drift, slope and shaft mine entries, and coal extraction methods including, long-wall and short-wall mining machines and advance and retreat continuous mining machines. Still other underground mines use traditional blasting and electric coal shovels to load coal. All are used as necessary to obtain the coal as economically and safely as possible.

A problem associated with almost all deep mines is subsidence, but it is usually only noticeable at the land surface when the overburden is less than 45 meters thick. However, subsidence has been reported in areas where the cover was up to 180 to 215 meters (Hobba 1981). Continued subsidence into underground mine void space increases cracks and fissures to the surface, which increases the potential for surface water recharge into mine water pools, along with increasing the oxygen intrusion into the mine. Subsidence may also increase the hydraulic conductivity and inter-connectedness of mines, which can cause an increase in underground mine drainage and seasonal water table fluctuations (Hobba 1981). As cracks and fissures open to the surface and the roof falls, pyritic material in the roof and in coal pillars (left to support the roof) break apart, thereby exposing fresh surfaces of pyrite to react perpetuating AMD discharge.

Some coal beds are located below the regional water table or below the elevation of major streams and rivers, and these coal beds are termed below-drainage coal. Mining of this coal requires continual pumping of the water that constantly fills the mined area to allow men and machines to work. As the mine progresses, more pump stations are added to keep the water out of the mine. Once mining is finished, the pumps are shut off and the mine voids fill with water. It is assumed that once the mine voids are filled with water, the water quality will return to pre-disturbance levels within a few years after abandonment. However, in acid-producing, below-drainage deep mines, pre-disturbance water quality may not re-establish for several decades.

Some coal beds are situated above the regional water table. Underground mining of these beds sometimes requires continual or sporadic pumping to remove infiltrating water. Since these mines drain, water moves toward the lowest elevational point in the mine. These mines are called above-drainage deep mines.

There are two types of above-drainage deep mines: mines that were developed from a low elevational point and progressively mined up-dip (where the portal entrance is the lowest elevational opening in the mine) and those that were developed at a high point and mined down-dip (where the portal entrance is the highest elevational opening in the mine).

Up-dip, above-drainage deep mines continually drain and do not fill with water unless some barrier or seal is placed near the entrance or portal face. If a seal is placed, the possibility of blowouts or water blasting out of the mine at the weakest point along the contour is a potential hazard. Therefore, most up-dip, above-drainage deep mines are closed with wet seals, which allow water to continually flow out of the mine through pipes in the seal. Once abandoned, roof falls or other caving material may block water and air flow in the mine, and cause small pools of water to form (Perry, personal communication).

Down-dip, above-drainage deep mines may fill with water since there is no proscribed outlet for the water. Theoretically, the down-dip mine should fill with water (like a below-drainage deep mine) and any water that comes from the mine must either flow out the top of the water pool at the portal face or the water may seep through the hillside and come out at some lower elevational point than the portal. Sufficient barrier or outcrop coal must be left in order to withstand the hydraulic head in the mine or else a “blow-out” of water may occur along the hillside contour, thereby draining the mine. With a blow-out, the previously down-dip mine becomes an up-dip, above-drainage deep mine. Down-dip mines, if the mine is full of water, may improve in water quality over time much like a flooded, below-drainage underground mine (Perry, personal communication).

Above-drainage deep mines may contribute polluted water for a long time period because pyrite materials in coal pillars left in the mine for roof support and in the coal pavement and overlying material are continually in contact with air and water. As water flows through the mine downward to the portal in an up-dip mine, the water picks up acidity and metal salts from pyrite oxidation. This water contamination process continues until the pyrite is exhausted along those flow paths. In underground mining, flooding the mine is the preferred method of reducing contamination because it is assumed that acid generation ceases when oxygen is depleted. So in most cases, flooding is assumed to eventually allow the water to become alkaline, but it will not return to its pre-mining quality. It will be highly mineralized due to extensive leaching (Perry, personal communication).

In watersheds where many abandoned deep mines occur, the deep mines serve as a constant source of water to streams, sometimes called baseflow (Hobba 1981). During drier periods of the year, a larger degree of stream flow comes from deep mine drainage or baseflow, thereby causing very acidic water. During wetter periods, deep mine discharges, making up the majority of the baseflow, are diluted by ephemeral springs and seeps, and also by runoff, thereby resulting in improved water quality in streams. However, stream clean-up efforts must effectively deal with improving the water quality during baseflow conditions (improving the deep mine discharges) or else any enhancement in stream quality and aquatic habitat will be transitory and destroyed each time rainfall declines or is irregular.

AMD Treatment Methods

The potential for AMD formation is widespread, so measures should be taken during mining to preclude or reduce the problem. Treating the acid rock directly and stopping or retarding acid production is a practice that has been implemented on many surface mines. The most common preventative measure is the use of alkaline amendments, such as limestone, fluidized bed combustion ash (FBC), kiln dust and steel slag (Brady et al. 1990; Perry and Brady 1995; Rich and Hutchinson 1990; Rose et al. 1995). These alkaline materials are blended with the acid-producing material to increase the neutralization potential or to act as seals or stabilizers. Surface reclamation is also useful for contaminated sites. Water quality improvements can occur through slope modification, erosion prevention, the building of sedimentation basins, and revegetating the site.

With underground mines, opportunities for alkaline amendment are limited. Rock dust and other lime products may be layered on underground floors, ceilings, and mine walls, but this technique has limited success in underground mines with high pyrite levels. Another technique being used after mining involves injection of alkaline materials to fill mine voids with non-permeable materials (Burnett et al. 1995). They act to decrease or stop oxygen intrusion and water infiltration.

Another important technique to aid in the improvement of water quality from abandoned areas is remining. In the process of remining, the operator returns to an area that has already been mined for further coal removal. Terms like daylighting and underground mine removal have also been used to describe remining. It has been shown that remining reduces acid drainage by

decreasing water infiltration, covering exposed acid-producing material with soil materials, and removing coal, which is a major source of pyrite (Griffiths et al. 2001, Richardson and Dougherty 1976). Hawkins (1994) studied 57 discharges from 24 previously abandoned, remined sites in Pennsylvania and found contaminant loads were either reduced or unchanged after remining occurred. Reduction in loads resulted primarily from decreased flow rather than large reductions in contaminant concentrations.

Unfortunately preventative measures have not always been used or may not have been 100% effective. Through the years, many treatment technologies have been developed for AMD remediation and currently there are a number of organized efforts in Appalachia using both active and passive treatment methods on a watershed scale. Active treatment methods incorporate the use of mechanized procedures for the addition of alkaline materials and require constant monitoring and maintenance. Basic chemicals are used as additives to increase the pH and cause the precipitation of metals, such as iron and aluminum. The chemicals commonly used are $\text{Ca}(\text{OH})_2$ (hydrated lime), NaOH (caustic soda), NH_3 (ammonia), CaO (pebble quicklime) and Na_2CO_3 (soda ash) (Faulkner 1997, Skousen et al. 1990). Other active treatment methods include dissolved air flotation and ion exchange devices, flocculants, coagulants, and oxidants (Skousen et al. 2000). Active methods are successful, but expensive. It is not uncommon for water treatment costs to exceed \$200,000 per year at AMD sites using active treatment. Another concern is the large volume of sludge produced from the precipitation of metals. Disposal costs for the sludge add to the cost of chemical treatment. Active methods may also cause environmental damage because potentially harmful chemicals are used. The high cost and possible side effects of active treatment can be avoided by the use of passive treatment systems.

Passive treatment systems, which require only limited maintenance, are an alternative approach to active treatment methods. They require no input of manufactured chemicals and have lower operation and maintenance costs. A downside is that they do require longer retention times and larger treatment areas (Hedin et al. 1994). Passive systems include constructed wetlands, ALD's vertical flow ponds, open limestone channels, diversion wells and bioremediation. Most passive systems are designed to encourage oxidation processes and the precipitation unwanted metals, while increasing the pH (Robb and Robinson 1995).

Longevity

It is vital to determine the origin of the deep mine discharges and whether the discharges have improved over time and vary with seasonal rainfall. A prediction of the longevity of acid mine discharges is needed to determine the most appropriate treatment technology. Studying longevity will help predict the time scale at which present loading rates will continue and the length of time the metal loadings will be at polluting levels. Determining the levels of acid discharge over time may provide an estimate of active treatment length, and when the system can be switched to passive treatment. Surface mine discharge longevity has been studied in more detail than underground mines, mainly due to the amount of data and historical information that can be collected.

Meek (1996) stated that acid generation at surface mines have a defined life of 16-20 years. During the subsequent 20 years after reclamation, the quality of the acid discharge begins to improve until all the acid salts are leached from the rocks by natural precipitation. Over a period of 20 years, the raw water quality could reach levels similar to pre-mining levels.

AMD discharge longevity from underground mines is less understood, but studies have been conducted in order to predict discharge longevity. Younger (1997) in the United Kingdom has conducted work on planning remediation based on an understanding of the physical and chemical processes that govern pollutant release over time. Younger (1997) states the longevity of underground minewater pollution is based on two types of acidity: 1) vestigial acidity, which occurs from 'geochemical trauma' as the mine voids fill with water the first time taking ferrous and ferric hydroxysulfates into solution, and 2) juvenile acidity, which occurs from the ongoing pyrite oxidation due to fluctuations in the water table. Vestigial acidity is thought to be produced in the first 40 years, while juvenile acidity may persist for hundreds of years. The longevity at a given site is dependent on the rate of depletion of both the vestigial and juvenile acidity. Vestigial acidity is affected by the volume of the flooded mine, the hydraulic conductivity, and the rate of recharge. Juvenile acidity is determined by the amount of pyrite oxidation that is occurring above the water table.

Younger states four main conclusions from his research: First, the poorest water quality from uncontrolled mines occurs within the first 40 years. Second, where rainfall is high or interconnected workings are minimal, the worst pollution occurs within the first 10-20 years. Third, asymptotic levels occur for iron at 10 to 30 mg/L; and fourth, higher iron and acidity

levels occur where water table fluctuations are extensive and where pyrite concentration is high (Younger 1997).

Other models and predictions have been made concerning longevity of AMD from underground mines. The former British Coal Corporation uses a 'rule of thumb' (for below-drainage mines) that states that the iron concentration in an uncontrolled mine will decrease by 50% in each subsequent period equal to that taken for the abandoned workings to fill with water. For example, if 10 years is required for a mine to fill with water, the rule of thumb states that iron concentration will decrease by half every 10 years. This is simulating an exponential decay (Glover 1983). Frost (1979) reported that chronic pollution from underground mines will last no longer than five years. Frost's conclusions are based on a convective mass transfer process where an exponential decline in the concentration of oxidized products occurs. This model is based only on a constant volume of flooded workings, because the rise and fall of the water table can flush out further products. Frost's model can be discredited because there are discharges known to have released pollution for more than 70 years.

Others have stated that the most severe drainage occurs within the first few decades and even the largest systems settle to lower levels within 40 years. A circum-neutral pH is reached within 30 years, and after 40 years the iron concentrations are less than 40 mg/L (Wood et al. 1999). Jones et al. (1994) also states that minewaters in Pennsylvania changed from acidic to neutral over a period of decades. These 40-year reductions in pollution from deep mine drainages do not occur from shallow drift mines and spoil heaps, where ventilation facilitates pyrite oxidation and contamination continues for decades until the pyrite is exhausted (Younger et al. 1997).

Other factors affect the longevity of discharges. The rate of dilution is greatest where the volume of the mine is small, water flow out of the mine is high, and recharge rate is high (Younger 1997). Another concern is the fluctuation of water levels due to seasonal variations in precipitation. During low water levels, pyrite oxidation forms iron-hydroxysulfate solids, which settle on coal and rock surfaces due to evaporation. When the water levels rise, these salts are dissolved and released into the mine pool. Pyrite oxidation then continues to occur on the clean mineral surfaces producing a continuing cycle of acidity production (Younger 1997).

In mines below the water table, contaminated water frequently displays stratification during groundwater rebound (Ladwig et al. 1984). A slow mixing of water at various depths occurs between the dilute, newly-recharged waters at the top of the mine pool and the denser, deeper

waters containing high dissolved solids. Depending on the location of discharge (whether pumped from low levels in the mine pool, or discharged freely at the top of the pool), the water quality coming from the same mine pool may be quite variable.

Lambert and Dzombak (2000) located three underground discharges in the Uniontown Syncline of Pennsylvania with distinct flooding histories. This study used underground mines in the Pittsburgh coal seam, one of the coal seams during this study. Water quality measurements had been taken in 1974 and 1999 in each mine. A flooded below-drainage mine closed in 1934 (40 and 65 yrs had passed since closure) had a pH of 6.0 in 1974 and 6.4 in 1999, Fe decreased from 45 to 25 mg/L, and sulfate was 1700 mg/L in 1974 and 1000 in 1999 (net alkaline water). In a flooded below-drainage mine that was closed in 1970 (instead of 1934), pH increased from 3.1 in 1974 to 5.9 in 1999, Fe decreased from 140 mg/L to 70 mg/L, while sulfate decreased from 2000 mg/L to 900 mg/L in 1999 (changed from strongly acidic water to slightly acidic water). Therefore, the researchers concluded that underground mine water quality changed from acidic to alkaline within 30 years after closure and flooding in their geologic setting. Water pH from an unflooded above-drainage mine closed in 1934 was 3.0 in 1974 and 3.5 in 1999, while Fe decreased from 10 mg/L in 1974 to <2 in 1999 and sulfate declined from 800 mg/L in 1974 to 600 mg/L in 1999. Water in all cases was net acidic from the unflooded mine. Therefore, unflooded above-drainage areas improved in drainage quality, but still remained net acidic (albeit with lower metal concentrations) 60 years after closure. Other researchers have found similar results in this region (Brady et al. 1998, Capo et al. 2001).

Donovan et al. (2000) monitored the water quality of a large underground mine pool in a setting similar to that of Lambert and Dzombak (2000). The Montour mine, and underground Pittsburgh coal seam mine in PA, had a section flooded in 1970 and also a section that was flooded in 1982. Water conditions in the connected mine pool were strongly acidic (pH ~3.0, acidity 2200 mg/L) for the first two years after the final flooding in 1982, after which acidity began to decline exponentially. Surprisingly, seven years after flooding (five years after peak acidity concentrations), the water in the mine pool became net alkaline and has stabilized at a pH of 6.4, net alkalinity at 200 mg/L, and iron around 60 mg/L. The good quality water in the 1970 flooded mine probably caused rapid neutralization of the water in the 1982 flooded mine.

Problems in models and comparisons occur due to lack of data or inadequate mine maps of the underground mines. Public mine records are useful for finding physical data relating to the

mines, but most lack subsurface water characteristics. Another problem is that waters sampled during mining are different than those that emerge after flooding of the mine has occurred (Younger 1994). Caution must be therefore taken when researching a site to assure accurate comparisons.

Flow Rate Effects on Acidity Concentrations

It is apparent that precipitation influences the discharge rate of underground mines. Most recharge occurs in the fall, winter and especially spring causing increased flow rates as seen in the Appalachian Plateau Sandstone of central Pennsylvania (O'Driscoll et al. 2005). Wendland (2001) reported groundwater response within the month of precipitation events or one to two months later, with recovery being reached another one to three months in the future, depending on the season. During drought conditions, much longer recovery times are needed for increased discharge rate (Wendland 2001).

Lopez and Stoertz (2001) studied the behavior of water composition and volumetric discharge of three up-dip mines that had different areas, discharge rates and concentrations of contaminants. They reported a 1 to 4 day time lag between precipitation and peak discharge in updrift mines in the Appalachian region. However, evidence by Borek et al (1991) contradicts this report. Studying underground mines in Randolph County, WV, they found that the highest flows were seen even when precipitation was below normal for a particular year.

Seasonal changes in water quality from above-drainage underground mines have been reported, including changes in pH, acidity, and metal concentrations. Pigati and Lopez (1999) reported that the observed seasonal variations in water chemistry from the above-drainage, 126-ha Majestic Mine in OH supported the “spring flush” idea. This idea involves flushing of acidity and metals deposited on surfaces during summer and fall (seasonal dry months in this region) by late winter-early spring snowmelt and rainfall. Therefore during the high recharge and discharge season of February to May, the high water flows carry high concentrations of acidity and metals. This is opposed to a “high concentration at low flow” idea, where the worst drainage from underground mines happens at base flow conditions (dry months) where acid and metals are thought to be concentrated and not diluted by infiltrating water during recharge events (Skousen and Ziemkiewicz 1996).

As presented by Demchak et al. (2004), the Omega Mine, a 68-ha above-drainage underground mine of the Upper Freeport coal bed in northern WV, was mined during the 1980s. In 1992, breakout of AMD caused mine closure, and flows and acidity concentrations were recorded continuously for the ensuing six years (GAI Consultants 2001). Acidity was highest during February to May (~4,500 mg/L) compared to about 3,800 mg/L during June to January. However, variation in the acidity values across both time periods was high. Above drainage mines, based on these and other examples, appear to discharge their worst acid and metal concentrations during high flow seasons (spring flush), with improved water quality during dry periods.

Alternatively, Griffiths et al. (2001) indicate at the Arnot underground mine in Tioga County, PA, that as the discharge rate increased, acidity decreased. This mine interestingly did not experience seasonal patterns, which may be explained by the wide range of “spring thaws” anytime from February to April skewing the trend. Lopez and Stoertz, (2001) suggest mine discharge chemistry is relatively uniform through time, suggesting equilibrium control on chemistry within the mine or a well mixed pool. They report, using studies conducted in the Monday Creek watershed in Ohio that minimal evidence exists for dilution of chemistry by high flows. They state that after the first high flow after baseflow, only a slight increase in concentration is seen due to the flushing of stored reaction products.

It seems evident that discharge chemistry from underground mines is affected by several factors, and efforts to determine the changes in water quality over time require accounting for these factors. First, the season of sampling is important to consider due to varying recharge potential within the mine. However, conflicting results from other studies do not indicate that a particular time of year of sampling will produce accurate acidity results for a particular mine. Part of the problem lies in the fact that two distinct discharge periods are being documented in the WV region: February to May and June to September. Flows in October, November, December and January from underground mines are especially hard to predict because these months alternate between very high flows like those of February to May and very low flows like those from June to September (GAI Consultants 2001, Pigati and Lopez 1999). In fact, evidence is mounting that acidity does not vary significantly with flow.

Literature Cited

Barnhisel, R., R. Darmody, and L. Daniels. 2000. Reclamation of drastically disturbed lands. Agronomy No. 41. American Society of Agronomy. Madison, WI.

Bennett, L. 1991. Abandoned Mines: Report from WV. *EPA Journal* **17**:16-18.

Biesecker, J.E. and J.R. George. 1966. Stream water quality in Appalachia as related to coal mine drainage, 1965. US Geological Survey Circular 526, #M981.

Borek S. L., T. E. Ackman, G. P. Watzlaf, R. W. Hammack, and J. P. Lipscomb. 1991. The long-term evaluation of mine seals constructed in Randolph County, W.V. in 1967. *In*: Proceedings of the 12th Annual West Virginia Surface Mine Drainage Task Force Symposium, April 3-4, 1991, Morgantown, W.V.

Brady, L., M.W. Smith, R.L. Beam, and C.A. Cravotta. 1990. Effectiveness of the use of alkaline materials at surface coal mines in preventing or abating acid mine drainage: Part 2. Mine site case studies. pp. 227-241 *In*: Proceedings, 1990 Mining and Reclamation Conference. West Virginia University. Morgantown, WV.

Brady, K.B., R.J. Hornberger, and G. Fleeger. 1998. Influence of geology on postmining water quality: northern Appalachian Basin. pp. 8-1 to 8-92 *In*: Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania. PA Department of Environmental Protection. Harrisburg, PA.

Burnett, J.M., M. Burnett, P. Ziemkiewicz, and D.C. Black. 1995. Pneumatic backfilling of coal combustion residues in underground mines. *In*: Proceedings, 16th Annual Surface Mine Drainage Task Force Symposium. Morgantown, WV.

Capo, R.C., W.R. Winters, T.J. Weaver, S.L. Stafford, R.S. Hedin, and B.W. Stewart. 2001. Hydrogeologic and geochemical evolution of deep mine discharges, Irwin Syncline, Pennsylvania. *In*: Proceedings of the 22nd West Virginia Surface Mine Drainage Task Force Symposium, April 3-4, 2001. Morgantown, WV.

Caruccio, F. 1968. An evaluation of factors affecting acid mine drainage production and the groundwater interactions in selected areas of western Pennsylvania. pp. 107-151. *In*: Proceedings of 2nd Symposium of Coal Mine Drainage Resources. Pittsburgh, PA.

Demchak, J., J. Skousen, and L.M. McDonald. 2004. Longevity of acid discharges from underground mines lying above the regional water table. *J. Environ. Qual.* **33**: 656-668.

Donovan, J., B. Leavitt, E. Werner, E. Perry, and K. McCoy. 2000. Long-term hydrogeological and geochemical response to flooding of an abandoned below-drainage Pittsburgh coal mine. *In: Proceedings of the 21st West Virginia Surface Mine Drainage Task Force Symposium*, April 4-5, 2000. Morgantown, WV.

Edenborn, H.M., L.A. Brickett, D.H. Dvorak, and S.L. Edenborn. 1993. Monitoring iron and manganese diagenesis in constructed wetlands with continuous gradient gel. pp 287-297. *In: Proceedings of the Minerals, Metals, and Materials Society*.

Faulkner, B.B. 1997. AMD inventory in West Virginia. *In: Proceedings of the 18th West Virginia Surface Mine Drainage Task Force Symposium*, April 15-16, 1997. Morgantown, WV.

Frost, R.C. 1979. Evaluation of the rate of decrease in the iron content of water pumped from a flooded shaft mine in County Durham, England. *J. Hydrology* **40**:101-111.

GAI Consultants. 2001. Omega Mine injection program: Monongalia County, West Virginia. Electric Power Research Institute, Inc. (EPRI), Allegheny Energy Supply, and the U.S. Department of Energy. Document #1004032. USDOE. Pittsburgh, PA.

Gleason, V.E. and H.H. Russell. 1987. A history of acid mine drainage research from 1910-1948. *In: Proceedings of AMD Seminar/Workshop*. Halifax, Nova Scotia.

Glover, H.G. 1983. Mine water pollution—an overview of problems and control strategies in the United Kingdom, *Water Science Technology* **15**: 59-70.

Griffiths, J.C., R.J. Hornberger, K. Miller, and M.W. Smith 2001. Statistical analysis of abandoned mine drainage in the assessment of pollution load (“The Griffiths Report”). EPA-821-B-01-014.

Hawkins, J.W. 1994. Assessment of contaminant load changes caused by remining abandoned coal. pp. 20-29. *In: International Land Reclamation and Mine Drainage Conference*, USDI, Bureau of Mines SP 06A-94. Pittsburgh, PA.

Hedin, R.S., R.W. Nairn, and R.L.P. Kleinmann. 1994. Passive treatment of coal mine drainage. Bureau of Mine Information Circular, IC9389, US Dept. of the Interior.

Hobba, W.A. 1981. Effects of underground mining and mine collapse on the hydrology of selected basins in WV. USGS, Report of Investigation, RI-33.

Hyman, D.M. and G.R. Watzlaf. 1995. Mine drainage characterization for the successful design and evaluation of passive treatment systems. *In: Proceedings, 17th Annual Conference of the National Association of Abandoned Mine Lands*, October 1995. French Lick, IN.

Jarvis, A.P., and P.L. Younger. 1997. Dominating chemical factors in minewater induced impoverishment of the invertebrate fauna of two streams in Durham Coalfield, UK. *Chemistry and Ecology* **40**: 249-270.

Jones, P.M., S.M. Mulvay, and D. Fish. 1994. The role of sulfate and ionic strength on the shift from acid to alkaline mine drainage in southwest Pennsylvania. pp. 289-295 *In*: Proceedings of the International Land Reclamation and Mine Drainage Conference and the Third International Conference of the Abatement of Acid Mine Drainage. Vol. 2: Mine Drainage. US Bureau of Mines Special Publication. SP 06B-94.

Kleinmann R.L.P., D.A. Crerar and R.R. Pacelli. 1981. Biogeochemistry of acid mine drainage and a method to control acid formation. *Mining Engineering* **33**:300-305.

Ladwig, K.J., P.M. Erickson, R.L.P. Kleinmann, and E.T. Posluszny. 1984. Stratification in water quality in inundated anthracite mines, eastern Pennsylvania. U.S. Bureau of Mines Report of Investigations RI 8837.

Lambert, D.C., and D.A. Dzombak. 2000. Evaluation of natural amelioration of acidic deep mine discharges in the Uniontown Syncline, Pennsylvania. *In*: Proceedings of the 21st West Virginia Surface Mine Drainage Task Force Symposium, April 4-5, 2000, Morgantown, WV.

Lopez, D.L. and M.W. Stoertz. 2001. Chemical and physical controls on waters discharged from abandoned coal mines. *Geochemistry: Exploration, Environment, Analysis* **1**: 51-60.

Lorenz, W.C. and R.W. Stephan. 1969. Factors that affect the formation of coal mine drainage pollution in Appalachia. pp. cc 1–cc 17. *In*: Stream Pollution by Coal Mine Drainage in Appalachia. Federal Water Pollution Control Administration. US Printing Office, Washington, D.C.

Meek, F.A. 1996. Evaluation of acid prevention techniques used in surface mining. Chapt. 11. *In*: Acid Mine Drainage Control and Treatment. National Mine Land Reclamation Center, Morgantown, WV.

Meyers, R.A. 1981. Coal Handbook. Marcel Decker, Inc. NJ & Basel.

O' Driscoll, M.A., D.R. DeWalle, K.J. McGuire, and W.J. Gburek. 2005. Seasonal variations and groundwater recharge for three landscape types in central Pennsylvania, USA. *J. Hydrology*. **303**: 108-124.

Paine, P.J. 1987. Environment Canada. *In*: Proceedings of AMD Seminar/Workshop. Halifax, Nova Scotia.

Paone, J., P. Struthers, and W. Johnson. 1978. Extent of disturbed lands and major reclamation problems in the United States. pp. 11-22. *In*: F.W. Schaller and P. Sutton (eds.), *Reclamation of Drastically Disturbed Lands*. American Society of Agronomy. Madison, WI.

Perry E.F., and K.B. Brady. 1995. Influence of neutralization potential on surface mine drainage quality in Pennsylvania. *In*: Proceedings, 16th Annual Surface Mine Task Force Symposium, April 4-5, 1995, Morgantown, WV.

Perry, E.F. personal communication. Office of Surface Mining.

Pigati, E., and D. Lopez. 1999. Effect of subsidence on recharge at abandoned coal mines generating acidic drainage: the Majestic Mine, Athens County, OH. *Mine Water and the Environment* **18**(1): 45-66.

Rauch, H.W., W.N. O'Steen, G. Ahnell, and D.F. Giannatos. 1984. Predictions of aquifer dewatering over underground mines in the Pittsburgh, Sewickley, and Upper Freeport Coals of Northern West Virginia. *In*: Proceedings, 1984 Mining and Reclamation Conference. West Virginia University, Morgantown, W.V.

Renton, J.J. and R.V Hidalgo. 1975. Some geochemical considerations of coal. *Coal Geology Bulletin* (4). West Virginia Geological and Economical Survey. Morgantown, WV.

Rich, D.H., and K.R. Hutchinson. 1990. Neutralization and stabilization of combined refuse using lime kiln dust at High Power Mountain. *In*: Proceedings, 1990 Mining and Reclamation Conference, April 21-24, 1990. West Virginia University. Morgantown, WV.

Richardson, A.R. and M.T. Dougherty. 1976. Feasibility study of Deer Creek daylighting project, Environmental Protection Technical Series, USEPA, EPA-600/2-76-110.

Robb, G. and J. Robinson. 1995. Acid drainage from mines. *The Geographical Journal*. **161**: 47-54.

Rose, A.W., L.B. Phelps, R.R. Parizek, and D.R. Evans. 1995. Effectiveness of lime kiln flue dust in preventing acid mine drainage at the Kauffman surface coal mine, Clearfield County, Pennsylvania. pp. 159-171. *In*: Proceedings, 1995 National Meeting of the American Society for Surface Mining and Reclamation June 3-8, 1995, Gillette, WY.

Skousen, J., K. Politan, T. Hilton, and A. Meek. 1990. Acid mine drainage treatment systems: chemicals and costs. *Green Lands* **20**(4): 31-37.

Skousen, J., and P. Ziemkiewicz. 1996. Acid mine drainage control and treatment. National Research Center for Coal and Energy, West Virginia University, Morgantown, WV.

Skousen, J., A. Sexstone, and P. Ziemkiewicz. 2000. Acid mine drainage control and treatment. pp. 131-168 *In: Reclamation of drastically disturbed lands*. Ed. Barnhisel, R. R. Darmody, and W. Daniels. American Society of Agronomy, Madison, WI.

Skousen, J., J. Simmons, L.M. McDonald, and P. Ziemkiewicz. 2002. Acid-base accounting to predict post-mining drainage quality on surface mines. *J. Environ. Qual.* **31**: 2034-2044.

U.S. Environmental Protection Agency. 1995. Streams with Fisheries Impacted by Acid Mine Drainage in MD, OH, PA, VA, and WV. Region III, Wheeling, WV.

USDA, Soil Conservation Service. 1976. The measure of our land. USDA. Soil Conserv. Serv. PA-128. #M3254.

Wendland, W.M. 2001. Temporal responses of surface water and groundwater to precipitation in Illinois. *J. American Water Resources Associations.* **37**: 685-693.

Wood, S.C., P.L. Younger, and N.S. Robins. 1999. Longterm changes in the quality of polluted minewater discharges from abandoned underground coal workings in Scotland. *Quarterly J. Engineering Geology* **32**: 69-79.

Younger, P.L. 1994. Minewater pollution: The revenge of Old King Coal. *Geoscientist* **4(5)**: 48-41.

Younger, P.L. 1997. The longevity of minewater pollution: a basis for decision-making. *Science of the Total Environment* **194/195**: 457-466.

Younger, P.L., T.P. Curtis, A.P. Jarvis, and R. Pennell. 1997. Effective passive treatment of aluminum-rich, acidic colliery spoil drainage using a composted wetland at Quaking Houses. County Durham. *J. Institution of Water and Environmental Management* **11**: 200-208.

Zeleznik, J, and J. Skousen. 1996. Survival of three tree species on old reclaimed surface mines in Ohio. *J. Environ. Qual.* **25(6)**: 1429-1435.

Ziemkiewicz, P.F. and J.G. Skousen. 1992. Prevention of acid mine drainage by alkaline addition. *Green Lands* **22(2)**: 42-51.

CHAPTER 3: LONGEVITY OF ACID DISCHARGES FROM UNDERGROUND MINES LYING ABOVE THE REGIONAL WATER TABLE

Introduction

Surface mining has disturbed approximately 1.8 million ha (4.4 million ac) in the Appalachian Region since 1930 (Barnhisel et al. 2000, Paone et al. 1978, Zeleznik and Skousen 1996). No estimates have been made on the areal extent of underground mining in this region. The West Virginia Department of Environmental Protection (WVDEP) estimates that in West Virginia alone about 610,000 ha (1.5 million ac) have been mined by underground methods, while about 276,000 ha (682,000 ac) have been surface mined in the state (Bennett, 2003). Therefore, extensive underground areas have been disturbed in this region, thereby influencing water supplies and water quality.

Acid mine drainage (AMD) is a serious problem in areas of extensive surface and underground coal mining, such as the Appalachian Region of the U.S, where pyrite and other metal sulfides are found within the coal and associated rocks. About 10,000 km of streams have been affected by AMD in the four states of Pennsylvania, Maryland, Ohio, and West Virginia (U.S. Environmental Protection Agency 1995). Many mines currently discharging AMD were operated and abandoned before enactment of the Surface Mining Control and Reclamation Act (SMCRA) of 1977. The Act provided standards for environmental protection during mining operations and placed the responsibility of AMD control and treatment on the operator (SMCRA 1977). The SMCRA also provided a means for reclaiming abandoned mines by taxing current coal operators, which generates funds for abandoned mine land reclamation programs. Even with millions of dollars spent in reclaiming abandoned mine lands, these abandoned mines still generate more than 90% of the AMD in streams and rivers in the region and most of this acidic drainage flows from underground mines (Faulkner 1997, Zipper 2000).

Because these sites were abandoned before 1977, no company or individual is responsible to treat the water, and therefore the receiving streams are continuously polluted and severely impact the aquatic ecosystem. High flows and high levels of pollution (high acidity and metal concentrations) require the use of chemicals for treatment, which tend to be expensive and labor

intensive (Skousen et al. 2000). Costs for chemicals, dispensing equipment, electricity for pumps, and manpower all add up to significant public expense if the treatment entity is a government agency or utility. Perhaps the largest cost to the public is the unavailability of the water resource for use, and its accompanying impaired aesthetics and degradation. Therefore, simple and inexpensive treatment approaches (such as passive treatment systems, Skousen et al. 1998) are being sought as well as a better understanding of the natural processes within mines that affect water quality over time.

An understanding of the behavior of acid-producing materials within abandoned mines would allow an estimate of the longevity of the acid discharge, which will aid in determining remediation strategies and the short and long-term costs of treatment. However, the changes in flow and water quality over time from surface and underground mines are not well documented.

Surface mining generally removes 90% or more of the coal (which often contains the highest sulfide content and hence the acid-producing potential) thereby leaving little in the backfill for continued reaction and acid generation. Pyrite is often dispersed among other rocks above and below the coal seam. The pyrite-bearing rocks and coal left behind were broken apart by blasting giving high surface area, and the acid products are leached fairly rapidly, typically within 10 to 20 years (Meek 1996). Carbonate rocks within the overburden may neutralize some or all of the AMD generated during surface mining. Special handling of toxic materials may reduce the amount of pyrite oxidized, and the addition of alkaline material during mining may neutralize acid *in-situ*, both of which decrease the total acid load coming from the site (Brady et al. 1990, Perry and Brady 1995, Rich and Hutchinson 1990, Rose et al. 1995, Skousen and Larew 1994). During the ensuing 20 years after reclamation, discharge water quality may reach pre-mining levels. Overburden analytical techniques such as Acid-Base Accounting help predict the overall potential for AMD during surface mining and reclamation, and can help regulators determine when surface mining should or should not be allowed (Skousen et al. 2002).

Acid discharge from underground mines usually lasts much longer than from surface mines (Wood et al. 1999). For underground mine discharges, a distinction is made between those that become inundated or flooded with water (the mined coal seam is located below the regional water table and called “below-drainage” underground mines) and those that do not fill with water because they are situated above creeks and rivers of the area (the coal seam is located above the regional water table and called “above-drainage”)(Figure 3-1). This distinction is critical

because acid-producing materials composed of pyrite react at much slower rates and produce only small amounts of AMD when left in an anaerobic condition underground (Evangelou 1995, Fennemore et al. 1998). Therefore, flooded below-drainage underground mines tend to have a finite life for discharging AMD because oxygen depletion limits acid generation.

The earliest model of longevity of AMD discharge from underground mines was the former British Coal Corporation's 'rule of thumb' for fully-flooded below-drainage mines. Iron concentrations in an abandoned mine were assumed to decrease by 50% during each subsequent pore volume flushing (the time period required for the mine pool to "turnover" or in other words to recharge and discharge that volume of water). For example, if 10 years are required for the water within an underground mine to turnover, the iron concentration should decrease by half every 10 years. This suggests an exponential decay as described by Glover (1983). Therefore, about three turnover cycles (or 30 years in this case) are necessary for the iron concentration to decline to about 12.5% of the original iron concentration if this rule is accurate. Younger et al. (2002) refer to this as the "first flush," where the acid products are washed out based on the mine's hydrology. However, they state that the duration of flushing manifests a much more complex hydraulic process based on the tortuosity and heterogeneous permeability of the old mine workings.

Other researchers have observed that the most severe drainage occurs within the first few decades after closure and even the largest underground mine systems settle to lower pollution levels within 40 years. For mines in the UK, a neutral pH was reached within 30 years, and after 40 years the pH remained neutral and the iron concentrations decreased from 200 mg/L to <40 mg/L (Wood et al. 1999). Younger (2000) found that flooded underground mines in the UK stabilized at pH 7 with gradually decreasing iron concentrations. Jones et al. (1994) also showed that water from flooded underground mines in Pennsylvania changed from acidic to neutral over a period of decades.

Lambert and Dzombak (2000) located three underground discharges in the Uniontown Syncline of Pennsylvania with distinct flooding histories. This study used underground mines in the Pittsburgh coal seam, one of the coal seams we sampled in our study. Water quality measurements had been taken in 1974 and 1999 in each mine. A flooded below-drainage mine closed in 1934 (40 and 65 yrs had passed since closure) had a pH of 6.0 in 1974 and 6.4 in 1999, Fe decreased from 45 to 25 mg/L, and sulfate was 1700 mg/L in 1974 and 1000 in 1999 (net

alkaline water). In a flooded below-drainage mine that was closed in 1970 (instead of 1934), pH increased from 3.1 in 1974 to 5.9 in 1999, Fe decreased from 140 mg/L to 70 mg/L, while sulfate decreased from 2000 mg/L to 900 mg/L in 1999 (changed from strongly acidic water to slightly acidic water). Therefore, the researchers concluded that underground mine water quality changed from acidic to alkaline within 30 years after closure and flooding in their geologic setting. Water pH from an unflooded above-drainage mine closed in 1934 was 3.0 in 1974 and 3.5 in 1999, while Fe decreased from 10 mg/L in 1974 to <2 in 1999 and sulfate declined from 800 mg/L in 1974 to 600 mg/L in 1999. Water in all cases was net acidic from the unflooded mine. Therefore, unflooded above-drainage areas improved in drainage quality, but still remained net acidic (albeit with low metal concentrations) 60 years after closure. Other researchers have found similar results in this region (Brady et al. 1998, Capo et al. 2001).

Donovan et al. (2000) monitored the water quality of a large underground mine pool in a setting similar as that of Lambert and Dzombak (2000). The Montour mine, a Pittsburgh coal seam underground mine in PA, had a section flooded in 1970 and also a section flooded in 1982. Water conditions in the connected mine pool were strongly acidic (pH ~3.0, acidity 2200 mg/L) for the first two years after the final flooding in 1982, after which acidity began to decline exponentially. Surprisingly, seven years after flooding (five years after peak acidity concentrations), the water in the mine pool became net alkaline and has stabilized at a pH of 6.4, net alkalinity at 200 mg/L, and iron around 60 mg/L. The good quality water in the 1970 flooded mine probably caused a more rapid neutralization of the water in the 1982 flooded mine.

Younger (1997) divided the acid load flowing from underground mines into two categories. “Vestigial” acidity is associated with the first-time flushing of acid products from the mine during initial abandonment and flooding. “Juvenile” acidity is produced from ongoing pyrite oxidation due to fluctuations in the water table. Juvenile acidity, he states, can persist for hundreds of years depending on the pyrite content and hydrology of the underground mine system. The longevity of AMD at a given site is dependent on the rate of depletion of both the vestigial and juvenile acidity.

In above-drainage underground mines, the mine voids and acid-generating materials are continually exposed to seasonal high and low water levels in the mine or mostly unflooded conditions throughout the year, and tend to be recharged rapidly by infiltrating rain and snowmelt. Furthermore, the water moving into the mine voids can be discharged just as rapidly

out of the mine depending on its connectivity with surface portals or seeps. The mine atmosphere contains sufficient oxygen to sustain pyrite oxidation because the mine atmosphere interacts with the outside atmosphere via fractures and unsealed openings, especially in response to changes in atmospheric pressure (i.e., they breathe). Therefore, oxygen and water are not limiting factors for continuing pyrite oxidation and transport of reaction products. Indeed, these quick recharge/discharge and breathing conditions are ideal for acid generation and pyrite reaction continues until the pyrite supply either becomes fouled by acid product coating (armoring) or becomes exhausted. Under these optimized oxidizing and flushing situations, it is possible that discharges could be contaminated for decades or centuries depending on the pyrite supply and flushing events.

In above-drainage mines, water usually discharges out at the down-dip side of the mine at the portal or at other low elevation areas in the mine through thin coal barriers or fractures. Regardless of the discharge point, the mine water continually flows out without fully flooding the mine and acid-generation may continue for decades until the pyrite is either exhausted or coated, which limits surface area for reaction (Lambert and Dzombak 2000, Younger et al. 1997). In these situations, the rate of water quality improvement over time (or acidity decline) is highest where the recharge rate of the mine is high, water flow out of the mine is high, residence time is low, and the mine volume is small (Younger 1997). The fluctuating water level and pooling effect due to seasonal variations in precipitation, however, aid acid generation. During low water levels, pyrite oxidation forms iron hydroxysulfate solids, which precipitate on coal and rock surfaces due to evaporation. Hydrated ferrous and ferric sulfate minerals such as melanterite, rozenite, copiapite, and jarosite have all been identified as precipitated minerals in coal mines (Nordstrom 1982, Younger 2000), and all of these minerals provide short-term storage of metals, acidity and sulfate that are soluble. When the water level rises, these acid products are dissolved, released into the mine pool, and flushed out of the mine during seasonal recharge times. Pyrite oxidation can continue to occur on the wet, oxidized mineral surfaces, producing an optimized and continuing cycle of acid generation (Younger 1997). Therefore, these above-drainage underground mines generally will discharge poor water quality for much longer periods than flooded mines because more of the pyrite is continuously exposed to a mixture of air and water to form acid products, and released.

Much discussion has occurred on the seasonal changes in water quality from above-drainage underground mines, including changes in pH, acidity, and metal concentrations. Pigati and Lopez (1999) reported that the observed seasonal variations in water chemistry from the above-drainage 126-ha Majestic Mine in OH supported the “spring flush” hypothesis (Johnson and Thornton 1987). Acidity and metals generated and deposited on surfaces during summer and fall (seasonal dry months in this region) were largely flushed with late winter-early spring snowmelt and rainfall. Therefore during the high recharge and discharge season of February to May, the high water flows carried high concentrations of acidity and metals. This is opposed to the “high concentration at low flow” hypothesis, where the worst drainage from underground mines happens at base flow conditions (dry months) where acid and metals are thought to be concentrated and not diluted by surface water during recharge events (Skousen and Ziemkiewicz 1996).

The Omega Mine, a 68-ha above-drainage underground mine in the 1.4-m thick Upper Freeport coal seam in northern WV, was mined during the 1980s. In 1992, breakout of AMD caused mine closure, and flows and acidity concentrations were recorded continuously for the ensuing six years (GAI Consultants 2001). From 1993-1999, average year-round water flow was 1.4 L/s (22.6 gpm) and acidity was 4,847 mg/L. Water flow from the mine averaged 2.7 L/s (43 gpm) during February to May (1993-1998), and only 1.1 L/s (18 gpm) during June to January (1993-1998). Acidity was highest during February to May (~4,500 mg/L) compared to about 3,800 mg/L during June to January. Above-drainage mines, based on these and other examples, appear to discharge their worst acid and metal concentrations during high flow seasons (spring flush), with improved water quality during dry periods.

It is clear that discharge chemistry from underground mines is affected by several factors, and efforts to determine the changes in water quality over time require accounting for these factors. First, the season of sampling is important to consider, with two distinct periods being documented in our region: February to May and June to September. Flows in October, November, December and January from underground mines are especially hard to predict because these months alternate between very high flows like those of February to May and very low flows like those from June to September (GAI Consultants 2001, Pigati and Lopez 1999).

Another important factor in mine water chemistry is the coal seam, and more specifically the pyrite content of the mined coal (Younger 2000). Each coal seam is unique with relatively

predictable chemical and physical features, which affects the magnitude of the discharge water quality.

The mining method and degree of coal removal within a mine are other variables affecting discharge chemistry. Room and pillar underground mining (the most common method in this area) left about 50% of the coal as support for the roof (Reece et al. 1978). After abandonment, this coal continues to weather and crack from the pillar and oftentimes the pillar completely collapses, allowing more pyrite in the coal pillar and overlying rocks that have dropped into the void to react. In “retreat” mining, many of the coal pillars left to support the roof are removed as the mining equipment is withdrawn, allowing more roof rock to subside into the mine voids. The coal pavement or floor rock also can contribute pyrite surfaces for reaction, depending on its flooded condition and slope. Remining underground mines by surface mining has the potential to improve pre-existing acid discharges by removing coal pillars and then reclaiming the site to current reclamation standards, which often includes mitigating any AMD potential (Hawkins 1994, Richardson and Dougherty 1976).

Acid discharges from abandoned mine sites can be affected by subsequent, adjacent surface mining (Skousen et al. 1997) or other nearby surface disturbances. The flow may decrease because the surface overlying the recharge area has been reclaimed and vegetated, thereby decreasing infiltration into the underground mine, or surface fractures or subsidence holes may have been repaired and closed off. Any of these surface disturbances could effectively decrease the flow rate into and therefore out of the mine. Adjacent surface mining and blasting may also cause collapse of the roof in portions of the mine and reduce the void space, thereby changing flow paths or altering interconnection of certain areas. The degree of disturbance in a mine is nearly impossible to measure (down hole cameras have been used to look into underground mines, but they allow only a small peek into the void space) and only observable surface disturbances overlying or adjacent to the underground mine provide evidence that such disturbance effects exist. Even so, the ensuing impact of surface disturbances on mine water chemistry is difficult to predict over time.

A research project was initiated in 1968 which identified and sampled over 150 underground mine discharges in the northern West Virginia coal region. Most of these discharges were coming from unflooded above-drainage underground mines in the Upper Freeport and Pittsburgh coal seams. We revisited many of those sites in 1999 and 2000 and collected and analyzed the

water from about 75 of the same discharge points. Based on the completeness of the 1968 data, 44 were chosen for further analysis. Twenty of these 44 sites had been sampled and the water analyzed in 1980, which provided an intermediate sampling time to assess water acidity and iron concentrations from the mine. From this data set, our objective was to determine the changes in water quality during this 30-year period.

Materials and Methods

From the original 75 sites sampled in 1999-2000, 44 underground mine discharge sites were used for water quality comparison because all parameters used for the analysis were available for both 1968 and 1999-2000 data sets. The sites were located in Preston and Monongalia Counties of West Virginia. The sites were found according to marked locations on Valley Point, Cuzzart, Kingwood, Masontown, and Morgantown North U.S. Geological Survey quadrangle maps. All sites discharged water from above-drainage, underground mines into various streams within the Monongahela River Basin. All mines removed coal from either the Upper Freeport or Pittsburgh coal seams.

The Pittsburgh coal seam is the lowest stratum of the Monongahela Group in the Pennsylvanian System. The seam has 1.5 to 2% sulfur, and an ash content of 6%. The Pittsburgh coal is composed of alternate layers of coal and black shale. A typical Pittsburgh coal cross-section shows a 1-m layer of pure coal, a 0.7-m layer of bone coal or slate, and another 2-m layer of good-quality coal. The Pittsburgh coal along the Monongahela and Cheat Rivers is located close to the surface, and can be mined by surface mining methods or shallow underground mines (Hennen and Reger 1914). In this region, few overlying limestone materials are available within 30 m above the coal seam to neutralize the high amounts of acid-producing material in this coal and associated rocks.

The Upper Freeport coal seam is the topmost stratum of the Allegheny Formation in the Pennsylvanian System. Upper Freeport coal contains <1.5% sulfur, and an ash content from 8 to 12%. It is a multiple-bedded seam that is divided into a top coal and bottom coal, separated by a shale interlayer, all averaging a total of 2 m in thickness (Hennen and Reger 1914). The strata above the Upper Freeport coal contain several massive sandstones and some shales. Limestone or alkaline-bearing rock units are not generally found within 50 m above the Upper Freeport coal

in this area, so very little overlying geologic material is available for acid neutralization (Hennen and Reger 1914).

1968 Study

A previous research project was conducted during the summers of 1968-1970 (June to September) where field crews were sent out to identify all coal mines within the Monongahela River Basin and to sample their discharges. Each crew worked from 7.5-minute U.S. Geological Survey topographic maps on which they outlined mine boundaries and indicated mine openings. Field sheets were also completed at each site with location and overburden information. Sites with a discharge were identified on the maps, flow rates were determined, and the water was sampled. The flow rate was measured when possible with a bucket and stopwatch. For larger flows, the crew installed a V-notch weir and measured flow rate. These values were recorded on the field sheet. In the field at the time of water collection, the pH of the discharge was measured using an electrometric pH meter, and temperature was checked with a lab grade thermometer. These values were recorded on the field sheet.

Two water samples were taken at each discharge in this early study: 1) a plastic, 1-L bottle was filled with water, put on ice, and then analyzed in the laboratory for acidity, alkalinity, conductivity, sulfate, and pH; and 2) a 50-ml glass bottle was filled, treated with acid, and then analyzed in the laboratory for metals (total iron, manganese, aluminum). Water samples were delivered to the laboratory each Friday where they were analyzed using methodology from the latest edition of Standard Methods (American Public Health Association 1965). Water analyses were monitored for accuracy and precision by running periodic samples of reference standards (Bryant 1999).

1999-2000 Study

After obtaining the 1968 maps, we located the point discharges marked by the 1968 crew on the topographic maps during the summers of 1999 and 2000 (June to September) and correlated these to underground mine maps and areas (Table 3-1). Underground mine maps were obtained from the West Virginia Geologic and Economic Survey in Morgantown, West Virginia, underground mine boundaries were determined, and mine size was determined with a digital planimeter (Sokkia Corp., Overland Park, KS). The year in which each mine was opened was also determined from records of the West Virginia Office of Miners Health Safety and Training.

Each site in 1999-2000 was categorized as disturbed or undisturbed. Undisturbed meant that the land surface around the underground mine site appeared to have remained untouched since 1968 and no obvious influence had occurred to the surface overlying or nearby to the underground mine. Disturbed suggested that either surface mining had occurred overlying or adjacent to the underground mine since 1968 or was reclaimed or remined.

Discharges were sampled as close to the mine portal as possible. Flows were calculated using a measured cross-sectional area and flow velocity. Two water samples were taken at each sample point: 1) a 250-mL unfiltered sample was taken for general water chemistry (pH, conductivity, total acidity and alkalinity by titration, and sulfate); and 2) a 25-mL, filtered sample was acidified to pH <2 with 0.5 mL concentrated nitric acid and used to determine metal concentrations.

Water pH, alkalinity, and acidity were determined by a Metrohm pH Stat Titrino System (Brinkman Instruments, Wesbury, NY). Conductivity was measured using an Orion Conductivity meter Model 115 (Orion Instruments, Beverly, MA). The metal analysis was preformed using an Inductively Coupled Spectrophotometer, Plasma 400 (Perkin Elmer, Norwalk, CT). Sulfate was measured turbidimetrically by flow injection analysis (Lachat Instruments, Milwaukee, WI).

The West Virginia Division of Water Resources also conducted periodic sampling and analyses of underground mine discharges in this area (West Virginia Division of Natural Resources 1985). We accessed their data and found that 20 of their sample sites matched our discharges sampled in 1968 and 1999-2000. Therefore, we used their water quality analyses as an intermediate data point between 1968 and 1999 to aid in estimating the rate of change (improvement) in water quality.

Statistical Analysis

A repeated measures analysis of variance was performed to test for changes in discharge water quality over time. We used a full model with the main effects of date, coal seam, disturbance, and all possible interactions as class variables using PROC GLM (SAS Institute 1989). For the comparison between 1968 and 1999-2000, coal seam (Pittsburgh and Upper Freeport) and disturbance (yes or no) were the between-subjects variables. For comparisons between 1968, 1980, and 1999-2000, there were not enough degrees of freedom to make

meaningful comparisons with disturbance as a model term. Therefore for the analysis of three dates, coal seam was the only between-subjects variable. The Greenhouse–Geiser criterion was used for parameters that did not meet the sphericity condition as determined using Mauchley’s test (Huck and Cormier 1996). Since our principal interest was the time dependent changes in discharge water quality, the assumption of homogeneity of variance was not tested in the between-subjects variables, and between-subjects comparison are neither provided, nor interpreted. For all statistical analyses, samples collected in 1999 were coded as if they were collected in 2000. Trends in discharge water quality improvements were plotted for the 1968, 1980, and 1999-2000 data.

To assess the potential effects of flow on discharge water chemistry and to determine the amount of variability within a sampling season, we gathered historical data from two discharges of above-drainage underground mines in this region with more frequent within-year sampling and examined seasonal changes in flow and concentrations. The Omega above-drainage underground mine is a 70-ha mine and is located in an adjacent watershed from most of our underground mines, but drains the same Upper Freeport coal seam as many of the discharges in this study. Six years of data (1993-1998) were available from this site (GAI Consultants 2001). The T&T above-drainage underground mine drains an area of about 600 ha and is located in the same watershed and in the same Upper Freeport coal seam as most of the underground mine discharges used in this study. Seven years (1994-2000) of data were available from this discharge. Analysis of variance with year and month as categorical variables was used to test for a relationship between flow and discharge water quality using 12-month versus four-month (June to September) data.

Results and Discussion

Flow and Concentration Differences within a Year

Analysis of the Omega data (GAI Consultants 2001) for 1993-1998 showed a significant difference in water flow between the months of February to May (2.7 L/s or 43 gpm) and June to September (1.3 L/s or 20 gpm) (analysis not shown). Acidity was highest at Omega during February to May (90 mmol H⁺ L⁻¹) compared to 75 mmol H⁺ L⁻¹ during June to September, but the difference was not significant. There was a 52% decrease in flow between high vs. low flow months, but only an 18% decrease in acidity. From T&T during 1994-2000, there was a

tendency for iron and acidity concentrations, and flow to decrease, and for pH to increase (Figure 3-2). A significant monthly effect was found for all water quality parameters when measured over 12 months (Table 3-2), but the only parameter for which there was a clear seasonal trend was flow (Figure 3-2). Maximum flows occurred in spring in this region as a consequence of snowmelt and higher rainfall (Pigati and Lopez 1999, Stewart and Skousen 2003). Although flow was positively correlated with acidity and iron for 12 months and for June to September, the correlation coefficients were small (Table 3-3). Therefore, we conclude that, except for flow, samples collected from June through September give comparable water quality data and that, within this period, differences in flow do not bias water quality.

Water quality variability within a year at T&T was fairly high (Table 3-4), with annual relative standard deviations of up to 44% for flow, 30% for acidity, and 32% for iron. When just the months of June to September were considered, average RSDs were always lower (e.g., 29 versus 44% for flow) than the 12-month period (Table 3-4). Of interest in this study was the magnitude of the relative difference between the minimum and maximum values (% Δ) as this gives a basis for comparing changes in water quality over time. The % Δ for each parameter was always larger than the RSD (Table 3-4). Percent differences more negative than the four-month % Δ was used as an estimate of a conservative criterion for demonstrated improvement in water quality on our 44 discharge sites.

Comparisons between 1968 and 2000

The average flow from above-drainage underground mines in 1999-2000 was 0.5 L/s, which was substantially less than the 1.4 L/s in 1968 (both were sampled during the June-September period) (Table 3-5). However, these differences were not statistically significant, either as a main effect ($p=0.07$) or as an interaction with coal seam ($p=0.72$). Based on this result and on the data analyses presented in the preceding section, flow was assumed to have a small or negligible effect on discharge water quality and water quality data were compared directly.

There were no significant changes in pH ($p=0.06$ between dates; $p=0.06$ for interaction date*coal seam) between 1968 and 1999-2000. The average pH for all years and all coal seams was 3.2. However, Pittsburgh coal mine discharge sites had a significantly lower pH in 1999-2000 than Upper Freeport coal mine discharge sites (Table 3-5).

For all other parameters, there were significant improvements between 1968 and 1999-2000 ($p < 0.001$), with average improvements of 66% for total acidity and 79% for iron (Table 3-5). The date*coal seam interactions were due to significant differences between coal seams in 1968 and a lack of differences in 1999-2000, except for pH in 1999-2000 (Table 3-5). Average decreases in Pittsburgh coal seam iron (85%) and total acidity (79%) were larger than the decreases in Upper Freeport coal seam iron (74%) and total acidity (56%). This is probably due to the higher sulfur content of the Pittsburgh coal seam and possibly to the higher amount of shale associated with the seam compared to Upper Freeport coal. The shales weathered quickly releasing the acid products resulting in high initial acidity, iron and sulfate concentrations that descended gradually over time. Upper Freeport coal had more sandstone, which reacted and released acid products more slowly than the shales.

Even though significant improvements in average iron and acidity concentrations were found, not every site showed improved water quality. Figure 3-3 is a cumulative frequency plot for the percent change in acidity and iron. All Pittsburgh sites showed some improvement (% change was < 0), while one Upper Freeport site showed an increase in iron and five Upper Freeport sites showed increases in acidity. Using zero percent change ($\% \Delta$) as the criterion for improvement is probably too liberal as it ignores the potential variability within a year that could bias the conclusions. Using a more conservative criterion for demonstrated improvement (-38.8 for acidity and -59.2 for iron, Table 3-2), 10 of 35 Upper Freeport sites did not improve in acidity and 11 of 35 sites failed to show improvement for iron. One Pittsburgh site also failed to show an improvement in iron.

Comparisons among 1968, 1980, and 1999-2000

When comparing the data across three dates (Table 3-6), there were no significant differences for flow among dates ($p = 0.20$) or coal seams ($p = 0.82$). Therefore, as in the two-date analysis, water quality data were compared directly.

There was a significant effect of date for pH when comparing the three dates ($p = 0.0002$), but no difference between coal seams ($p = 0.39$). The date effect is a consequence of the lower pH measured in 1980 compared to either 1968 or 1999-2000 (Table 3-6). There was a significant effect of date for both acidity and iron ($p < 0.001$), and differences due to coal seam for acidity

($p < 0.001$) and iron ($p < 0.01$). The trends were for a curvilinear decrease in acidity ($p = 0.015$) and a linear decrease in iron ($p < 0.01$) (Table 3-6).

Despite these overall trends, not all sites behaved similarly. When each site was plotted individually, all five Pittsburgh coal seam discharges showed some improvement in total acidity and iron (Figure 3-4). For acidity, all but one (Lake Lynn 1) showed an apparent curvilinear trend with time. For iron, only Cheat River 4 and Cheat River 5 showed this curvilinear trend (Figure 3-4). For the 10 Upper Freeport discharges (out of 15) that showed improvements in acidity, most of those trends (eight out of 10) were apparently linear (Figure 3-5). For the Upper Freeport sites that did not show improvement in acidity, three of the five had an increasing linear trend with time. For the other two sites, acidity in 1980 was lower than in either 1968 or 1999-2000 (Figure 3-5). For Upper Freeport sites with a decrease in iron concentration, only four of 11 showed an apparent curvilinear trend (Figure 3-6). In Upper Freeport sites that did not show improvement in iron, most were because the 1980 iron concentrations were the lowest.

Effects of Disturbance, Mine Size, and Time Since Closure

Disturbance did not have a significant effect on acidity concentrations ($p = 0.43$), which suggests that reclamation at the portal face or at the surface overlying these underground mines did not change flow paths or amounts of water moving through the underground mine to sufficiently change concentrations over time.

We evaluated the effect of mine size on acidity and found no relationship in our discharge data ($p = 0.38$). While this result seems counter-intuitive, there are some reasons that may account for this finding. Several of the discharges in our study were found to be coming from the same underground mine (based on old underground mine map locations). Examples of this are the Glade Run 4 and 5 discharges, and the Bull Run 1 and 2 discharges in Table 3-1. One would assume that discharges coming from the same underground mine (even though one discharge might be located around the hillside or in the next valley from the other) would be similar in quality. However, some of the discharges coming from the same mine were very different in quality, which resulted in poor correlations between mine size and acidity. Stratification has been noted from underground mine pools (Ladwig et al. 1984), but this stratification has been measured in flooded underground mines with long residence times. One certainly would not expect large differences in discharge quality from shallow, unflooded above-

drainage underground mines, which are generally flushed within days of rain events. If large differences were found, then the residence time of the water in the underground mine was substantially increased, there may have been stagnant pools of water in the mine formed by roof caving or pillar collapse, the coal seam characteristics (pyrite or shale content) were drastically changed over a short distance to cause an increase in acidity concentrations, or the water drainage from the mine came from a different section of the mine. A hydrologic situation where residence times could increase may be with an undulating coal seam, where the coal seam dips and rises causing the creation of many small cells or pools of water. This effectively creates pockets of high acid water that may be discharged only during and after rainfall events. Other reasons for mine water variability within one mine is oxygen availability in distinct sections of the mine which can vary dramatically with short distances, and the order of water contact with rocks in the mine (Younger 2003).

We found no relationship ($p=0.31$) between the date the mine was opened and acidity. While a relationship would be expected to exist between time since mine closure (not mine opening date) and discharge quality, we were unable to accurately assess this relationship for a couple of reasons. The historical records were too sketchy to determine when all the mines ceased operation. We were able to find the opening date of all the mines because certificates and permits were required, but such paperwork was not necessary for closure. Therefore, even if a mine opened in 1945, the coal may have been mined for only a few years or for more than 30 years. Mine size could help indicate the length of operation, but some mines worked slowly with few men and machines, while other mines operated quickly. So the closure date could have been 1950 or 1975, and one would predict the drainage quality to be better from a mine that was closed 50 years ago compared to one closed 25 years ago. Sometimes mines ceased operation during bad market or labor conditions, then reopened when conditions changed, or sections of the mine may have been closed off early in the life of the mine. All of these influences could confound the effect of mine opening or closure on discharge water quality.

While predictions for annual acidity declines or decay rates have not been made here, such as those made by Ziemkiewicz (1994), Younger (2000), and Demchak et al. (2001), these predictions have proved helpful in determining remediation strategies and costs. For example, given the scenario that the first 15 to 20 years after closure will likely produce the highest acidity levels (as was found here), suitable chemical treatment systems can be installed to treat the low

pH, metal-laden water. Intermediate levels of acidity are likely to be released during the next 10 to 20 years, resulting in lower chemical costs and management. Accordingly, 30 to 40 years after closure, acidity levels from these above-drainage underground mines tend to be much lower than initial concentrations and may be treated by low-cost passive systems.

Efforts must continue to determine water quality improvements from underground mines in other coal seams, and to better determine the effects of mine size and time since mine closure. The remediation strategies and cost predictions are based on our data as well as other research where water quality appears to improve within 40 years after closure. Our data suggest that the water quality improvement predictions of Younger (1997) and Glover (1983) do not fit all the above-drainage underground mines we sampled, but certainly are appropriate for the flooded below-drainage mines they encountered in the UK and also those in the eastern US.

There is still much work to be done on mine drainage improvement over time. It is critical to have a better understanding of the time needed for mine drainage improvement so as to plan suitable watershed restoration projects. Situations where the flow or the underground mine pool has been altered (due to sealing, grout injection or other such remediation strategy) could help us measure the effects of these factors on discharge improvement, and lessons can be learned as data sets are generated with more frequent sampling from underground mines.

Conclusions

Our data indicate that the drainage from the majority (34 of 44 sites or 77%) of above-drainage underground mines showed significant improvement in acidity over time, and this is good news for watersheds with numerous underground mine discharges. While significant coal seam effects were found, still a 50 to 80% reduction in acidity, iron, and sulfate was found for these mines in northern West Virginia between 1968 and 2000. Twenty mines had measurements of water quality in 1980, and five showed that much of the improvement in water chemistry occurred between 1968 and 1980, which suggests an apparent exponential rate of decline. However, 10 sites showed a more linear rate of decline, and five sites showed increased acidity over time. For those five sites with increased acidity over time, it is not clear what caused this increase. We cannot conclude that every above-drainage underground mine in this region will improve with time and, in fact, some have gotten considerably worse. Therefore, in contrast to surface mines and below-drainage underground mines, which all seem to improve

over time and within a relatively short time frame, we cannot accurately predict water quality trends for all above-drainage underground mine sites with time.

The factors that appear to complicate our prediction capacity are the ongoing changes in the underground mine including collapse of coal pillars left in the mine to support the roof, the potential for the creation of fresh faces of pyrite that can generate more acid products, ever changing flow paths with blockages and mine pools forming at different places and at different times based on seasonal flow, and variability of oxygen and pyrite within the mine over short distances. Additionally, it appears that coal barriers or seals between mines can leak or completely break thereby allowing additional flow and acidity to be introduced to an adjacent mine. Such factors as these are very difficult to measure and account for in our prediction of mine drainage improvement.

Acknowledgments

The authors thank Gary Bryant of the U.S. Environmental Protection Agency for providing the 1968 underground mine drainage data. We also thank Mike Sheehan and Sheila Vukovich of the West Virginia Department of Environmental Protection for insight into the sampling and collection of 1980 water data.

Literature Cited

American Public Health Association. 1965. Standard Methods for the Examination of Water and Wastewater. 10th Edition. APHA, Washington, DC.

Barnhisel, R., R. Darmody, and L. Daniels. 2000. Reclamation of Drastically Disturbed Lands. Agronomy No. 41. American Society of Agronomy, Madison, WI.

Bennett, Lyle. 2003. Personal communication. West Virginia Department of Environmental Protection, Division of Water Resources, Charleston, WV.

Brady, K.B., R.J. Hornberger, and G. Fleeger. 1998. Influence of geology on postmining water quality: northern Appalachian Basin. pp. 8-1 to 8-92. *In*: Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania. PA Department of Environmental Protection. Harrisburg, PA.

Brady, L., M.W. Smith, R.L. Beam, and C.A. Cravotta. 1990. Effectiveness of the use of alkaline materials at surface coal mines in preventing or abating acid mine drainage: Part 2. Mine site case studies. pp. 227-241. *In*: Proceedings, 1990 Mining and Reclamation Conference, April 21-24, 1990. West Virginia University, Morgantown, WV.

Bryant, Gary. 1999. Personal communication. U.S. Environmental Protection Agency, Wheeling, WV.

Callaghan, T., G. Fleeger, S. Barnes, and A. Dalberto. 1998. Groundwater flow on the Appalachian Plateau of Pennsylvania. Chapt. 2. *In: Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania*. Pennsylvania Department of Environmental Protection, Harrisburg, PA.

Capo, R.C., W.R. Winters, T.J. Weaver, S.L. Stafford, R.S. Hedin, and B.W. Stewart. 2001. Hydrogeologic and geochemical evolution of deep mine discharges, Irwin Syncline, Pennsylvania. *In: Proceedings of the 22nd West Virginia Surface Mine Drainage Task Force Symposium*, April 3-4, 2001, Morgantown, WV.

Demchak, J., J. Skousen, and L.M. McDonald. 2001. Water quality improvement over time and longevity of acid mine discharges from underground mines in northern West Virginia. pp. 174-182. *In: Proceedings, 2001 National Meeting of the American Society for Surface Mining and Reclamation*, June 3-7, 2001, Albuquerque, NM.

Donovan, J., B. Leavitt, E. Werner, E. Perry, and K. McCoy. 2000. Long-term hydrogeological and geochemical response to flooding of an abandoned below-drainage Pittsburgh coal mine. *In: Proceedings of the 21st West Virginia Surface Mine Drainage Task Force Symposium*, April 4-5, 2000, Morgantown, WV.

Evangelou, V.P. 1995. Pyrite oxidation and its control. CRC Press, New York, NY.

Faulkner, B.B. 1997. AMD inventory in West Virginia. *In: Proceedings of the 18th West Virginia Surface Mine Drainage Task Force Symposium*, April 15-16, 1997, Morgantown, WV.

Fennemore, G.G., W.C. Neller, and A. Davis. 1998. Modeling pyrite oxidation in arid environments. *Environmental Science and Technology*. **32**: 2680-2687.

GAI Consultants. 2001. Omega Mine injection program: Monongalia County, West Virginia. Electric Power Research Institute, Inc. (EPRI), Allegheny Energy Supply, and the U.S. Department of Energy. Document #1004032. USDOE. Pittsburgh, PA.

Glover, H.G. 1983. Mine water pollution—an overview of problems and control strategies in the United Kingdom, *Water Science Technology*. **15**: 59-70.

Hawkins, J.W. 1994. Assessment of contaminant load changes caused by reining abandoned coal. pp. 20-29. *In: International Land Reclamation and Mine Drainage Conference*, April 19-21, 1994. USDI, Bureau of Mines SP 06A-94. Pittsburgh, PA.

Hennen, R.V., and D.B. Reger. 1914. West Virginia Geological Survey, County Reports, Preston, County. U.S. Geological Survey. Morgantown, WV.

Huck, S.W., and W.H. Cormier. 1996. Reading Statistics and Research. 2nd Edition. Harper Collins, NY.

Johnson, C.A., and I. Thornton. 1987. Hydrological and chemical factors controlling the concentrations of Fe, Cu, Zn, and As in a river system contaminated by acid mine drainage. *Water Resources* **21**: 359-365.

Jones, P.M., S.M. Mulvay, and D. Fish. 1994. The role of sulfate and ionic strength on the shift from acid to alkaline mine drainage in southwest Pennsylvania. pp. 289-295 *In*: Proceedings of the International Land Reclamation and Mine Drainage Conference and the Third International Conference of the Abatement of Acid Mine Drainage. Vol. 2: Mine Drainage. US Bureau of Mines Special Publication. SP 06B-94.

Ladwig, K.J., P.M. Erickson, R.L.P. Kleinmann, and E.T. Posluszny. 1984. Stratification in water quality in inundated anthracite mines, eastern Pennsylvania. U.S. Bureau of Mines Report of Investigations RI 8837. Pittsburgh, PA

Lambert, D.C., and D.A. Dzombak. 2000. Evaluation of natural amelioration of acidic deep mine discharges in the Uniontown Syncline, Pennsylvania. *In*: Proceedings of the 21st West Virginia Surface Mine Drainage Task Force Symposium, April 4-5, 2000. Morgantown, WV.

Meek, F.A. 1996. Evaluation of acid prevention techniques used in surface mining. Chapt. 11. *In*: Acid Mine Drainage Control and Treatment. National Mine Land Reclamation Center, Morgantown, WV.

Nordstrom, D.K. 1982. Aqueous pyrite oxidation and the consequent formation of secondary iron minerals. pp. 37-56. *In*: Acid Sulfate Weathering, Soil Science Society of American Special Publication Number 10. Madison, WI.

Paone, J., P. Struthers, and W. Johnson. 1978. Extent of disturbed lands and major reclamation problems in the United States. pp. 11-22. *In*: F.W. Schaller and P. Sutton (eds.), Reclamation of Drastically Disturbed Lands, American Society of Agronomy, Madison, WI.

Perry E.F., and K.B. Brady. 1995. Influence of neutralization potential on surface mine drainage quality in Pennsylvania. *In*: 16th Annual Surface Mine Task Force Symposium, April 4-5, 1995. Morgantown, WV.

Pigati, E., and D. Lopez. 1999. Effect of subsidence on recharge at abandoned coal mines generating acidic drainage: the Majestic Mine, Athens County, OH. *Mine Water and the Environment* **18(1)**: 45-66.

Reece, R.G., B.B. Dash, and P.A. Hamilton. 1978. Coal recovery from underground bituminous coal mines in the United States by mining method. Bureau of Mines Info. Cir. 8785. Pittsburgh, PA.

Rich, D.H., and K.R. Hutchinson. 1990. Neutralization and stabilization of combined refuse using lime kiln dust at High Power Mountain. *In*: 1990 Mining and Reclamation Conference, April 21-24, 1990. West Virginia University. Morgantown, WV.

Richardson, A.R. and M.T. Dougherty. 1976. Feasibility study of Deer Creek daylighting project, Environmental Protection Technical Series, USEPA, EPA-600/2-76-110.

Rose, A.W., L.B. Phelps, R.R. Parizek, and D.R. Evans. 1995. Effectiveness of lime kiln flue dust in preventing acid mine drainage at the Kauffman surface coal mine, Clearfield County, Pennsylvania. pp. 159-171. *In*: Proceedings, 1995 National Meeting of the American Society for Surface Mining and Reclamation June 3-8, 1995, Gillette, WY.

SAS Institute. 1989. SAS. SAS Institute. Cary, NC.

Skousen, J., R. Hedin, and B. Faulkner. 1997. Water quality changes and costs of reining in Pennsylvania and West Virginia. pp. 64-73. *In*: Proceedings, 1997 National Meeting of the American Society for Surface Mining and Reclamation, May 10-15, Austin, TX.

Skousen, J., and G. Larew. 1994. Alkaline overburden addition to acid-producing materials to prevent acid mine drainage. pp. 375-381. *In*: International Land Reclamation and Mine Drainage Conference. Vol. 1. April 19-21, 1994. USDI, Bureau of Mines SP 06B-94. Pittsburgh, PA.

Skousen, J., A. Rose, G. Geidel, J. Foreman, R. Evans, W. Hellier. 1998. Handbook of technologies for avoidance and remediation of acid mine drainage. Acid Drainage Technology Initiative (ADTI) of the U.S. Office of Surface Mining. National Mine Land Reclamation Center, West Virginia University. Morgantown, WV.

Skousen, J., A. Sexstone, and P. Ziemkiewicz. 2000. Control and treatment of acid mine drainage. pp. 131-168. *In*: Reclamation of Drastically Disturbed Lands, Agronomy No. 41, American Society of Agronomy, Madison, WI.

Skousen, J., J. Simmons, and P. Ziemkiewicz. 2002. Acid-base accounting to predict post-mining drainage quality on surface mines. *J. Environ. Qual.* **31(6)**: 2034-2044.

Skousen, J., and P. Ziemkiewicz. 1996. Acid mine drainage control and treatment. National Research Center for Coal and Energy, West Virginia University. Morgantown, WV.

Stewart, J., and J. Skousen. 2003. Water quality changes in a polluted stream over a twenty-five-year period. *J. Environ. Qual.* **32(2)**: 654-661.

Surface Mining Control and Reclamation Act. 1977. Public Law 95-87. U.S.C. 1201 et.seq.

West Virginia Department of Natural Resources. 1985. Cheat River subbasin abandoned mine drainage assessment. WV DNR, Division of Water Resources. Charleston, WV.

Wood, S.C., P.L. Younger, and N.S. Robins. 1999. Long-term changes in the quality of polluted minewater discharges from abandoned underground coal workings in Scotland. *Quarterly Journal of Engineering Geology*. **32**: 69-79.

Younger, P.L. 1997. The longevity of minewater pollution: a basis for decision-making. *Science of the Total Environment*. **194/195**: 457-466.

Younger, P.L. 2000. Predicting temporal changes in total iron concentrations in groundwaters flowing from abandoned deep mines: a first approximation. *J. Contaminant Hydrology*. **44**:47-69.

Younger, P.L. 2003. Personal communication, University of Newcastle, Newcastle, U.K.

Younger, P.L., S.A. Banwart, and R.S. Hedin. 2002. Mine Water Hydrology, Pollution, Remediation. Kluwer Academic Publishers. Boston, MA.

Younger, P.L., T.P. Curtis, A.P. Jarvis, and R. Pennell. 1997. Effective passive treatment of aluminum-rich, acidic colliery spoil drainage using a composted wetland at Quaking Houses. County Durham. *Journal of the Institution of Water and Environmental Management*. **11**: 200-208.

U.S. Environmental Protection Agency. 1973. The status of active deep mines in the Monongahela River Basin. Region III. Wheeling, WV.

U.S. Environmental Protection Agency. 1995. Streams with Fisheries Impacted by Acid Mine Drainage in MD, OH, PA, VA, and WV. Region III, Wheeling, WV.

Zeleznik, J, and J. Skousen. 1996. Survival of three tree species on old reclaimed surface mines in Ohio. *J. Environ. Qual.* **25(6)**: 1429-1435.

Ziemkiewicz, P. 1994. AMD-TIME: A simple spreadsheet for predicting acid mine drainage. pp. 395-400. *In*: International Land Reclamation and Mine Drainage Conference. Vol. 1. April 19-21, 1994. USDI, Bureau of Mines SP 06B-94. Pittsburgh, PA.

Zipper, C.E. 2000. Coal mine reclamation, acid mine drainage, and the Clean Water Act. pp.169-191. *In*: Reclamation of Drastically Disturbed Lands, Agronomy No. 41. American Society of Agronomy, Madison, WI.

Table 3-1. Discharge and Mine Overview

Discharge point, mine name, the year the mine opened, disturbance category (D=disturbed and UD=undisturbed), coal seam mined (UF=Upper Freeport and Pitts=Pittsburgh), size of mine, and number of data points (2=1968 and 2000, 3=1968, 1980, and 2000) for each discharge.

Discharge Point	Mine Name	Year Opened	Category	Coal Seam	Size (ha)	Data Points
Bull Run 1	Kimberly	1955	D	UF	21	2
Bull Run 2	Roxy Ann	1957	D	UF	923	2
Bull Run 3	Roxy Ann	1957	D	UF	923	2
Bull Run 4	Sherrey	1955	UD	UF	282	3
Bull Run 5	Marys	1955	UD	UF	58	2
Cheat River 2	Morgantown North D	1935	D	Pitts	131	2
Cheat River 3	Frederick No. 1	1938	D	Pitts	89	2
Cheat River 4	Morgantown North A	1940	UD	Pitts	44	3
Cheat River 5	Canyon	1940	D	Pitts	448	3
Cheat River 6	Mountain Run	1952	D	UF	311	2
Cheat River P1	Morgantown North B	1935	D	Pitts	63	2
Cheat River P2	Morgantown North C	1935	UD	Pitts	112	2
Fickey Run 1	Valley Point C	1945	UD	UF	28	2
Fickey Run 3	Valley Point F	1945	D	UF	62	3
Fickey Run 5	Valley Point K	1950	D	UF	38	3
Fickey Run 6	Valley Point L	1950	D	UF	75	3
Fickey Run 7	Valley Point T	1950	D	UF	60	2
Fickey Run 8	Tri State	1952	D	UF	78	3
Fickey Run 9	Tri State 1	1945	D	UF	47	2
Glade Run 1	Liston	1955	D	UF	26	2
Glade Run 2	Valley Point F	1950	UD	UF	52	2
Glade Run 3	Valley Point G	1950	UD	UF	69	2
Glade Run 4	Valley Point A	1950	D	UF	156	3
Glade Run 5	Valley Point A	1950	D	UF	156	3
Green Run 1	Pleasant	1945	UD	UF	33	3
Green Run 2	Ricks	1945	UD	UF	42	2
Green Run 3	Lowery	1950	D	UF	88	3
Lake Lynn 1	Hollow	1943	UD	Pitts	34	3
Lake Lynn 2	Canyon	1935	D	Pitts	448	3
Lake Lynn 3	Canyon	1935	D	Pitts	448	3
Martin Ck 2	Me	1955	D	UF	11	3
Martin Ck 3	Me	1955	D	UF	11	2
Middle River 1	Mountain Run	1952	D	UF	310	3
Morgan Run 5	Ford	1940	UD	UF	41	2
Muddy Ck 2	Cuzzart C	1940	UD	UF	72	3
Muddy Ck 3	Shermike	1935	D	UF	278	3
Muddy Ck 4	Pottage	1940	D	UF	19	2
Muddy Ck 5	Gloria	1950	UD	UF	148	2
Muddy Ck 6	Cuzzart B	1945	UD	UF	98	2
Muddy Ck 7	Cuzzart D	1945	D	UF	86	2
Muddy Ck 8	Cuzzart F	1940	UD	UF	44	2
Muddy Ck 9	Tri State	1952	D	UF	78	3
Muddy Ck 10	Short	1940	D	UF	121	2
Muddy Ck 11	Ruthbell #3	1943	D	UF	35	3

Table 3-2. Analysis of variance results and model fits for T&T water quality data for 1996 to 2001.

Months	Parameter	R ²	Model Pr>F	Month	Year	Month*Year
-----p value-----						
Jan – Dec	Flow	0.92	<0.0001	<0.0001	<0.0001	0.0005
	Acidity	0.59	0.0463	0.9777	<0.0001	0.7448
	Iron	0.73	<0.0001	0.0033	<0.0001	0.0244
	Sulfate	0.80	<0.0001	0.0184	<0.0001	0.0004
	pH	0.74	<0.0001	0.0151	<0.0001	0.0054
	Conductivity	0.76	<0.0001	0.0252	<0.0001	0.1066
Jun – Sept	Flow	0.85	<0.0001	0.0186	<0.0001	0.4278
	Acidity	0.57	0.2527	0.9801	0.0133	0.8130
	Iron	0.77	0.0035	0.0808	<0.0001	0.1953
	Sulfate	0.89	<0.0001	0.2304	<0.0001	0.0293
	pH	0.49	0.5374	0.4216	0.1073	0.9846
	Conductivity	0.80	0.0010	0.7003	<0.0001	0.4952

Table 3-3. Correlation coefficients between water quality parameters for the T&T underground mine site.

Months	Parameter	Flow	Parameter				
			Acidity	Iron	Sulfate	pH	Cond
Jan - Dec	Flow	1.00	0.50**	0.43**	-0.17 ^{ns}	-0.42**	0.46**
	Acidity		1.00	0.46**	0.18*	-0.35**	0.51**
	Iron			1.00	0.15 ^{ns}	-0.38**	0.42**
	Sulfate				1.00	0.10 ^{ns}	0.12 ^{ns}
	pH					1.00	-0.41**
	Conductivity						1.00
Jun - Sept	Flow	1.00	0.31*	0.39*	-0.26 ^{ns}	-0.30*	0.50**
	Acidity		1.00	0.44**	0.13 ^{ns}	-0.16 ^{ns}	0.42**
	Iron			1.00	0.31*	-0.21 ^{ns}	0.32*
	Sulfate				1.00	0.23 ^{ns}	0.04 ^{ns}
	pH					1.00	-0.24 ^{ns}
	Conductivity						1.00

¹ ns = not significant, * = significant at the p=<0.05 level, ** = significant at the p=<0.01 level.

Table 3-4. Characterization of T&T flows and concentrations (1996 to 2001) across all months (January to December) and during low-flow sampling times (June to September).

Parameter	January - December			June – September		
	mean	RSD ^a	% ^b	mean	RSD ^a	% ^b
Flow (L s ⁻¹)	21.4	44.5	-76.9	19.8	29.2	-52.9
Acidity (mmol H ⁺ L ⁻¹)	15.9	30.5	-69.7	15.2	20.0	-38.8
Iron (mg L ⁻¹)	164	32.4	-75.8	150	28.7	-59.2
Sulfate (mg L ⁻¹)	1346	19.1	-55.5	1329	11.9	-27.0
pH	2.9	10.1	-29.1	2.8	7.0	-16.0
Conductivity (mhos cm ⁻¹)	3212	21.5	-59.9	3131	9.1	-25.9

^a RSD = relative standard deviation = 100*standard deviation/mean.

^b % = percent change = 100*(minimum-maximum)/maximum

Table 3-5. Average values for 1968 and 1999-2000 water quality data (two dates) from Pittsburgh and Upper Freeport underground mines.

Parameter	Coal Seam	n	Year		Significant Between Dates
			1968	1999-2000	
Flow (L s ⁻¹)	ns	42	1.4	0.5	No
Acidity (mmol H ⁺ L ⁻¹)	Pittsburgh	10	66.8 ^{a1}	14.0 ^a	Yes
	Upper Freeport	35	23.8 ^b	10.4 ^a	Yes
Iron (mg L ⁻¹)	Pittsburgh	10	591 ^a	88.1 ^a	Yes
	Upper Freeport	35	214 ^b	54.7 ^a	Yes
Sulfate (mg L ⁻¹)	Pittsburgh	9	3581 ^a	1093 ^a	Yes
	Upper Freeport	33	1561 ^b	886 ^a	Yes
pH	Pittsburgh	10	3.0 ^a	3.0 ^a	No
	Upper Freeport	35	3.1 ^a	3.8 ^b	No
Conductivity (mhos cm ⁻¹)	Pittsburgh	10	5010 ^a	1826 ^a	Yes
	Upper Freeport	25	2347 ^b	1764 ^a	Yes

¹Values for each parameter between coal seams with the same letter are not significantly different at the 0.05 level.

Table 3-6. Average water quality value from Pittsburgh and Upper Freeport underground mines
Average values for 1968, 1980, and 1999-2000 water quality data (three dates) from Pittsburgh and Upper Freeport underground mines. Trends across years are shown in Figures 3-4 through 3-6.

Significant Parameter	Coal Seam	n	Year			Significant Among Dates
			1968	1980	1999-2000	
Flow (L s^{-1})	Pittsburgh	4	2.4	1.4	0.2	No
	Upper Freeport	13	2.6	3.0	0.7	No
Acidity ($\text{mmol H}^+ \text{L}^{-1}$)	Pittsburgh	5	65.9 ^{a1}	17.3 ^a	13.1 ^a	Yes
	Upper Freeport	15	23.5 ^b	12.7 ^a	5.2 ^a	Yes
Iron (mg L^{-1})	Pittsburgh	5	477 ^a	150 ^a	21 ^a	Yes
	Upper Freeport	15	245 ^b	92 ^a	66 ^a	Yes
Sulfate (mg L^{-1})	Pittsburgh	5	2066 ^a	1244 ^a	580 ^a	Yes
	Upper Freeport	14	1587 ^a	1050 ^a	1067 ^a	Yes
pH	Pittsburgh	5	3.0 ^a	2.2 ^a	3.1 ^a	Yes
	Upper Freeport	15	2.8 ^a	2.5 ^a	3.4 ^a	Yes
Conductivity (mhos cm^{-1})	Pittsburgh	2	4472 ^a	2395 ^a	1065 ^a	Yes
	Upper Freeport	10	1980 ^b	1104 ^a	1805 ^a	Yes

¹Values for each parameter between coal seams for each date with the same letter are not significantly different at the 0.05 level.

Figure 3-1. Below drainage vs. Above drainage

A simplified illustration of underground mines that are distinguished as “below-drainage” or “above-drainage.” This refers to their capacity to be completely flooded after abandonment due to their relative location to the regional water table or regional flow system. See Callaghan et al. (1998) for a more thorough and detailed discussion of groundwater flow in the Appalachian Region.

Figure 3-2. Average values for flow, acidity, iron, and pH across years and months for the T&T data set.

Figure 3-3. Cumulative frequency 1968 vs. 2000

Cumulative frequency plot for acidity and iron for two dates (1968 and 1999-2000). The percent change values of -38.8 for acidity and -59.2 for iron (Table 3-4) are used as conservative thresholds to indicate that changes more negative than these values are significantly different from a percent change of zero.

Figure 3-4. Pittsburgh acidity & iron over years

Changes in acidity and iron for five Pittsburgh sites where we had data for 1968, 1980, and 1999-2000. All five sites showed decreasing acidity and iron values.

Figure 3-5. Changes in acidity for Upper Freeport sites

Changes in acidity for Upper Freeport sites where we had data for 1968, 1980, and 1999-2000. The top graph shows 10 sites with acidity decreases, while five sites showed acidity increases.

Figure 3-6. Changes in iron for Upper Freeport sites

Changes in iron for Upper Freeport sites where we had data for 1968, 1980, and 1999-2000. The top graph shows 11 sites with iron decreases, while four sites showed iron increases.

CHAPTER 4: FLOW EFFECTS ON ACIDITY AT TWO MINE SITES IN WV: OMEGA AND T&T

Introduction

It is apparent that precipitation influences the discharge rate of underground mines. Most recharge occurs in the fall, winter and especially spring causing increased flow rates as seen in the Appalachian Plateau Sandstone of central Pennsylvania (O'Driscoll et al. 2005). Wendland (2001) reported groundwater response within the month of precipitation events or one to two months later, with recovery being reached another one to three months in the future, depending on the season. During drought conditions, much longer recovery times are needed for increased discharge rate (Wendland 2001).

Pigati and Lopez (1999) studied the Majestic Mine in Ohio looking at seasonal variations in water chemistry. They report the Majestic Mine behaves similarly to a karst spring with quickflow and baseflow occurring, along with substantial subsidence causing the quick recharge into the mine. Their data supported the “spring flush” idea. The “spring flush” idea assumes that acidity and metals generated and deposited on surfaces during summer and fall (seasonal dry months in this region) are largely flushed from the mine with high flows from late winter-early spring snowmelt and rainfall. Therefore during the high recharge and discharge season of February to May (which also lacks evapotranspiration), the high water flows carry high concentrations of acidity and metals. This is opposed to the “high concentration at low flow” concept, where the worst drainage from underground mines happens at base flow conditions (dry months) where acid and metals are thought to be concentrated and not diluted by surface water during recharge events (Skousen and Ziemkiewicz 1996).

Further research by Lopez and Stoertz (2001) measured water chemistry and discharge rate of three up-dip mines of different sizes in the Monday and Raccoon Creek watersheds in eastern Ohio. They reported a 1- to 4-day time lag between precipitation and peak discharge in updrift mines in the Appalachian region, along with a seasonal affect. At the Majestic Mine, highest flows occurred in the spring (130 L/s) with lows flows in the late summer and fall (9 L/s). Lopez and Stoertz (2001) report iron and sulfate were highest during late winter and early spring at the Majestic Mine due to the water table rising, flushing out the oxidation products. However, they

stated the drainage concentration was relatively uniform, suggesting either equilibrium controls on chemistry or drainage of a well mixed pool. Evidence by Borek et al (1991) contradicts this report. Studying underground mines in Randolph County, WV, they found that the highest flows were seen even when precipitation was below normal for a particular year.

Dyer (1986) showed that seasonal variation in chemistry occurred from auger mined sites in eastern Kentucky. Auger mining in this area is similar to underground mines which use continuous miners. The large augers leave 4 meter wide tunnels with pillars intact. A discharge from one of the tunnels had a pH of 2.7 and an acidity concentration of 5300 mg/L only a few hours after a heavy rainfall event in the spring of 1984. Dyer felt that the acidity was being flushed out of the mine tunnel. He corresponded these large increases of discharge from the mine into adverse affects being seen in the surrounding stream.

As presented by Demchak et al. (2004), the Omega Mine, a 68-ha above-drainage underground mine of the Upper Freeport coal bed in northern WV, was mined during the 1980s. In 1992, breakout of AMD caused mine closure, and flows and acidity concentrations were recorded continuously for the ensuing six years (GAI Consultants 2001). Acidity was highest during February to May (~4,500 mg/L) compared to about 3,800 mg/L during June to January. However, variation in the acidity values across both time periods was high. Above drainage mines, based on these and other examples, appear to discharge their worst acid and metal concentrations during high flow seasons (spring flush), with improved water quality during dry periods.

Alternatively, Griffiths et al. (2001) indicate at the Arnot underground mine in Tioga County, PA, that as the discharge rate increased, other parameters (acidity, iron, and aluminum) decreased. This mine interestingly did not experience seasonal patterns, which may be explained by the wide range of “spring thaws” anytime from February to April skewing the trend.

Contradicting other reports, Lopez and Stoertz, (2001) suggest mine discharge chemistry may be relatively uniform through time, especially at small mines with little recharge, suggesting equilibrium control on chemistry within the mine or a well mixed pool. They report, using studies conducted in the Monday and Raccoon Creek watersheds in southeast Ohio that minimal evidence exists for dilution of chemistry by high flows, at least at the Carbondale mine. The Carbondale mine is only 13 ha, but is interconnected with 160 ha of additional mines. They state

that slow sustained processes are occurring with this mine, versus quickflow processes which may occur at other mines.

It seems evident that discharge chemistry from underground mines is affected by several factors, and efforts to determine the changes in water quality over time require accounting for these factors. First, the season of sampling is important to consider due to varying recharge potential within the mine. However, conflicting results from other studies do not indicate that a particular time of year of sampling will produce accurate acidity results for a particular mine. Part of the problem lies in the fact that two distinct discharge periods are being documented in the WV region: February to May and June to September. Flows in October, November, December and January from underground mines are especially hard to predict because these months alternate between very high flows like those of February to May and very low flows like those from June to September (GAI Consultants 2001, Pigati and Lopez 1999). In fact, evidence is mounting that acidity does not vary significantly with flow.

In watersheds where many abandoned deep mines occur, the deep mines serve as a constant source of water to streams, sometimes called baseflow (Hobba 1981). During drier periods of the year, a larger degree of stream flow comes from deep mine drainage or baseflow, thereby causing very acidic water. During wetter periods, deep mine discharges, making up the majority of the baseflow, are diluted by ephemeral springs and seeps, and also by runoff, thereby resulting in improved water quality in streams. However, stream clean-up efforts must effectively deal with improving the water quality during baseflow conditions (improving the deep mine discharges) or else any enhancement in stream quality and aquatic habitat will be transitory and destroyed each time rainfall declines or is irregular. Therefore, it is vital to determine the origin of the deep mine discharges and whether the discharges improve over time and with seasonal rainfall variations.

In order to assess the relationship between discharge rates and acidity, two underground mines were studied. Data sets for T&T and Omega were obtained from the West Virginia Division of Environmental Protection. These data sets were fairly complete in their daily precipitation and flow measurements, along with biweekly water quality analysis. The data sets were used to assess the relationships of precipitation, flow rates, and acidity concentrations.

Methods and Materials

T&T

T&T is a 605-ha deep mine with three discrete parallel openings. The Freeport Coal (located at the top of the Allegheny Formation of the Pennsylvania Period) was mined at these sites using the room and pillar method. The pillars were left intact, creating a checkerboard in plane view as shown on mine maps. The coal seam averages 1.6 m in thickness; the dip is 9% to the southeast. The mines underlie an upland plateau dissected by Muddy Creek on the east and Cheat River on the south. Land surface elevation above these mines rises to a level of between 580 m to 640 m, so that the overburden locally exceeds 90 m. The #2 portal opens on the west side of the valley of Muddy Creek at 455 m elevation. The overburden above Portal #2 is about 12 to 30 m. Geophysical approaches have been applied to determine mine pool information and flow within the mine workings. They have used very low frequency surveys coupled with magnetometers profiles. The traces do not appear to indicate the existence of fractures overlying the mine workings.

There are two discharges from this underground mine. Pitmouth is the primary portal of discharge as it is located 2.1 m lower than the Yellow Pipe. During dry periods, the Pitmouth discharge continually flows while the Yellow Pipe ceases to flow. The discharge rate from Pitmouth and Yellow Pipe were added together for total flow from T&T. Weighted averages were calculated for acidity concentrations at T&T. The acidity value was determined by first calculating the acid load at Pitmouth and Yellow Pipe, adding the two values together and then dividing by total flow. This gave a weighted acidity average at T&T. This value was then compared against total flow in the analysis.

Omega

The Omega mine is located 2 miles south of Morgantown, WV and was closed in the early 1980s. The site is located in the Appalachian Plateau physiographic province. The rock strata is part of Pennsylvanian age Conemaugh and Allegheny Formations which consist of sandstone, claystone, limestone, and coal.

The UF bed is about 1.3 m thick at depths varying between 20 and 60 m. The Upper Freeport coal bed was mined over 68 ha. The dip is to the southeast at 9%. The elevation ranges from 530

m above the mean sea level on the south end to 450 m at the north end. The mine was developed along a north to south ridgetop with the ridge serving as an anticline in the mine with sections on each side of the ridge being slightly lower. Water initially broke out on the eastern side of the mine, and a grouting project was attempted at the mine to fill the mine voids in specific places (WVDEP, personal communication).

Room and pillar methods extracted 50% of the coal with pillar size being from 5.5 m by 9 m. Some areas had 60% coal removal, while others had 72% removal. Additional small UF mines were apparently operated in the vicinity in the 1920s, but no maps are available. When mining ceased in the 1980s water began ponding inside the mine, allowing two mine pools to develop. Unmapped punch mines have allowed water from Omega to drain through the outcrop. Steep slopes of >30% cause rapid run-off and flash-flood type flow which results in limited recharge potential of the local aquifers and mine pool. A sandstone aquifer (Lower Mahoning) located above the UF bed is perched and of limited extent of area.

Sampling

Samples were collected by the West Virginia Division of Environmental Protection technicians and delivered to a certified laboratory where pH, acidity, alkalinity, iron, aluminum, manganese, and sulfate were determined using standard methods. Flows were also taken by the technicians who worked at the mines every day using a flow gauge fitted to a v-notch weir. Precipitation was measured daily with a rain gauge located at the office trailer.

Measured vs. Calculated Acidity

When looking at the measured values of acidity from the data set, some of the data were suspect. In order to remove outliers and correct the data, a comparison between measured acidity to calculated acidity was done using the following formula (Skousen et al., 1998).

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

The results showed that T&T had an $R^2 = 0.78$ while Omega had an $R^2 = 0.72$ (Figures 4-1 and 4-2). When measured acidity values were more than 10% different from calculated values, the calculated value was used. Outliers were removed from the datasets completely; 10 values were deleted from the T&T dataset and 7 values were deleted from Omega.

Statistical Analysis

A repeated measures analysis of variance with year, flow category, average flow, month, average precipitation, and season as categorical variables was used to test for the relationships between flow and acidity using PROC GLM (SAS Institute 1989). Means for significant ($\alpha = 0.05$) model terms were separated using Tukey's Honestly Significant Difference ($\alpha = 0.05$). Correlation analysis was also conducted on the raw water quality to look for overall trends.

In order to test for significance or trends within the data set, the data were broken into categories. Flow categories were determined by plotting raw flow data and visually observing data breaks. At T&T the breaks were flows < 20 L/s (300 gpm), flows between 20 L/s (300 gpm) and 40 L/s (600 gpm) and > 40 L/s (600 gpm). At Omega the average flow was significantly smaller, so different breaks were used. The low flow was < 3 L/s (50 gpm), between 3 L/s (50 gpm) and 6 L/s (100 gpm) and > 6 L/s (100 gpm). Season was also tested in the model to determine if a seasonal trend occurred. Four seasons were used: Summer (June, July, August), Fall (September, October and November), Winter (December, January, and February) and Spring (March, April, May).

Results and Discussion

Precipitation Effects on Flow Rate

Since daily flow rates were available from T&T and Omega, precipitation records were collected and plotted with flow rate. No estimates were made of other inputs or outflows from the mine such as barrier leakage, evaporation, transpiration or runoff. The main interest was to see trends of flow out of the mine with precipitation.

In this region of the U.S., rainfall is relatively evenly distributed throughout the year, with slightly higher rainfall in the spring, and slightly lower rainfall in the late summer and fall. Figures 4-3 and 4-4 showed this trend at these two mines. Patterns across season did emerge for flow rate. The highest flows were seen in the spring, while low flows were visible from late fall into winter. These results are similar to those found by Lopez and Stoertz (2001) at the Majestic Mine in Ohio. The Majestic Mine was 130 ha in size, but connects to about 360 ha of additional mines. This total size is much larger than the Omega mine, but not quite as large as the T&T complex.

As snow melt and spring rain occurs, the mine pool rises causing an increase in discharge rate. During the summer months when less precipitation falls, high intensity rainfall runs off, and evaporation and transpiration by vegetation is at a maximum, the mine pool lowers resulting in less water flowing from the portal during late summer and fall. This seasonal influence on flow will be used in the discussion on acidity concentrations.

It appears that the size of the mine or overburden depth does not affect the overall seasonal trend of flow rates. While the baseflows are significantly different at T&T and Omega, discharge trends are similar at both mines. Baseflow for T&T averaged 500 gpm and baseflow for Omega averaging 80 gpm. During the spring when snow melt has occurring or greater amounts of precipitation are occurring, the flow rate increases. During the summer months, when evapotranspiration is at its highest and little to no recharge enters the mine, flow rates start to decrease through late summer into fall. This trend is clearly seen, regardless of the size of the mine.

Acidity Values Plotted Over Time

The average monthly flow and acidity were plotted over the study years for both T&T and Omega. Flow showed the observed seasonal trends of troughs in the late summer through winter with high flow in the spring at T&T (Figure 4-5). Acidity at this site does not show any clear visible trends except for a gradual overall decline. The regression line for T&T (Figure 4-6) showed an increase in acidity with increased flow, but the fit was very poor ($R^2 = 0.08$). At Omega, the same pattern emerged for flow: troughs in the fall and winter with spikes in the spring (Figure 4-7). However, acidity appeared to decrease during high flow, but the overall fit was also poor ($R^2 = 0.09$, Figure 4-8).

These relationships at both sites give evidence that flow has a very limited effect on acidity concentration from these above-drainage underground mines. Further, these results do not support either a flushing or a dilution idea. Lopez and Stoertz (2001) report equilibrium of chemistry within the mines which would account for the lack of trends between flow and acidity. The results from the present study seem to support this idea that no large fluctuations occur across seasons for acidity concentrations.

Lopez and Stoertz (2001) note the lack of trend strongly at the small Carbondale mine. This mine was only 13 ha in size, but was later found to be interconnected to an additional 160 ha of

mines. This overall mine area is still relatively small. This lack of trend may be described by the potential equilibrium which may also be occurring at T&T and Omega. A steady state has emerged within these mines due to the establishment of discrete mine pools within the complexes. Even though these mines are described as free flowing, that does not appear to be the case. Evidence at both sites show the formation of mine pools which may be acting to regulate flow, and therefore, chemistry out of the mine.

Year, Seasonal and Monthly Flow Effects on Acidity

In order to determine any other influence of flow on acidity, the data were divided into flow groups including year, flow category and season. Each flow group was analyzed as main effects with all interactions. The R^2 at both sites was 0.82. The overall model at both sites was significant, T&T = 0.0007 and Omega = 0.0003. Individual model terms showed significant differences in acidity averages across years at T&T (Tables 4-1 and 4-2). The acidity means ranged from 565 mg/L in 2002 to 1127 mg/L in 1996. Omega also showed significant differences in acidity across years (Tables 4-3 and 4-4) ranging from 945 mg/L in 2002 to 1616 mg/L in 2000. There appears to be no strong trend for acidity decreasing over time as reported in Chapter 1 for similar above drainage mines. This, however, is most likely due to the relatively short time since these two mines have been closed. Figures 4-9 and 4-13 represent acidity concentrations as grouped per year. The wide variation within a year can be seen in these graphs.

T&T and Omega both resulted in year being significant as a model term, this would be expected. Acidity concentrations will vary from year to year as affected by cumulative precipitation and depth of the mine pools. A high precipitation year would increase recharge into the mine, raising the mine pool elevations, allowing the water to contact oxidation products which would have accumulated during dry times. These products would then dissolve and be removed from the mine as increased acidity concentrations. These variations would be expected at both mines during wet and dry years.

The second main effect term in this model was flow category. Flow categories were determined by plotting raw flow data and visually observing data breaks. At T&T the breaks were flows < 20 L/s (300 gpm), flows between 20 L/s (300 gpm) and 40 L/s (600 gpm) and > 40 L/s (600 gpm). At Omega the average flow was much smaller due to the much smaller size, so different breaks were used. The low flow was < 3 L/s (50 gpm), between 3 L/s (50 gpm) and 6

L/s (100 gpm) and > 6 L/s (100 gpm) (Table 4-5). Flows were divided into Low, Mid, and High categories and acidity mean concentrations corresponding to these flow categories were calculated. At T&T, the ANOVA showed no significant difference in flow categories with acidity values ranging from 718 mg/L for Low to 875 mg/L for High (Table 4-1). At Omega, the overall model showed a significance of the year and flow category interaction ($p = 0.0036$), but not for flow category as a main effect. Acidity values ranged from 1518 mg/L for Low and 1157 mg/L for Mid. Figure 4-12 shows acidity concentration as grouped by flow category at T&T. This graph shows a strong correlation (0.92) for increasing acidity as flow increases, but the data is highly variable with the Low and Mid categories having as high acidity values as the High category. A similar result is shown for Omega (Figure 4-16). Both Pigati and Lopez (1999) and Dyer (1986) report results describing situations where high flows resulted in high acidities. They state that during high flows or soon after high precipitation events, flushing of acidity from the underground mines occur. In this study, variation in acidity values was very high among the flow categories that a similar conclusion could not be reached.

The third main effect term in this model was season. Seasonal trends in acidity were marginally significant in the ANOVA model for T&T ($p=0.0551$). At T&T, the highest acidity concentration occurred in the summer months at 813 mg/L, but the lowest was in the spring at 770 mg/L, neither being very different from the other. The large size of T&T may act to buffer the spring thaw resulting in a delayed flush event. At Omega, similar results were seen with Season being marginally significant ($p = 0.0682$), whereas the interaction of flow category and season was also marginally significant ($p = 0.0577$). At Omega, the highest acidity values occurred in the spring (1383 mg/L) and the lowest mean was in the winter (1206 mg/L). The flush events are occurring during the high seasonal recharge at this smaller mine, which also has shallower overburden allowing for “quickflow” to occur.

There were no clear trends across sites. Figures 4-9 to 4-16 provide relationships between flow groupings and acidity values and present the wide variation across years, flow categories, and seasons. In general, these graphs give further evidence of the lack of trends between acidity concentrations and flow. The lack of seasonal trends was also reported by Griffiths et al. (2001) for work conducted at the Arnot mine in Pennsylvania. He credited this lack of seasonality to the wide range or time frame in which spring thaws occur in northern Pennsylvania and that flow was therefore relatively constant across seasons.

Analyses were then performed on individual flow values within flow groupings by using a model of acidity = year * average flow * season. At T&T, the R^2 was 0.92 with a significant overall model of 0.0012. The model interaction of year and season ($p = 0.0488$) was significant, but no individual terms were significant. The Tukey results gave significant differences among years, but not seasons. At Omega, the R^2 was 0.88 with an overall model significance (0.0190). However, with Omega there was no significance for individual model terms or interactions. The results are therefore similar to those using the flow categories.

An analysis was also performed for months using a model of acidity = average flow * month. No significance was determined at either site. Figures 4-11 and 4-15 show the variation of acidity across months. It was thought that differences in months may occur if there is truly one time of year when “flush events” are occurring. This was expected more at Omega due to the size of the mine.

Tables 4-6 and 4-7 summarize the average precipitation received for years, seasons and flow categories, and provide the average flows and average acidity values. At both T&T and Omega, flow appears related to the cumulative precipitation. Lower flows are associated with a lower cumulative precipitation for a given year or season. Acidity, however, does not show a similar trend. An ANOVA model was ran using flow category and average precipitation as main effect with interactions (model results not shown). The R^2 was 0.09 at T&T, with no overall or individual significance. At Omega, an R^2 of 0.21 was shown, again with no significance of a whole model or individual terms. Average precipitation does not affect the acidity concentration, but it is more the cumulative precipitation and its subsequent effect on flow which plays the larger role.

Daily Flow Effects on Acidity

Questions remain as to how acidity concentrations may be influenced by more localized events such as those during brief dry periods or shortly after large rainfall events. This was difficult because daily flow values did not have corresponding daily acidity values. Table 4-8 gives data that represent both dry and wet events at T&T. The first part of the table shows precipitation events greater than 1.3 cm and how many days after that event where both acidity and flow were measured simultaneously. The days range from 1 to 7 days after the rain event. For example, on 9 April 2001, which was two days after a 2.1 cm rainfall event, the acidity was

596 mg/L with a flow of 28 L/s (452 gpm). On 1 April 2003 (during the same month and season), two days after a 1.3 cm rainfall event, the acidity was 1100 mg/L with a flow of 46.3 L/s (735 gpm). Therefore, the flow and acidity do not appear to relate to an individual rainfall event, but may related to the cumulative precipitation. 2003 was a much wetter year than 2001. On 29 January 1997, the acidity was 851 mg/L with a flow of 33 L/s (533 gpm). On 12 November 1996, the acidity was 803 mg/L at a flow of 34 L/s (536 gpm). In this example, similar flows resulted in similar concentrations. When looking at other dates, the effect of rainfall events after dry periods shows no evidence of patterns.

The second part of Table 4-8 shows the acidity and flow values during dry conditions of no rain. Dry periods of 7 days resulted in acidity values ranging from 211 to 288 mg/L, while a dry period of 3 days gave acidity values from 497 to 3310 mg/L. This continues to show the wide variation in acidity values across years, seasons, and even short-term dry periods.

At Omega, the results are similar to T&T with the same analysis (Table 4-9). For example, on 14 April 2000, five days after a 1.7 cm event, the flow was 13 L/s (209 gpm) with an acidity of 1880 mg/L, while one year later on 16 April 2001, four days after a 1.4 cm event, the flow was identical at 13 L/s (209 gpm) but the acidity was cut nearly in half to 1000 mg/L. The cumulative rainfall was similar among years. During dry periods, the data also lacked a clear trend. On 13 Oct 2003, 7 days of no rain produced a flow of 3 L/s (53 gpm) and an acidity of 1200 mg/L, while on 15 November 2001, 7 days of no rain produced a flow of 1 L/s (17 gpm) and an acidity of 1460 mg/L.

Conclusion

Graphs plotting precipitation and flow data showed that the highest flows generally occurred in the spring, with low flows in the fall. These conclusions were also reached by Lopez and Stoertz (2001) when working with up-dip above-drainage underground mines in Ohio. While the statistics are not shown here, there is no statistical evidence showing that average precipitation directly affected flow rate.

In comparing measured to calculated acidity, the R^2 was greater than 0.70 for both sites. The time graphs showed no clear acidity trends with flow. There was slight evidence for lower flows to result in higher acidity values at Omega. These results are supported by work done at the

Arnot mine in Pennsylvania which showed that there were no differences in acidity values across different flow times.

Significant differences were seen in acidity across years at both sites, with acidity values decreasing over time. Flow category had no significance on acidity values at T&T. This contradicts trends identified by other studies in Ohio and Kentucky which reported higher acidity concentrations at higher flows. At Omega, the individual flow category term was not significant, but the flow category * year interaction was. This site showed significantly higher acidity values at low flows. There was no difference for acidity values within a season at T&T and Omega.

Analysis of flow and acidity data from these two mines gave weak relationships between flow rates and acidity concentrations. While two ideas have existed about flow rate on discharge acidity concentration from above drainage underground mines (flushing versus dilution), neither idea is strongly supported by this analysis. Changes occurred within these mines during the study period that may have confounded the data and made our conclusions suspect. Both sites had grouting and alkalinity injection within the mine. While recognizing these disturbance effects, these mines were the only ones where a sufficient data set with daily flows and frequent analysis provided the opportunity to evaluate these trends.

Literature Cited

Borek S. L., T. E. Ackman, G. P. Watzlaf, R. W. Hammack, and J. P. Lipscomb. 1991. The long-term evaluation of mine seals constructed in Randolph County, W.V. in 1967. *In: Proceedings of the 12th Annual West Virginia Surface Mine Drainage Task Force Symposium*, April 3-4, 1991, Morgantown, W.V.

Demchak, J., J. Skousen, and L.M. McDonald. 2004. Longevity of acid discharges from underground mines lying above the regional water table. *J. Environ. Qual.* **33**: 656-668.

Dyer, Kenneth. 1986. Seasonal acid mine drainage from a surface mined watershed in eastern Kentucky. *In: Proceedings of American Society for Surface Mining and Reclamation*. Jackson, Mississippi.

GAI Consultants. 2001. Omega Mine injection program: Monongalia County, West Virginia. Electric Power Research Institute, Inc. (EPRI), Allegheny Energy Supply, and the U.S. Department of Energy. Document #1004032. USDOE. Pittsburgh, PA.

Griffiths, J.C., R.J. Hornberger, K. Miller, and M.W. Smith 2001. Statistical analysis of abandoned mine drainage in the assessment of pollution load ("The Griffiths Report"). EPA-821-B-01-014.

Hobba, W.A. 1981. Effects of underground mining and mine collapse on the hydrology of selected basins in WV. USGS, Report of Investigation, RI-33.

Lopez, D.L. and M.W. Stoertz. 2001. Chemical and physical controls on waters discharged from abandoned coal mines. *Geochemistry: Exploration, Environment, Analysis* **1**: 51-60.

O' Driscoll, M.A., D.R. DeWalle, K.J. McGuire, and W.J. Gburek. 2005. Seasonal variations and groundwater recharge for three landscape types in central Pennsylvania, USA. *J. Hydrology*. **303**: 108-124.

Pigati, E., and D. Lopez. 1999. Effect of subsidence on recharge at abandoned coal mines generating acidic drainage: the Majestic Mine, Athens County, OH. *Mine Water and the Environment* **18(1)**: 45-66.

SAS Institute. 1989. SAS. SAS Institute. Cary, NC.

Skousen, J., and P. Ziemkiewicz. 1996. Acid mine drainage control and treatment. National Research Center for Coal and Energy, West Virginia University, Morgantown, WV.

Skousen, J., A. Rose, G. Geidel, J. Foreman, R. Evans, W. Hellier. 1998. Handbook of technologies for avoidance and remediation of acid mine drainage. Acid Drainage Technology Initiative (ADTI) of the U.S. Office of Surface Mining. National Mine Land Reclamation Center, West Virginia University. Morgantown, WV.

Wendland, W.M. 2001. Temporal responses of surface water and groundwater to precipitation in Illinois. *J. American Water Resources Associations*. **37**: 685-693.

WVDEP personal communication.

Table 4-1: Characterization of T&T flows and acidity (1996 to 2003) using Tukey analysis.

Model	Year	Acidity Mean	Flow Category	Acidity Mean	Season	Acidity Mean
Year *FC * Season	1996	1127 ^a	Low	718 ^a	Summer	813 ^a
	1997	914 ^{ab}	Mid	789 ^{ab}	Fall	805 ^a
	1998	700 ^{bc}	High	875 ^b	Winter	811 ^a
	1999	736 ^{bc}			Spring	770 ^a
	2000	871 ^{ab}				
	2001	589 ^c				
	2002	565 ^c				
	2003	1054 ^a				

Table 4-2: Analysis of variance results and model fits for T&T water quality data for 1996 to 2003.

Year * Flow Category * Season		Year * Avg Flow * Season	
	Acidity		Acidity
Mean	800	Mean	800
MSE	150	MSE	125
R ²	0.82	R ²	0.92
Pr>F	0.0007	Pr>F	0.0012
	p-value		p-value
Year	0.0039	Year	0.3915
FC	0.9973	Average Flow	0.8056
Year * FC	0.3202	Year * Avg Flow	0.2780
Season	0.0551	Season	0.6213
Year * Season	0.3577	Year * Season	0.0488
FC * Season	0.7657	Avg Flow * Season	0.7863
Year * FC * Season	na	Year * Avg Flow * Season	0.0830

Table 4-3: Characterization of Omega flows and acidity (2000 to 2003) using summary statistics and Tukey analysis.

Model	Year	Acidity Mean	Flow Category	Acidity Mean	Season	Acidity Mean
Year * FC * Season						
	2000	1616 ^a	Low	1518 ^a	Summer	1256 ^a
	2001	1515 ^a	Mid	1157 ^b	Fall	1317 ^a
	2002	945 ^b	High	1222 ^b	Winter	1206 ^a
	2003	1070 ^b			Spring	1383 ^a

Table 4-4: Analysis of variance results and model fits for Omega water quality data for 2000 to 2003.

Year * Flow Category * Season		Year * Avg Flow * Season	
	Acidity		Acidity
Mean	1294	Mean	1294
MSE	283	MSE	301
R ²	0.82	R ²	0.88
Pr>F	0.0003	Pr>F	0.0190
	p-value		p-value
Year	0.0003	Year	0.2768
FC	0.2173	Average Flow	0.2734
Year * FC	0.0036	Year * Avg Flow	0.4075
Season	0.0682	Season	0.8036
Year * Season	0.1642	Year * Season	0.2611
FC * Season	0.0577	Avg Flow * Season	0.7677
Year * FC * Season	na	Year * Avg Flow * Season	0.3589

Table 4-5: Description of data categories for T&T and Omega using flow categories.

Site	Category	Range	Count
T&T	Low	<300	26
	Mid	300-600	29
	High	>600	29
Omega	Low	<50	15
	Mid	50-100	13
	High	>100	11

Table 4-6. Average flow & acidity for T&T by category

Average values for flow and acidity on a daily basis at the T&T mine divided into year, season and categories. The total cumulative precipitation for year, season, and category is also presented.

Year	Total Cumulative Precip for Year (cm)	Average Flow (L/s)	Average Acidity (mg/L)
1996	166	43	1127
1997	145	36	914
1998	139	37	700
1999	104	19	736
2000	145	31	871
2001	136	37	402
2002	139	37	264
2003	184	34	1054
Season	Avg Precip per Season (cm)	Average Flow (L/s)	Average Acidity (mg/L)
Summer	41	32	813
Fall	31	15	805
Winter	29	30	811
Spring	43	43	770
Flow Category	Avg Precip per day (cm)	Average Flow (L/s)	Average Acidity (mg/L)
Low	0.3	11	718
Mid	0.4	29	789
High	0.5	47	875

Table 4-7. Average flow & acidity for Omega by category

Average values for flow and acidity on a daily basis at the Omega mine divided into year, season and categories. The total cumulative precipitation for year, season, and category is also presented.

Year	Total Cumulative Precip for Year (cm)	Average Flow (L/s)	Average Acidity (mg/L)
2000	124	4	1616
2001	119	5	1515
2002	132	4	945
2003	179	8	1069
Season	Avg Precip per Season (cm)	Average Flow (L/s)	Average Acidity (mg/L)
Summer	48	5	1256
Fall	31	2	1317
Winter	26	6	1206
Spring	34	8	1383
Flow Category	Avg Precip per day (cm)	Average Flow (L/s)	Average Acidity (mg/L)
Low	0.3	2	1518
Mid	0.5	5	1157
High	0.4	10	1221

Table 4-8: Flow rates and acidity amounts at the T&T mine by rainfall event

Flow rates and acidity amounts at the T&T mine following dry periods of no rain along with high rainfall events. Seasonal averages of acidity are Summer = 813 mg/L, Fall = 236 mg/L, Winter = 483 mg/L, and Spring = 712 mg/L.

	Date of Sampling	Days Since Precipitation Event	Precipitation (cm)	Flow (L/s)	Acidity (mg/L)
Winter	14-Dec-1999	4	1.8	7	695
	29-Jan-1997	1	1.5	34	851
	16-Feb-2000	2	2.3	15	1120
Spring	2-Apr-1997	7	3.8	42	766
	9-Apr-2001	2	2.1	28	596
	1-Apr-2003	2	1.3	46	1100
	15-May-1996	6	1.5	64	3580
Summer	26-Jun-1996	1	3.8	33	997
	24-Jul-1996	5	8.6	45	827
	2-Jul-1997	5	6.1	29	822
	7-Jul-1998	6	2.5	31	636
	10-Jul-2001	4	4.3	23	580
	1-Jul-2002	3	2.1	21	600
	7-Aug-1996	7	3.6	41	912
	1-Aug-2000	7	1.8	12	1250
Fall	23-Oct-1996	2	2.0	27	918
	7-Oct-1998	1	2.2	11	664
	1-Oct-2002	4	4.03	8	451
	12-Nov-1996	4	1.5	34	803
	2-Nov-2002	3	2.3	6	440

(continues on next page)

	Date of Sampling	Days of 0 Precip	Precipitation (cm)	Flow (L/s)	Acidity (mg/L)
Winter	18-Dec-1996	3	0	21	1090
	22-Jan-1997	3	0	34	571
Spring	8-Mar-2000	5	0	18	1080
	22-May-1996	3	0	72	3310
	4-May-1999	7	0	19	624
	10-May-2000	4	0	22	623
Summer	5-Jun-1996	5	0	67	1110
	2-Jun-1999	7	0	13	592
	2-Jul-1997	4	0	29	822
	10-Jul-2000	4	0	11	1070
	7-Aug-1996	4	0	41	912
	7-Aug-1998	6	0	23	624
	8-Aug-2001	3	0	13	497
Fall	2-Sep-1997	7	0	18	779
	14-Sep-1999	3	0	6	685
	2-Sep-2002	3	0	6	690
	4-Nov-1996	5	0	33	1820
	7-Nov-2001	3	0	5	696

Table 4-9: Flow rates and acidity amounts at the Omega mine following dry periods of no rain along with high rainfall events.

Seasonal averages of acidity are Summer =1256 mg/L, Fall = 1317 mg/L, Winter = 1206 mg/L, and Spring = 1383 mg/L.

	Date of Sampling	Days Since Precipitation Event	Precipitation (cm)	Flow (L/s)	Acidity (mg/L)
Winter	15-Dec-2000	1	2.4	1.7	1580
	15-Dec-2002	1	1.8	4.7	440
	16-Jan-2002	5	1.8	3.7	590
	24-Feb-2003	1	2.4	18.2	780
Spring	14-Apr-2000	5	1.6	13.2	1880
	16-Apr-2001	4	1.4	13.2	1000
	15-Apr-2002	1	2.3	10.3	780
Summer	15-Jun-2000	7	1.9	5.2	1050
	18-Jun-2001	1	1.9	4.3	1580
	17-Jun-2003	2	3.2	12.1	440
	15-Aug-2001	2	2.5	2.4	1580
	13-Aug-2003	4	1.7	3.7	1320
Fall	15-Nov-2000	5	2.9	1.1	1680
	18-Nov-2003	6	5.2	5.9	440

	Date of Sampling	Days of no precipitation	Precipitation (cm)	Flow (L/s)	Acidity (mg/L)
Winter	15-Jan-2001	4	0	1.5	1730
	9-Feb-2000	3	0	1.4	2230
Spring	15-Mar-2002	7	0	3.5	1040
	15-Mar-2003	3	0	7.0	1510
Summer	15-Jul-2001	3	0	5.5	1410
	12-Aug-2002	5	0	1.8	1300
Fall	13-Oct-2003	7	0	3.3	1200
	15-Nov-2001	7	0	1.1	1460
	18-Nov-2003	4	0	5.9	440

Figure 4-1: Regression analysis of the measured and calculated acidity at the T&T mine site.

Figure 4-2: Regression analysis of the measured and calculated acidity at the Omega mine site.

Figure 4-3: Daily flow and precipitation at the T&T mine site from 10 Nov 1995 to 31 Dec 2003.

Figure 4-4: Daily flow and precipitation at the Omega mine site from 1 Feb 2000 through 31 Dec 2003.

Figure 4-5: Acidity concentrations and flow plotted over time at the T&T mine site using monthly averages.

Figure 4-6: Regression analysis of flow and acidity concentration at the T&T mine site.

Figure 4-7: Acidity concentrations and flow plotted over time at the Omega mine site using monthly averages.

Figure 4-8: Regression analysis of flow and acidity concentration at the Omega mine site.

Figure 4-9: Acidity concentration from 1995 through 2003 years at the T&T mine site.

Figure 4-10: Acidity concentration over seasons at the T&T mine site.

Figure 4-11: Acidity concentrations over months (January to December) at the T&T mine site.

Figure 4-12: Acidity concentrations over flow categories (Low, Mid, and High) with a trend line and regression shown at the T&T mine site.

Figure 4-13: Acidity concentration from 1995 through 2003 years at the Omega mine site.

Figure 4-14: Acidity concentration over seasons at the Omega mine site.

Figure 4-15: Acidity concentrations over months (January to December) at the T&T mine site.

Figure 4-16: Acidity concentrations over flow categories (Low, Mid, and High) at the Omega mine site.

CHAPTER 5: DISSERTATION SUMMARY

The first objective of this research was to determine water quality changes from underground mines over a 30-year period and the second objective was to assess the relationship between discharge rates and acidity concentrations emanating from two underground mines.

A research project was initiated in 1968 which identified and sampled over 150 underground mine discharges in the northern West Virginia coal region. Most of these discharges were coming from unflooded, above-drainage underground mines in the Upper Freeport and Pittsburgh coal seams. The sites were revisited in 1999 and 2000, AND Water samples were collected and analyzed from about 75 of the same discharge points. Based on the completeness of the 1968 data, 44 were chosen for further analysis. Twenty of these 44 sites had been sampled and the water analyzed in 1980, which provided an intermediate sampling time to assess water acidity and iron concentrations from the mine.

In order to meet the second objective data sets for T&T and Omega were gathered through the WVDEP. These data sets were fairly complete in their daily precipitation and flow measurements, along with biweekly water quality analysis. The data sets were used to assess the relationships of precipitation, flow rates, and acidity concentrations.

The foremost conclusion reached is that the majority (34 of 44 sites or 77%) of above-drainage underground mines showed significant improvement in acidity over time, and this is good news for watersheds with numerous underground mine discharges. This information can be used practically when developing restoration plans for a watershed and designing conceptual treatment for a particular discharge. By knowing that water quality will improve over time, it will allow for a better understanding of the necessary long term treatment of a particular discharge and the subsequent effect on the watershed. A 50 to 80% reduction in acidity, iron, and sulfate was found for these mines in northern West Virginia between 1968 and 2000. Of the twenty mines which had measurements of water quality in 1980, five showed that much of the improvement in water chemistry occurred between 1968 and 1980, while 10 others improved more linearly through 2000. However, five of the sites actually showed increased acidity over time. This is evidence that all mines will not behave the same, and widespread conclusions can not be reached. Accurately predicting water quality trends for all above-drainage underground mine sites with time can not be made.

The factors that appear to complicate our prediction capacity are the ongoing changes in the underground mine including collapse of coal pillars left in the mine to support the roof, the potential for the creation of fresh faces of pyrite that can generate more acid products, ever changing flow paths with blockages and mine pools forming at different places and at different times based on seasonal flow, and variability of oxygen and pyrite within the mine over short distances. Additionally, it appears that coal barriers or seals between mines can leak or completely break thereby allowing additional flow and acidity to be introduced to an adjacent mine. Such factors as these are very difficult to measure and account for in our prediction of mine drainage improvement. However, the overall trends can be used for practical purposes or watershed management with caution.

When assessing the relationship of flow and acidity concentration, no clear conclusion can be made. This is contradictory to ideas that exist (dilution vs. flush) and there is no one idea that can be used as a sweeping explanation for what is occurring in these above-drainage underground mines. As with changes over time, there are numerous factors that can affect the water quality emanating from the mine at any given time of year. Some may depend on precipitation events or others may depend on flow rates and still others may not be related to these at all.

Assessment shows that the highest flows occurred in the spring, with lows flows in the fall. Individual precipitation events did not appear to directly affect flow, not even on a delayed basis. Acidity, however, does not show similar trends. Omega did show slight evidence for lower flows having higher acidities, while T&T showed the opposite trend.

Analysis of flow and acidity data from these two mines gave hardly any relationship between flow rates and acidity concentrations. The lessons learned, however, are that generalizations can not be made across all above-drainage mines and additional factors must be analyzed. However, information learned from an individual mine relating the trends of flow to acidity can be used to help in designing treatment systems for remediation of the discharge. By observing seasonal trends or yearly trends, data can be extrapolated to better design the most cost effective treatment system, active or passive.

The results of this study can be used as tools in watershed management. The Appalachian region is plagued by AMD impacted streams and any information that can further the cause of restoration efforts will be welcomed by watershed groups, consultants and government agencies.

Appendix A

MAPS

Area Summary

9 0 9 18 27 Miles

A-1

Area 1

- Sampled points
- Mines
- Area

0.8 0 0.8 1.6 2.4 Miles

A-2

Area 1

● Sampled points
■ Mines

0.8 0 0.8 1.6 2.4 Miles

A-3

Area 2

- Sampled points
- Mines
- Area

0.8 0 0.8 1.6 2.4 Miles

A-4

Area 2

- Sampled points
- Mines

0.8 0 0.8 1.6 2.4 Miles

A scale bar with alternating black and white segments, corresponding to the distances 0.8, 0, 0.8, 1.6, and 2.4 miles.

A-5

Area 3

- Sampled points
- Mines
- Area

0.8 0 0.8 1.6 2.4 Miles

A-6

Area 3

- Sampled points
- Mines

0.8 0 0.8 1.6 2.4 Miles

A-7

Area 4

1 0 1 2 3 Miles

A-8

Area 4

- Sampled points
- Mines

1 0 1 2 3 Miles

A-9

Sampling points

ID	Point name
1	Bull Run 1
2	Bull Run 2
3	Bull Run 3
4	Bull Run 4
5	Bull Run 5
6	Cheat River 1
7	Cheat River 2
8	Cheat River 3
9	Cheat River 4
10	Cheat River 5
11	Cheat River 6
12	Cheat River PA1
13	Cheat River PA2
14	Fickey Run 1
15	Fickey Run 3
16	Fickey Run 5
17	Fickey Run 6
18	Fickey Run 7
19	Fickey Run 8
20	Fickey Run 9
21	Glade Run 1
22	Glade Run 2
23	Glade Run 3
24	Glade Run 4
25	Glade Run 5
26	Green Run 1
27	Green Run 2
28	Green Run 3
29	Lake Lynn 1

ID	Point name
30	Lake Lynn 2
31	Lake Lynn 3
32	Martin Creek 2
33	Martin Creek 3
34	Middle River 1
35	Morgan Run 5
36	Muddy Creek 10
37	Muddy Creek 11
38	Muddy Creek 2
39	Muddy Creek 3
40	Muddy Creek 4
41	Muddy Creek 5
42	Muddy Creek 6
43	Muddy Creek 7
44	Muddy Creek 8
45	Muddy Creek 9
46	Pringle Run 3
47	Pringle Run 2
48	Pringle Run 1
49	Morgan Run 1
50	Morgan Run 3
51	Lick Run 1
52	Morgan Run 2
53	Morgan Run 4
54	Morgan Run 6
55	Martin Creek 1
56	Muddy Creek 1
57	Conner Run 1

Appendix B

Site Descriptions for Underground Mines

Discharge #		Mine Name	Mining Method	Category	Coal Seam	Lat/Long (degree, minute)	Comments from the 1960s Study	Comments from the 2000 Study
Old	New							
170190	Muddy Creek 7	Cuzzart A	I-Strip	Undisturbed	Bakerstown	39,34.3' 79, 37.3'	Kingwood Mining Co., probably active when coal mining was good, numerous auger holes	Numerous benches and abandoned high walls in the area, seep comes directly in the middle of the piles, no iron floc visible
170210	Muddy Creek 6	Cuzzart B	I-Strip	Undisturbed	Upper Freeport	39,34.7' 79,36.7'	Kingwood Mining, very rough, no regrading	Highwalls, numerous seeps, and water in surrounding area, discharge pops up at bottom of large rock pile, flows along bottom of high wall into large wet area, large amount of small particle floc
170240	Muddy Creek 2	Cuzzart C	A-Strip	Undisturbed	Upper Freeport	39,35.4' 79,35.3'	Kingwood Mining, five flows	Mine area now a dump, water seeping out of the side of a collapsed hill where the portal was located, little iron floc
170430	Muddy Creek 4	Cuzzart D	I-Drift	Disturbed	Upper Freeport	39,37.4' 79,34.4'	Guseman Mine	Both sides of the road were surface mined, at bottom of hill is large area of cattails, red floc where discharging, emerges clean at the bottom
170440	Muddy Creek 3	Ruthbell Mg	I-Drift	Disturbed	Upper Freeport	39,35.4' 79,36.7'	Assumed closed to allow for unknown amount of gob reclamation	Sample collected from pipe with a filter net, area covered in gray sand, discharge flowing out of spoil, little floc accumulated on the bottom
170500	Muddy Creek 1	Sugar #1	I-Strip	Undisturbed	Upper Freeport	39,35.7' 79,34.7'	Flow from backfill, Kingwood mining	No comments

Discharge #		Mine Name	Mining Method	Category	Coal Seam	Lat/Long (degree, minute)	Comments from the 1960s Study	Comments from the 2000 Study
Old	New							
170520	Muddy Creek 5	Cuzzart E	I-Strip	Undisturbed	Lower Freeport	39,34.9' 79,37.0'	Kingwood Mining Co, barren, very rough	Small discharge flows into impoundment into a beaver dam, little if no flow pops up out of the ground, little or no floc
170570	Muddy Creek 8	Cuzzart F	I-Strip	Undisturbed	Upper Freeport	39,34.3' 79,36.6'	Kingwood Mining Co, may be reactivated, four seeps from the spoil	Water appears ponded among collapsed sandstone with orange colorations, no floc visible, only seep along the highwall
320030	Cheat River 7	Kingwood C	--	Disturbed	Upper Freeport	--	No comments	Flows over a hilly area, two discharges come together, red stained rocks
320120	Cheat River 8	Bellfield Barnett	--	Undisturbed	Upper Freeport	--	No comments	Flows out of collapsed portal, cows possibly drinking the water, no floc
320240	Pringle Run 3	Kingwood A	--	Undisturbed	Upper Freeport	--	No comments	Wooded area, flows out of collapsed portal, bits of floc
320260	Pringle Run 2	Kingwood B	--	Disturbed	Upper Freeport	--	No comments	Seepy and flowing into and out of gob piles, large wetland, survey conducted, possible clean-up, deep red stains
320270	Pringle Run 1	Reliable #12	--	Undisturbed	Upper Freeport	--	No comments	Water comes off of hill in different places, wetland area that flows into a stream, little floc, red stained rocks
320500	Morgan Run 1	Lucky Jack Slope	--	Disturbed	Upper Freeport	--	No comments	Portal has a pipe directly into it, bright orange floc
320590	Morgan Run 3	Lucky Jack Slope	--	Undisturbed	Upper Freeport	--	No comments	Flows from area above, collapsed portal, flows under road to stream, little to no floc

Discharge #		Mine Name	Mining Method	Category	Coal Seam	Lat/Long (degree, minute)	Comments from the 1960s Study	Comments from the 2000 Study
Old	New							
320850	Lick Run 1	Mary Sara	A-Drift	Disturbed	Upper Freeport	39,29.2' 79,42.9'	Sandy Creek Fuel Owners, pulling pillars	Discharge pumped into a limestone channel, the entire area is surface disturbed, revegetated, large limestone boulders in the stream channel, highwall channeled, red stained rocks
320980	Morgan Run 2	Kingwood D	--	Undisturbed	Upper Freeport	--	No comments	Flows off hill, piped under road to degraded stream, dark purple color
321030	Morgan Run 5	Kingwood E	--	Undisturbed	Upper Freeport	--	No comments	Portal not affected, water seeping up to about 20' from the portal, little floc
321090	Morgan Run 4	Lucky Jack	--	Undisturbed	Upper Freeport	--	No comments	No flow, water was collected at the pool in the portal, could see the timbers and rails, reddish color water
321250	Morgan Run 6	Reams #2	--	Undisturbed	Upper Freeport	--	No comments	Discharge in wooded area, coming from portal area on hill above, portal undisturbed, deep purple water, medium floc
321500	Green Run 1	Beth #4	I-Drift	Undisturbed	Upper Freeport	32,29.4' 79,44.0'	Open but dry	Flows out of old highwall, flows directly to creek, little floc
321580	Green Run 2	Industrial #14	I-Strip	Undisturbed	Upper Freeport	32,29.5' 79,43.3'	Probably okay	Impoundment, no visible flow, orange/red color
321600	Green Run 3	Industrial #14	I-Drift	Disturbed	Upper Freeport	32,29.6' 79,43.2'	Seep from openings sampled	Two portals approximately 20' apart, this one is still flowing, surface mined behind

Discharge #		Mine Name	Mining Method	Category	Coal Seam	Lat/Long (degree, minute)	Comments from the 1960s Study	Comments from the 2000 Study
Old	New							
360870	Bull Run 4	Sherrey	I-Drift	Undisturbed	Upper Freeport	39,33.2' 79,45.2'	Old wet farm mines, owner wants to stay open	Free flowing through wooded area, undisturbed area near farms, medium amount of floc with stained rocks
361090	Bull Run 2	Roxy Ann	I-Drift	Disturbed	Upper Freeport	39,33.2' 79,46.7'	Flow from filled openings	AML site, pipe into the mine, whole site vegetated, discharges down fabric to limestone ditch, stained rocks
361150	Bull Run 1	Kimberly	I-Drift	Disturbed	Upper Freeport	39,34.7' 79,46.5'	Drains mine, has 4' deep trench into one opening	Disturbed, revegetated site, discharges at pipe, down rip-rap, deep purple water, medium amount of orange floc
361280	Cheat River 6	Mountain Run	I-Strip + Drift	Disturbed	Upper Freeport	39,35.8' 79,46.3'	Two okay portals, strip needs disturbed	Collapsed area, impounded water, lots of deep red/orange floc
361320	Middle River 1	Mountain Run	A-Strip + Drift	Disturbed	Upper Freeport	39,34.8' 79,47.2'	Preston Coal Co.	Large area discharging, many portals
361370	Bull River 3	Roxy Ann	I-Drift	Disturbed	Upper Freeport	39,33.4' 79,46.7'	Subsided flow, good access	Flows as a small stream, no floc
380220	Cheat River 5	Canyon Mine	I-Drift	Disturbed	Pittsburgh	39,40.2' 79,55.0'	Caved in, Sand Ridge Coal Co.	Entire hill below cemetery, highwall remains, runs along road, cement ditch to stop erosion, deep red floc
382050	Lake Lynn 1	Hollow Mine	I-Drift	Undisturbed	Pittsburgh	39,40.6' 79,54.4'	Fox Coal Co., reclamation needed	Runs out of rocks, collapsed portal, other areas are dry, garbage around, little fine brown granules
382120	Lake Lynn 3	Canyon Mine	I-Drift	Disturbed	Pittsburgh	39,40.9' 79,53.9'	Canyon Coal Mine, sealed stripped out	Area above and around has been disturbed, ponded water, no floc

Discharge #		Mine Name	Mining Method	Category	Coal Seam	Lat/Long (degree, minute)	Comments from the 1960s Study	Comments from the 2000 Study
Old	New							
382150	Lake Lynn 2	Canyon Mine	I-Drift	Disturbed	Pittsburgh	39,40.2' 79,54.6'	Trenched to drain low spot in the mine	Three discharges from hill piped, deep red floc
382620	Cheat River 4	Morgantown North A	I-Drift	Undisturbed	Pittsburgh	39,41.8' 79,52.7'	Lyman mine first, Tate mine later	Highwall left, little flow, seepy wet area, little floc
383170	Cheat River 1	Morgantown North E	I-Strip	Undisturbed	Pittsburgh	39,43.1' 79,52.7'	Much gob in spoil pile of strip	Seep comes in from rock, flows along road, sampled where emerged, little floc
383180	Cheat River 2	Morgantown North D	A-Drift	Disturbed	Pittsburgh	39,43.0' 79,52.8'	Ray Chess, may also pump	Surface mined, pipe must extend into the mine, discharging at end of disturbed area, area vegetated, large floc granules
383210	Cheat River PA1	Morgantown North B	I-Strip + Drift	Disturbed	Pittsburgh	39,44.8' 79,53.0'	Bertoni and Agelini Coal Co., no reclamation, flows from visible openings, portal under debris	AML project, disturbed ditches, discharge at edge, moss, algae, little floc on the rocks
383230	Cheat River PA2	Morgantown North C	I-Drift	Undisturbed	Pittsburgh	39,44.6' 79,53.2'	Six open, six covered, heavily subsided	Seeps at edge of spoil, swampy area, lots of leaves/garbage, little floc
383630	Cheat River 3	Frederick No. 1 Mine	I-Drift	Disturbed	Pittsburgh	39,41.7' 79,45.0'	Heavy subsidence, Mine Seal #1	Pipe flowing out and spreading to large dead area, lots of floc
590060	Bull Run 5	Terri Lynn	I-Strip + Drift	Undisturbed	Upper Freeport	39,33.6' 79,45.0'	No reclamation, old workings stripped out and drained	Large area with seeps flowing to the stream, entire area has iron precipitation and dead vegetation.
590150	Muddy Creek 11	RuthBell #3	I-Drift	Disturbed	Upper Freeport	39,32.6' 79,37.7'	Ruth Bell Coal Co, at end of syncline, may be tough to seal	AML project, sealed portals into 2 pipes that flow together down limestone/cement ditch, deep red stain on rocks

Discharge #		Mine Name	Mining Method	Category	Coal Seam	Lat/Long (degree, minute)	Comments from the 1960s Study	Comments from the 2000 Study
Old	New							
590200	Martin Creek 3	Me	I-Strip + Drift	Disturbed	Upper Freeport	39,33.2' 79,38.2'	Roughly Disturbed, flow from spoil, large area destroyed, runs like a stream creating large swampy area	Area behind and across surface mined, large amount of deep red floc
590250	Conner Run 1	Rock Bull	I-Strip + Drift	Disturbed	Upper Freeport	39,33.8' 79,40.7'	80% Disturbed	Spoil around area where sample taken, three areas where water coming out of ground, took sample where mix, small amount of large flaked floc
590260	Glade Run 5	Valley Point A	I-Strip + Drift	Disturbed	Upper Freeport	39,34.0' 79,39.7'	Assume need 50% reclamation to cover coal and drift openings	Large area down off of hill, comes out of large spoil area, leaves and floc mixed
590270	Glade Run 4	Valley point B	I-Strip + Drift	Disturbed	Upper Freeport	39,34.2' 79,37.9'	Flow from spoil, area okay	Seep is causing a large dead area with orange coloration, small impoundment near the side of the road, surface mined in the surrounding area
590280	Fickey Run 5	Kambric #36A	I-Drift	Disturbed	Upper Freeport	39,33.9' 79,38.5'	Scattered gob piles, closed by roof fall	SAPS constructed at this site, flows out of portal, precipitation on rocks, light iron coating
590290	Fickey Run 9	Tri State	I-Drift	Disturbed	Upper Freeport	39,33.1' 79,38.1'	R&O Coal Co., flows form two openings and gob pile	Large area like small stream, looks as though flow can be much higher, runs off side hill from surface mined area
590300	Muddy Creek 9	Tri State	A-Drift	Disturbed	Upper Freeport	39,33.4' 79,38.0'	Old Tri State Mine, pillars being pulled by KCD Coal Co.	Water and precipitation is dark purple, flows through limestone channel, directly to Muddy Creek

Discharge #		Mine Name	Mining Method	Category	Coal Seam	Lat/Long (degree, minute)	Comments from the 1960s Study	Comments from the 2000 Study
Old	New							
590340	Fickey Run 2	Tri State	I-Drift	Disturbed	Upper Freeport	39,34.2' 79,38.1'	Portals caved	Area has been surface mined, seep emanates near bottom of tree-line, looks like pond left in, may contain lime
590350	Fickey Run 4	Tri State	I-Drift	Disturbed	Upper Freeport	39,34.2' 79,38.1	Scattered gob, may drain in wet weather, portals caved	Area was/is being treated with lime, ditch runs along bottom of disturbed area, rock wall, cattails, little floc
590360	Fickey Run 1	Valley Point C	I-Drift	Undisturbed	Upper Freeport	39,34.8' 79,37.9	Liston Coal Co., portals caved	Collected sample after mixing of 3 portals and additional seeps, flows into large impoundment, large amount of orange floc coating bottom of the channel
590600	Glade Run 1	Liston	I-Strip + Drift	Disturbed	Upper Freeport	39,35.3' 79,38.1'	Stripped into workings, flow also ran from spoil	Area surrounding has been mined, sample taken at seep out of ground, green algae, no iron floc
590710	Martin Creek 2	Me	I-Drift	Undisturbed	Upper Freeport	39,33.3' 79,39.2'	Caved portals, water flows through gob	Discharge channeled through valley, entire area is swampy, see shiny oil areas (bacteria), little floc
590720	Martin Creek 1	Valley Point D	I-Drift	Disturbed	Upper Freeport	39,33.7' 79,38.5'	Should be backfilled	Water deep purple, low pH, flows as stream from bottom of gob pile, area above and surrounding has been surface mined
590730	Fickey Run 7	#36B	I-Drift	Disturbed	Upper Freeport	39,33.6' 79,38.5'	Near auger holes all wet	Tipple area, water running off hill from collapsed portal, long boney piles in area, runs under road into stream, no floc, orange color in mud

Discharge #		Mine Name	Mining Method	Category	Coal Seam	Lat/Long (degree, minute)	Comments from the 1960s Study	Comments from the 2000 Study
Old	New							
590740	Fickey Run 8	Grooves	I-Drift	Disturbed	Upper Freeport	39,33.3' 79,38.6'	One air shaft, one closed portal	Flows up out of ground at edge of surface mined area, water flow through pipe down over hill to a stream
590750	Fickey Run 6	#36B	I-Drift	Disturbed	Upper Freeport	39,33.8' 79,38.5'	Two covered portals, flows over gob	Free flowing down ditch area, area above all strip mined
590770	Muddy Creek 10	Tri State	I-Drift	Disturbed	Upper Freeport	39,33.1' 79,38.0'	Spring, possible openings	Seep that flows into Muddy Creek, opposite side of road is AML project, hardly flowing, ponded water, floc
590820	Fickey Run	Martin	A-Drift	Disturbed	Upper Freeport	39,34.6' 79,38.1'	Zip Coal Co, gravity flow	Seep from bottom of disturbed area, flows through ditch, dry sometimes during the year
590880	Glade Run 3	Valley Point E	I-Drift	Undisturbed	Upper Freeport	39,35.0' 79,38.2'	Liston Bros Coal, caved openings	Free flow into impoundment, water clear with coarse floc settled out
590890	Glade Run 2	Valley Point F	I-Drift	Undisturbed	Upper Freeport	39,35.1' 79,38.2'	Possible dog holes from mines, two open, one draining	Free flowing from opening, fine iron floc, mixes with small tributary

Stream Information and Study Area

The study area is located in Cheat River Basin in northern West Virginia (Appendix A). The study sites drain to various streams in the USGS quadrangles of Cuzzart, Kingwood, Valley Point, Masontown, and Morgantown North (Appendix A).

The Cheat River Basin lies in the Allegheny Mountains of the Appalachian Plateau, having large parallel ridges separated by mature valleys. The streams in the area are characterized by steep gradients, rocky channels, and high velocities. The geography of the area is dominated by rocks of the Paleozoic Age, with systems in the Pennsylvanian, Mississippian, and Devonian Age. The rocks are massive sandstones, silt and clay shale, limestones, fire clays and coal. Coal beds are dominantly from the Pennsylvanian Age, and are associated with thin and erratic limestone layers, creating little potential for neutralization. The total area of the basin is 3675 km², with the total length of the Cheat River being 250 km. The climate of the area is moderate, with normal variations associated with the latitude and elevation. The average annual temperature is 10°C (50°F) with a summer average of approximately 18°C (65°F) and a winter temperature of 4.5°C (40°F). The normal precipitation within the basin is 115 cm, and an average snowfall of 270 cm near the head, and 80 cm near Morgantown at the mouth (DNR 1982).

The first settlement in the Basin occurred near Bruceton Mills, Preston County in 1769. Up until the 1850s the area was still mostly inaccessible and undeveloped. Coal played a major role in the development of the economic and social environment of the Cheat River Basin. Logging was also an important economic force in the area, which created a greater need for coal as an energy source. During WWI, the demand for coal increased dramatically, but decreased again during the depression. Another surge was seen during WWII with the opening of numerous drift mines and the expansion of surface mining. In recent years, the area has become more recreational, being dominated by hunting, fishing and vacationing (DNR 1982).

Approximately 527 km of streams were affected by coal mine drainage within the Basin in 1971 when an extensive study was conducted to determine where remediation should be focused. The Cheat River consists of five watersheds: Lower Cheat, Big Sandy, Upper Cheat, Shavers Fork, and Blackwater River. This study focused on tributaries of the Upper and Lower Cheat watersheds, where the majority of the pollution is entering the Cheat. The Lower Cheat River drains 440 km² and is located between Albright, West Virginia and Point Marion, PA. In this area there are 14 mineable coals, and many small drift mines exist. During the study in 1971, 191 openings were found from both active and abandoned surface and underground mines. It was determined that 80% of the total net acid load was from inactive mines, contributing 86% of the total acid loads discharging to the Cheat River. Over 232 km of stream were affected in this area, mostly from Muddy Creek, which contributes 25% of the acid load. The Upper Cheat River drains 854 km² and is found from Parsons to Albright, WV. Most of the mining in this area occurred on Upper Freeport coal since the late 1800s. In this area, 213 sites were found, with 25% of the pollution emanating from inactive deep mines. Over 48 km of streams are degraded between Tunnelton and Kingwood (EPA 1971).

The major tributaries contributing most of the pollution to the Cheat River are Muddy Creek, Bull Run, Greens Run, Morgan Run, Pringle Run, Heather Run, and Lick Run. Muddy Creek drains 88 km² and flows 25 km in a westerly direction through Preston County to the Cheat River at Albright. Nine coal beds exist in the Muddy Creek area, with the Upper Freeport and Bakerstown being the most extensively mined. Martin Creek is the big contributor to the degradation of Muddy Creek. Martin has a pH of 6.8 at the headwaters and decreases to 3.2 at the mouth. Martin dumps 75% of the total acidity and iron, along with 80% of the total manganese into Muddy Creek. Other tributaries, such as Fickey and Glade, also adversely affect Muddy Creek. Bull Run drains 45 km² and the area has been extensively mined, and inadequately reclaimed. The main pollution loadings come from Lick Run tributary which is

lined with abandoned mine sites. These streams are sparsely populated, and extensively mined for the Upper Freeport coal. Most of the drainage seeps from old abandoned spoil. Morgan Run drains 15 km² and has been mined for both the Bakerstown and Upper Freeport coals. This stream is dominated by low levels of dissolved oxygen, mainly due to human waste found in the stream. Pringle, Heather, and Lick Run are each heavily affected with AMD 100% of the time, and also contain high levels of iron, manganese, and sulfate. The streams receive drainage from both large abandoned spoils and deep mine portals (EPA 1971).

Coal Beds

The Pittsburgh coal bed is the lowest member of the Monongahela Series. The bed has a low overall sulfur content (1.37%) and also a low ash content (5.48%). It is characterized by its regularity of structure and the uniform purity of composition. The Pittsburgh coal is composed of alternate layers of coal and slate or shale. A typical Pittsburgh coal cross-section shows a 3-m layer of good coal, a 0.7-m layer of bone coal or slaty coal, and another 2-3-m layer of good coal. The Pittsburgh coal located at the Monongahela River, near Morgantown, is located close to the surface (Hennen and Reger 1914).

The Bakerstown coal bed is the lowest mineable coal in the Conemaugh measure of Preston County. It averages only 0.6-m thick. This bed has a low sulfur content (1.84%) and also a low ash content (4.80%). A typical cross-section is a layer of shale, boney coal, good coal, and finally another layer of shale. The Bakerstown coal lays 22 to 30 m below the Ames limestones, and therefore rarely releases AMD during and after surface mining (Hennen and Reger 1914).

The Upper Freeport coal bed is the topmost strata of the Allegheny Formation of the Pennsylvanian System. Freeport coal is uniformly low in sulfur (<1.5%) and has a comparatively low ash content (8 to 12%). It is multiple-bedded and is divided into a top coal and bottom coal, separated by a shale interlayer, all of which average a total of 1.8 m thick (Hennen and Reger 1914). The Allegheny Formation is capped by the Upper Freeport coal, and the overlying strata

in the Conemaugh Group contains several massive sandstones and some shales. Limestone or alkaline-bearing rock units are not generally found within 50 m above the Upper Freeport coal in this area, so very little overlying geologic material is available for acid neutralization.

The Lower Freeport coal bed occurs 14 to 18 m below the top of the Allegheny series. The coal is fairly high in sulfur content (3.5%), but remains relatively low in ash content (15%). It is a multiple bedded bed and ranges from 0.3 to 1.5 m thick. It is generally too thin and worthless for mining in most of Preston County. It was originally mined and used as a domestic fuel by local farmers. An advantage to mining Lower Freeport coal is that it normally has Lower Freeport limestone associated with it, adding alkalinity and neutralization (Hennen and Reger 1914).

The Upper Kittanning coal bed is found 24 to 30 m below the Upper Freeport. It has a relatively high sulfur content (2.37%), but the ash content remains relatively low (10.07%). It is very irregular in its distribution, and often is completely absent. When found, the bed seldom exceeds 1.2 m. The Upper Kittanning bed is double bedded and sometimes multiple bedded. The bed carries a thin layer of parting slate approximately 20 to 30 cm above the base.

Historical and Additional Data

The history of each mine site was researched to gather additional information. Most information was found in the Annual Report of the West Virginia Department of Mines that have been submitted since the 1800s on active operations. The Report contains the mine name, operator name, tons of coal removed, the number of employees, injuries, etc. We were able to track some of the mines for their entire working period, and others, due to name changes, were impossible to find. Other information was found at the West Virginia Geologic and Economic Survey in Morgantown, WV. Mine maps were found with outlines of the underground mine workings, coal outcrops and coal bed depths. The maps were used to determine which mine was

being sampled in 1968. We also obtained additional information from the Mine Map Repository in Pittsburgh, Pennsylvania.

The mine sites we investigated are listed above in table format, along with their associated discharge points. The discharges are labeled according to the particular stream into which they discharge. Some of the mines discharge water at more than one location. The discharges from the same mine pool may differ in chemistry due to varying flow paths within the mines, but the overall trends are related.

Appendix C

Water Quality Results for Underground Mines for 1968, 1980, 1999-2000

Year	pH (SU)	Flow (L/min)	Acidity (mg/L)	Acidity (kg/day)	Alkalinity (mg/L)	Iron (mg/L)	Iron (kg/day)	Aluminum (mg/L)	Manganese (mg/L)	Calcium (mg/L)	Sulfate (mg/L)	Conductivity (umhos/cm)
Bull Run 1, Upper Freeport, Masontown, Disturbed												
1968	2.4	37	2805	145	0	800	41	260			3458	3750
2000	2.9	19	1401	37	0	205	5	94	3	120	2055	1480
Bull Run 2, Upper Freeport, Masontown, Disturbed												
1968	2.4	4	1905	44	0	394	9	87			2561	3063
2000	2.9	16	756	4	0	126	1	45	1	109	1644	1730
Bull Run 3, Upper Freeport, Masontown, Disturbed												
1968	3.2	19	640	15	0	57	1	37			663	1826
2000	7.5	17	0	0	1772	2	0	1	1	187	687	1140
Bull Run 4, Upper Freeport, Masontown, Undisturbed												
1968	3.3	11	250	4	0	82	1	1			556	1066
2000	3	28	530	21	0	48	2	44	8	453	1199	2600
Bull Run 5, Upper Freeport, Valley Point, Undisturbed												
1968	2.9	56	1370	108	0	624	50	67			3276	3520
1999	3	94	336	44	0	15	2	36	27	200		2200
Cheat River 1, Pittsburgh, Morgantown North, Undisturbed												
1968	2.9	1	8818	18	0	366	1	90			7150	8106
2000	2.1	56	1428	113	0	201	16	49	5	130	1519	2700
Cheat River 2, Pittsburgh, Morgantown North, Disturbed												
1968	3.3	12	1061	17	0	258	4	320			9750	9282
2000	2.2	15	1033	22	0	203	4	54	10	103	1817	3000
Cheat River 3, Pittsburgh, Morgantown North, Disturbed												
1968	2.6	7	3300	35	0	600	6	142			3848	4324
2000	3.1	30	1369	59	0	200	8	77	5	77	1773	2200
Cheat River 4, Pittsburgh, Morgantown North, Undisturbed												
1968	3.1	19	3603	95	0	824	22	65			4238	4614
2000	2.7	4	431	2	0	19	0	41	5	149	917	1260
Cheat River 5, Pittsburgh, Morgantown North, Disturbed												
1968	2.6	19	1825	48	0	458	12	101			2392	3097
1980	2.6					25			10		1100	2100

Year	pH (SU)	Flow (L/min)	Acidity (mg/L)	Acidity (kg/day)	Alkalinity (mg/L)	Iron (mg/L)	Iron (kg/day)	Aluminum (mg/L)	Manganese (mg/L)	Calcium (mg/L)	Sulfate (mg/L)	Conductivity (umhos/cm)
Cheat River 6, Upper Freeport, Masontown, Disturbed												
1968	2.6	78	1450	154	0	28	31	104			1612	2442
2000	2.8	38	487	26	0	48	3	46	2	56	775	3000
Cheat River 7, Upper Freeport, Kingwood, Disturbed												
2000	3.3	19	101	3	0	17	1	14	1	34	176	720
Cheat River 8, Upper Freeport, Kingwood, Undisturbed												
1968		4										
2000	5	6	0	0	42	1	0	1	1	16	22	130
Cheat River PA1, Pittsburgh, Morgantown North, Disturbed												
1968	3.3	298	2457	1027	0	449	188	141			2602	3078
2000	3.7	22	563	18	0	78	2	34	5	79	833	2100
Cheat River PA2, Pittsburgh, Morgantown North, Undisturbed												
1968	2.7	12	4310	77	0	852	15	282			4550	4880
2000	3.1	4	1314	7	0	96	1	84	6	42	1237	2700
Conner Run 1, Upper Freeport, Valley Point, Disturbed												
1999	3.1	19	88	0	0	4	1	7	8	85		1870
2000	3.3	19	215	6	0	2	1	28	18	219		
Fickey Run 1, Upper Freeport, Valley Point, Undisturbed												
1968	3	6	3270	26	0	672	5	180			3744	4047
1999	3.3	113	154	25	0	7	1	5	3	172	1883	1460
Fickey Run 2, Upper Freeport, Valley Point, Disturbed												
1968		0										
1999	6.2	37.8	162	9	84	75	4	1	15	312		260
Fickey Run 3, Upper Freeport, Valley Point, Disturbed												
1968	2.9	31	420	12	0	82	2	7			1456	2539
1999	2.8	189	3694	977	0	194	51	168	22	252		560
Fickey Run 4, Upper Freeport, Valley Point, Disturbed												
1968		0										
1999	6.8	4	0	0	217	3	1	1	9			310
Fickey Run 5, Upper Freeport, Valley Point, Disturbed												
1968	3.1	9	515	7	0	88	1	24			585	1463
1980	2.5	1	460	1	0	42	1		0		500	493

Year	pH (SU)	Flow (L/min)	Acidity (mg/L)	Acidity (kg/day)	Alkalinity (mg/L)	Iron (mg/L)	Iron (kg/day)	Aluminum (mg/L)	Manganese (mg/L)	Calcium (mg/L)	Sulfate (mg/L)	Conductivity (umhos/cm)
Fickey Run 6, Upper Freeport, Valley Point, Disturbed												
1968	2.4	1	1300	0	0	288	1	112			1456	
1999	3.6	11	118	2	1	13	1	1	2	307	1249	
Fickey Run 7, Upper Freeport, Valley Point, Disturbed												
1968	2.8	3	1670	7	0	237	78	157			2007	2997
1999	2.2	56	1086	86	0	19	1	78	12	194	1118	2200
Fickey Run 8, Upper Freeport, Valley Point, Disturbed												
1968	3	49	1505	103	0	288	20	84			1872	2671
1980	2.3	1	625	1	0	120	1		1.2		100	1700
Fickey Run 9, Upper Freeport, Valley Point, Disturbed												
1968	2.8	17	1920	45	0	378	9	88			1501	3400
Spr												
1999	2.6	19	498	13	0	16	1	42	42	283	1311	3300
Glade Run 1, Upper Freeport, Valley Point, Disturbed												
1968	3.1	15	1705	36	0	228	5	146			2626	3000
1999	3.2	4	151	1	0	7	1	14	1	31	170	850
Glade Run 2, Upper Freeport, Valley Point, Undisturbed												
1968	3.6	4	390	2	0	53	1	29			702	1374
1999	4.3	19	179	5	2.5	17	1	40	2	64	520	440
Glade Run 3, Upper Freeport, Valley Point, Undisturbed												
1968	2.8	11	675	11	0						1118	2208
1999	3.8	11	412	7	0	37	1	53	2	72	368	1110
Glade Run 4, Upper Freeport, Valley Point, Disturbed												
1968	2.9	19										
1980	2.7	0	285	0	0	6	0		1		560	484
Glade Run 5, Upper Freeport, Valley Point, Disturbed												
1968			1765		0	158		150			2184	2991
1999	3.6	8	283	3	0	4	1	33	25	300		1990
Green Run 1, Upper Freeport, Kingwood, Undisturbed												
1968		6										
2000	2.2	25	702	6	0	117	1	42	3	61		1900
Green Run 2, Upper Freeport, Kingwood, Undisturbed												
1968	4		8		6	1	0	1			14	80
2000	4.5	1	4	0	13	6	0	2	1	13	47	20

Year	pH (SU)	Flow (L/min)	Acidity (mg/L)	Acidity (kg/day)	Alkalinity (mg/L)	Iron (mg/L)	Iron (kg/day)	Aluminum (mg/L)	Manganese (mg/L)	Calcium (mg/L)	Sulfate (mg/L)	Conductivity (umhos/cm)
Green Run 3, Upper Freeport, Kingwood, Disturbed												
1968	2.5		1504		0	288		108			1508	2104
2000	2.1	30	1932	82	0	203	9	121	14	30	1521	3000
Lake Lynn 1, Pittsburgh, Morgantown North, Undisturbed												
1968	2.8	38	1368	72	0	495	26	100			8861	1320
1980	2	1	605	1	0	90	1		2		1000	2060
Lake Lynn 2, Pittsburgh, Morgantown North, Disturbed												
1968	3.2	38	4690	248	0	131	7	302			1105	5550
1980	2	1	3800	1	0	1000	1		0		960	5660
Lake Lynn 3, Pittsburgh, Morgantown North, Disturbed												
1968	3.1	480	4988	3352	0	477	321	532			2593	5847
1980	2	1	1930	1	0	350	1		8	2600	3690	
Lick Run 1, Upper Freeport, Kingwood, Disturbed												
2000	2.2	19	1409	38	0	200	5	106	2	131	226	3100
Martin Creek 1, Upper Freeport, Valley Point, Undisturbed												
1999	2.6	30	1479	63	0	131	6	81	3	96	770	2500
Martin Creek 2, Upper Freeport, Valley Point, Undisturbed												
1968	2.7	57	2315	184	0	640	51	161			990	3047
1980	2.4	1	545	1	0	80	1		0		1100	1832
Martin Creek 3, Upper Freeport, Valley Point, Disturbed												
1968	3	6	490	4	0	105	1	17			520	1250
1999	5.5	57	253	20	80	70	6	1	19	346	1543	210
Middle River 1, Upper Freeport, Masontown, Disturbed												
1968	2.7	334	917	430	0	165	78	46			2405	2131
2000	3.2	38	291	15	0	23	1	30	1	56	578	2600
Morgan Run 1, Upper Freeport, Kingwood, Disturbed												
2000	3.5	38	104	6	0	1	1	1	1	22	36	1030
Morgan Run 2, Upper Freeport, Kingwood, Undisturbed												
1968		161										
2000	2.5	95	93	13	0	5	1	1	1	130	561	1290
Morgan Run 2, Upper Freeport, Kingwood, Undisturbed												
2000	3.9	28	72	3	9	2	1	13	1	105		1070
Morgan Run 4, Upper Freeport, Kingwood, Undisturbed												
2000	2.1	0	588	6	0	93	0	32	11	41	631	2200

Year	pH (SU)	Flow (L/min)	Acidity (mg/L)	Acidity (kg/day)	Alkalinity (mg/L)	Iron (mg/L)	Iron (kg/day)	Aluminum (mg/L)	Manganese (mg/L)	Calcium (mg/L)	Sulfate (mg/L)	Conductivity (umhos/cm)
Morgan Run 5, Upper Freeport, Kingwood, Undisturbed												
1968		4		39	0		12					
2000	2.5	6	459	4	0	18	1	59	15	47	347	1440
Morgan Run 6, Upper Freeport, Kingwood, Undisturbed												
1968		12										
2000	2.2	47	597	39	0	112	7	30	2	9	645	1780
Muddy Creek 1, Upper Freeport, Valley Point, Undisturbed												
1968	3.6	9										
1999	3.7	4	145	1	0	1	1	3	1	10		160
Muddy Creek 2, Upper Freeport, Cuzzart, Undisturbed												
1968	2.8	317	687	305	0	116	52	14			1878	2425
1980	2.1	1	1200	1	0	120	1		1		100	1700
Muddy Creek 3, Upper Freeport, Cuzzart, Disturbed												
1968	3.3	4	170	1	0	1	0	6			377	876
2000	5.3	30	45	2	30	0	1	1	1	32	111	2200
Muddy Creek 4, Upper Freeport, Cuzzart, Surface Disturbed												
1968	5.8	8			35	1	0	6			455	966
2000	5.6	4	108	1	92	4	1	1	2	166	703	1230
Muddy Creek 5, Lower Freeport, Cuzzart, Undisturbed												
1968	6.5	4	20	0	150	8	1	1			13	122
2000	5.5	4	30	1	15	7	1	1	1	8	39	600
Muddy Creek 6, Upper Freeport, Cuzzart, Undisturbed												
1968	2.7	11	4400	70	0	110	2	266			6045	4900
2000	4.5	4	92	1	25	5	1	1	5	35	147	3300
Muddy Creek 7, Bakerstown, Cuzzart, Disturbed												
1968	3.1	158	520	115	0	86.6	19				1300	2240
2000	5.2	8	7	1		0	0	1	1	8	15	400
Muddy Creek 8, Upper Freeport, Cuzzart, Undisturbed												
1968	7.4	8	565	6	15	63	1	41			41	1349
2000	6.6	4	23	1	9	1	0	1	3	15	34	
Muddy Creek 9, Upper Freeport, Valley Point, Disturbed												
1968	2.9	102	1515	216	0	422	60	301			1951	2687
1980	2.2	1	1225	3	0	80	1		20		2200	3310

Year	pH (SU)	Flow (L/min)	Acidity (mg/L)	Acidity (kg/day)	Alkalinity (mg/L)	Iron (mg/L)	Iron (kg/day)	Aluminum (mg/L)	Manganese (mg/L)	Calcium (mg/L)	Sulfate (mg/L)	Conductivity (umhos/cm)
Muddy Creek 10, Upper Kittanning, Valley Point, Disturbed												
1968	2.9	68	1440	137	0	120	11	139			2080	
1999	5.1	8	87	1	34	13	1	8	2	30		160
Muddy Creek 11, Upper Freeport, Valley Point, Disturbed												
1968	2.6	1134	2140	3397	0	576	914	108			2704	4002
1980	2.4	1	634	1	0	85	1		1.5		1200	2120
Pringle Run 1, Upper Freeport, Kingwood, Undisturbed												
2000	5.6	19	0	0	129	6	1	2	1	62	48	450
Pringle Run 2, Upper Freeport, Kingwood, Disturbed												
1968		2										
2000	3.5	75	236	26	0	6	2	28	2	25	1387	1130
Pringle Run 3, Upper Freeport, Kingwood, Undisturbed												
2000	4.1	28	0	0	29	4	1	1	2	21	37	170

Appendix D

ANOVA Results for Flow and Acidity Models for T&T and Omega

T&T ANOVA RESULTS

Model : Flow Category * Year

The GLM Procedure

Class Level Information

Class	Levels	Values
Year	8	1996 1997 1998 1999 2000 2001 2002 2003
flowCategory	3	1 2 3

Number of observations 66

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	20	2181298.795	109064.940	3.54	0.0002
Error	45	1387479.223	30832.872		
Corrected Total	65	3568778.017			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.611217	21.93653	175.5929	800.4589

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Year	7	1843288.952	263326.993	8.54	<.0001
flowCategory	2	9631.970	4815.985	0.16	0.8559
Year*flowCategory	11	328377.873	29852.534	0.97	0.4880

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Year	7	964846.2771	137835.1824	4.47	0.0008
flowCategory	2	30474.3948	15237.1974	0.49	0.6133
Year*flowCategory	11	328377.8728	29852.5339	0.97	0.4880

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	45
Error Mean Square	30832.87
Critical Value of Studentized Range	4.49390
Minimum Significant Difference	308.5
Harmonic Mean of Cell Sizes	6.542751

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Year
A	1127.41	6	1996
A			
A	1054.00	3	2003
A			
B A	914.43	11	1997
B A			
B A C	871.37	11	2000
B C			
B C	736.32	11	1999
B C			
B C	700.15	10	1998
C			
C	589.56	10	2001
C			
C	565.84	4	2002

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	45
Error Mean Square	30832.87
Critical Value of Studentized Range	3.42751
Minimum Significant Difference	128.9
Harmonic Mean of Cell Sizes	21.79931

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	flow Category
A	875.52	25	3
A			
B A	789.26	21	2
B			
B	718.39	20	1

Model: Flow Category * Year* Season

The GLM Procedure

Class Level Information

Class	Levels	Values
Year	8	1996 1997 1998 1999 2000 2001 2002 2003
flowCategory	3	1 2 3
season	4	1 2 3 4

Number of observations 66

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	38	2953894.248	77734.059	3.41	0.0007
Error	27	614883.769	22773.473		
Corrected Total	65	3568778.017			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.827705	18.85279	150.9088	800.4589

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Year	7	1843288.952	263326.993	11.56	<.0001
flowCategory	2	9631.970	4815.985	0.21	0.8107
Year*flowCategory	11	328377.873	29852.534	1.31	0.2714
season	3	57951.276	19317.092	0.85	0.4797
Year*season	13	702366.747	54028.211	2.37	0.0282
flowCategory*season	2	12277.431	6138.715	0.27	0.7657
Year*flowCate*season	0	0.000	.	.	.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Year	7	639977.7947	91425.3992	4.01	0.0039
flowCategory	2	121.2639	60.6320	0.00	0.9973
Year*flowCategory	5	140639.3247	28127.8649	1.24	0.3202
season	3	195841.4943	65280.4981	2.87	0.0551
Year*season	10	264360.3880	26436.0388	1.16	0.3577
flowCategory*season	2	12277.4307	6138.7153	0.27	0.7657
Year*flowCate*season	0	0.0000	.	.	.

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	27
Error Mean Square	22773.47
Critical Value of Studentized Range	4.63783
Minimum Significant Difference	273.62
Harmonic Mean of Cell Sizes	6.542751

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Year
A	1127.41	6	1996
A			
A	1054.00	3	2003
A			
B A	914.43	11	1997
B A			
B A	871.37	11	2000
B			
B C	736.32	11	1999
B C			
B C	700.15	10	1998
C			
C	589.56	10	2001
C			
C	565.84	4	2002

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	27
Error Mean Square	22773.47
Critical Value of Studentized Range	3.50643
Minimum Significant Difference	113.33
Harmonic Mean of Cell Sizes	21.79931

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	flow Category
A	875.52	25	3
A			
B A	789.26	21	2
B			
B	718.39	20	1

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	27
Error Mean Square	22773.47
Critical Value of Studentized Range	3.87009
Minimum Significant Difference	146.41
Harmonic Mean of Cell Sizes	15.9116

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	season
A	813.28	20	1
A			
A	811.40	12	3
A			
A	805.43	18	2
A			
A	770.63	16	4

Model: Average Flow * Year

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	15	1941881.864	129458.791	3.98	0.0001
Error	50	1626896.154	32537.923		
Corrected Total	65	3568778.017			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.544131	22.53491	180.3827	800.4589

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Year	7	1843288.952	263326.993	8.09	<.0001
AvgFlowA	1	8123.389	8123.389	0.25	0.6195
AvgFlowA*Year	7	90469.523	12924.218	0.40	0.8995

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Year	7	347663.7816	49666.2545	1.53	0.1801
AvgFlowA	1	11403.5042	11403.5042	0.35	0.5565
AvgFlowA*Year	7	90469.5231	12924.2176	0.40	0.8995

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	50
Error Mean Square	32537.92
Critical Value of Studentized Range	4.47270
Minimum Significant Difference	315.42
Harmonic Mean of Cell Sizes	6.542751

NOTE: Cell sizes are not equal.
Means with the same letter are not significantly different.

Tukey Grouping			Mean	N	Year
	A		1127.41	6	1996
	A				
	A		1054.00	3	2003
	A				
B	A		914.43	11	1997
B	A				
B	A	C	871.37	11	2000
B		C			
B		C	736.32	11	1999
B		C			
B		C	700.15	10	1998
		C			
		C	589.56	10	2001
		C			
		C	565.84	4	2002

Model: Average Flow * Year * Season

The GLM Procedure
Class Level Information

Class	Levels	Values
Year	8	1996 1997 1998 1999 2000 2001 2002 2003
season	4	1 2 3 4

Number of observations 66

The GLM Procedure
Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	49	3316984.570	67693.563	4.30	0.0012
Error	16	251793.447	15737.090		
Corrected Total	65	3568778.017			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.929445	15.67196	125.4476	800.4589

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Year	7	1843288.952	263326.993	16.73	<.0001
season	3	10102.032	3367.344	0.21	0.8852
Year*season	17	905707.161	53276.892	3.39	0.0094
AvgFlowA	1	21199.416	21199.416	1.35	0.2628
AvgFlowA*Year	6	86763.849	14460.641	0.92	0.5068
AvgFlowA*season	3	53038.015	17679.338	1.12	0.3691
AvgFlowA*Year*season	12	396885.145	33073.762	2.10	0.0830

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Year	6	106250.2720	17708.3787	1.13	0.3915
season	3	28560.6838	9520.2279	0.60	0.6213
Year*season	12	458391.9798	38199.3316	2.43	0.0498
AvgFlowA	1	985.4433	985.4433	0.06	0.8056
AvgFlowA*Year	6	131182.9619	21863.8270	1.39	0.2780
AvgFlowA*season	3	16751.1496	5583.7165	0.35	0.7863
AvgFlowA*Year*season	12	396885.1454	33073.7621	2.10	0.0830

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	15737.09
Critical Value of Studentized Range	4.89622
Minimum Significant Difference	240.13
Harmonic Mean of Cell Sizes	6.542751

Means with the same letter are not significantly different.

Tukey Grouping			Mean	N	Year
	A		1127.41	6	1996
	A				
B	A		1054.00	3	2003
B	A				
B	A	C	914.43	11	1997
B		C			
B		C	871.37	11	2000
		C			
	D	C	736.32	11	1999
	D	C			
	D	C	700.15	10	1998
	D				
	D		589.56	10	2001
	D				
	D		565.84	4	2002

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	16
Error Mean Square	15737.09
Critical Value of Studentized Range	4.04609
Minimum Significant Difference	127.25
Harmonic Mean of Cell Sizes	15.9116

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	season
A	813.28	20	1
A			
A	811.40	12	3
A			
A	805.43	18	2
A			
A	770.63	16	4

Model: Average Flow * Month

The GLM Procedure
Class Level Information

Class	Levels	Values
Month	12	1 2 3 4 5 6 7 8 9 10 11 12

Number of observations 66

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	1232293.582	53577.982	0.96	0.5261
Error	42	2336484.436	55630.582		
Corrected Total	65	3568778.017			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.345298	29.46577	235.8614	800.4589

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Month	11	124383.9548	11307.6323	0.20	0.9965
AvgFlowA	1	631212.9196	631212.9196	11.35	0.0016
AvgFlowA*Month	11	476696.7072	43336.0643	0.78	0.6587

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Month	11	326589.4775	29689.9525	0.53	0.8691
AvgFlowA	1	441620.8258	441620.8258	7.94	0.0073
AvgFlowA*Month	11	476696.7072	43336.0643	0.78	0.6587

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	42
Error Mean Square	55630.58
Critical Value of Studentized Range	4.89022
Minimum Significant Difference	501.55
Harmonic Mean of Cell Sizes	5.288562

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Month
A	854.4	7	7
A			
A	843.3	6	11
A			
A	837.6	4	12
A			
A	834.7	5	3
A			
A	833.4	6	6
A			
A	799.6	4	1
A			
A	796.9	4	2
A			
A	793.3	6	9
A			
A	779.8	6	4
A			
A	779.7	6	10
A			
A	754.9	7	8
A			
A	695.6	5	5

Model: Flow Category * Average Precipitation

The GLM Procedure

Class Level Information

Class	Levels	Values
flowCategory	3	1 2 3

Number of observations 66

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	336768.162	67353.632	1.25	0.2973
Error	60	3232009.855	53866.831		
Corrected Total	65	3568778.017			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.094365	28.99491	232.0923	800.4589

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AvgPrecip	1	7200.1966	7200.1966	0.13	0.7159
flowCategory	2	277676.6397	138838.3198	2.58	0.0844
AvgPrecip*flowCatego	2	51891.3262	25945.6631	0.48	0.6201

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AvgPrecip	1	222.4910	222.4910	0.00	0.9490
flowCategory	2	152861.2224	76430.6112	1.42	0.2500
AvgPrecip*flowCatego	2	51891.3262	25945.6631	0.48	0.6201

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	60
Error Mean Square	53866.83
Critical Value of Studentized Range	3.39867
Minimum Significant Difference	168.95
Harmonic Mean of Cell Sizes	21.79931

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	flow Category
A	875.52	25	3
A			
A	789.26	21	2
A			
A	718.39	20	1

Model: Average Flow * Average Precipitation

The GLM Procedure

Number of observations 66

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	327600.331	109200.110	2.09	0.1108
Error	62	3241177.687	52277.059		
Corrected Total	65	3568778.017			

	R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean		
	0.091796	28.56384	228.6418	800.4589		
Source	DF	Type I SS	Mean Square	F Value	Pr > F	
AvgPrecip	1	7200.1966	7200.1966	0.14	0.7118	
AvgFlowA	1	286402.2625	286402.2625	5.48	0.0225	
AvgPrecip*AvgFlowA	1	33997.8714	33997.8714	0.65	0.4231	
Source	DF	Type III SS	Mean Square	F Value	Pr > F	
AvgPrecip	1	18278.0432	18278.0432	0.35	0.5565	
AvgFlowA	1	156281.3955	156281.3955	2.99	0.0888	
AvgPrecip*AvgFlowA	1	33997.8714	33997.8714	0.65	0.4231	

Omega ANOVA Results

Model: Flow Category * Year

The GLM Procedure
Class Level Information

Class	Levels	Values
Year	4	2000 2001 2002 2003
flowCategory	3	1 2 3

Number of observations 43

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	10	5957030.279	595703.028	5.01	0.0002
Error	32	3806814.000	118962.938		
Corrected Total	42	9763844.279			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.610111	26.64211	344.9100	1294.605

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Year	3	3453391.370	1151130.457	9.68	0.0001
flowCategory	2	533259.955	266629.977	2.24	0.1228
Year*flowCategory	5	1970378.955	394075.791	3.31	0.0160

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Year	3	2956390.655	985463.552	8.28	0.0003
flowCategory	2	554725.836	277362.918	2.33	0.1134
Year*flowCategory	5	1970378.955	394075.791	3.31	0.0160

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	32
Error Mean Square	118962.9
Critical Value of Studentized Range	3.83162
Minimum Significant Difference	403.42
Harmonic Mean of Cell Sizes	10.73171

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Year
A	1616.4	11	2000
A			
A	1515.5	11	2001
B	1069.8	11	2003
B			
B	945.0	10	2002

Model: Flow category * Year * Season

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	32
Error Mean Square	118962.9
Critical Value of Studentized Range	3.47525
Minimum Significant Difference	317.77
Harmonic Mean of Cell Sizes	14.22801

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey Grouping		Mean	N	flow Category
A		1518.7	14	1
A				
B	A	1221.8	13	3
B				
B		1157.6	16	2

-

The GLM Procedure

Class Level Information

Class	Levels	Values
Year	4	2000 2001 2002 2003
flowCategory	3	1 2 3
season	4	1 2 3 4

Number of observations 43

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	21	8078496.946	384690.331	4.79	0.0003
Error	21	1685347.333	80254.635		
Corrected Total	42	9763844.279			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.827389	21.88255	283.2925	1294.605

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Year	3	3453391.370	1151130.457	14.34	<.0001
flowCategory	2	533259.955	266629.977	3.32	0.0558
Year*flowCategory	5	1970378.955	394075.791	4.91	0.0039
season	3	653765.360	217921.787	2.72	0.0706
Year*season	7	1144292.973	163470.425	2.04	0.0980
flowCategory*season	1	323408.333	323408.333	4.03	0.0577
Year*flowCate*season	0	0.000	.	.	.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Year	3	2353955.541	784651.847	9.78	0.0003
flowCategory	2	263702.476	131851.238	1.64	0.2173
Year*flowCategory	2	1197477.333	598738.667	7.46	0.0036
season	3	662394.684	220798.228	2.75	0.0682
Year*season	4	581733.896	145433.474	1.81	0.1642
flowCategory*season	1	323408.333	323408.333	4.03	0.0577
Year*flowCate*season	0	0.000	.	.	.

-

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	21
Error Mean Square	80254.63
Critical Value of Studentized Range	3.94188
Minimum Significant Difference	340.88
Harmonic Mean of Cell Sizes	10.73171

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Year
A	1616.4	11	2000
A			
A	1515.5	11	2001
B	1069.8	11	2003
B			
B	945.0	10	2002

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	21
Error Mean Square	80254.63
Critical Value of Studentized Range	3.56463
Minimum Significant Difference	267.72
Harmonic Mean of Cell Sizes	14.22801

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	flow
			Category
A	1518.7	14	1
B	1221.8	13	3
B			
B	1157.6	16	2

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	21
Error Mean Square	80254.63
Critical Value of Studentized Range	3.94188
Minimum Significant Difference	342.49
Harmonic Mean of Cell Sizes	10.63087

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	season
A	1383.0	12	4
A			
A	1317.5	11	2
A			
A	1256.7	9	1
A			
A	1206.4	11	3

Model: Average Flow * Year

The GLM Procedure
Class Level Information

Class	Levels	Values
Year	4	2000 2001 2002 2003

Number of observations 43

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	4181366.860	597338.123	3.75	0.0040
Error	35	5582477.419	159499.355		
Corrected Total	42	9763844.279			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.428250	30.84909	399.3737	1294.605

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Year	3	3453391.370	1151130.457	7.22	0.0007
AvgFlowA	1	586822.922	586822.922	3.68	0.0633
AvgFlowA*Year	3	141152.568	47050.856	0.29	0.8287

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Year	3	655850.5074	218616.8358	1.37	0.2678
AvgFlowA	1	516055.2653	516055.2653	3.24	0.0807
AvgFlowA*Year	3	141152.5685	47050.8562	0.29	0.8287

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	35
Error Mean Square	159499.4
Critical Value of Studentized Range	3.81400
Minimum Significant Difference	464.97
Harmonic Mean of Cell Sizes	10.73171

NOTE: Cell sizes are not equal.

Means with the same letter are not significantly different.

Tukey Grouping		Mean	N	Year
	A	1616.4	11	2000
	A			
B	A	1515.5	11	2001
B				
B	C	1069.8	11	2003
	C			
	C	945.0	10	2002

Model: Average Flow * Year * Season

The GLM Procedure

Class Level Information

Class	Levels	Values
Year	4	2000 2001 2002 2003
season	4	1 2 3 4

Number of observations 43

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	30	8671627.919	289054.264	3.18	0.0190
Error	12	1092216.360	91018.030		
Corrected Total	42	9763844.279			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.888137	23.30379	301.6919	1294.605

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Year	3	3453391.370	1151130.457	12.65	0.0005
season	3	325752.207	108584.069	1.19	0.3539
Year*season	9	2161147.369	240127.485	2.64	0.0600
AvgFlowA	1	212168.361	212168.361	2.33	0.1527
AvgFlowA*Year	3	630945.636	210315.212	2.31	0.1281
AvgFlowA*season	3	990693.347	330231.116	3.63	0.0452
AvgFlowA*Year*season	8	897529.628	112191.204	1.23	0.3589

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Year	3	396460.002	132153.334	1.45	0.2768
season	3	90190.494	30063.498	0.33	0.8036
Year*season	8	1076419.707	134552.463	1.48	0.2611
AvgFlowA	1	119911.204	119911.204	1.32	0.2734
AvgFlowA*Year	3	285768.012	95256.004	1.05	0.4075
AvgFlowA*season	3	104763.584	34921.195	0.38	0.7667
AvgFlowA*Year*season	8	897529.628	112191.204	1.23	0.3589

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	91018.03
Critical Value of Studentized Range	4.19852
Minimum Significant Difference	386.66
Harmonic Mean of Cell Sizes	10.73171

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Year
A	1616.4	11	2000
A			
A	1515.5	11	2001
B	1069.8	11	2003
B			
B	945.0	10	2002

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	91018.03
Critical Value of Studentized Range	4.19852
Minimum Significant Difference	388.49
Harmonic Mean of Cell Sizes	10.63087

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	season
A	1383.0	12	4
A			
A	1317.5	11	2
A			
A	1256.7	9	1
A			
A	1206.4	11	3

Model: Average flow * Month

The GLM Procedure

Class Level Information

Class	Levels	Values
Month	12	1 2 3 4 5 6 7 8 9 10 11 12

Number of observations 43

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	5177071.292	225090.056	0.93	0.5682
Error	19	4586772.987	241409.105		
Corrected Total	42	9763844.279			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.530229	37.95244	491.3340	1294.605

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Month	11	1737070.279	157915.480	0.65	0.7623
AvgFlowA	1	1973392.644	1973392.644	8.17	0.0100
AvgFlowA*Month	11	1466608.369	133328.034	0.55	0.8430

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Month	11	1387314.483	126119.498	0.52	0.8647
AvgFlowA	1	205310.192	205310.192	0.85	0.3680
AvgFlowA*Month	11	1466608.369	133328.034	0.55	0.8430

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	19
Error Mean Square	241409.1
Critical Value of Studentized Range	5.23083
Minimum Significant Difference	1388
Harmonic Mean of Cell Sizes	3.428571

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	Month
A	1580.0	4	3
A			
A	1530.5	4	2
A			
A	1512.5	4	9
A			
A	1445.0	4	8
A			
A	1292.5	4	4
A			
A	1276.5	4	5
A			
A	1266.7	3	10
A			
A	1230.0	2	7
A			
A	1160.5	4	11
A			
A	1144.7	3	1
A			
A	1023.3	3	6
A			
A	928.5	4	12

Model: Average Precipitation * Flow Category

The GLM Procedure
Class Level Information

Class	Levels	Values
flowCategory	3	1 2 3

Number of observations 43

The GLM Procedure

Dependent Variable: AvgMeasAcid AvgMeasAcid

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	2119142.123	423828.425	2.05	0.0939
Error	37	7644702.156	206613.572		
Corrected Total	42	9763844.279			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.217040	35.11092	454.5477	1294.605

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AvgPrecip	1	954170.1898	954170.1898	4.62	0.0382
flowCategory	2	514471.2631	257235.6316	1.25	0.2997
AvgPrecip*flowCatego	2	650500.6701	325250.3350	1.57	0.2207

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AvgPrecip	1	107189.9284	107189.9284	0.52	0.4759
flowCategory	2	398544.1735	199272.0868	0.96	0.3906
AvgPrecip*flowCatego	2	650500.6701	325250.3350	1.57	0.2207

The GLM Procedure

Tukey's Studentized Range (HSD) Test for AvgMeasAcid

NOTE: This test controls the Type I experimentwise error rate, but it generally has a higher Type II error rate than REGWQ.

Alpha	0.05
Error Degrees of Freedom	37
Error Mean Square	206613.6
Critical Value of Studentized Range	3.45278
Minimum Significant Difference	416.08
Harmonic Mean of Cell Sizes	14.22801

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	flow Category
A	1518.7	14	1
A			
A	1221.8	13	3
A			
A	1157.6	16	2

Model: Average Flow * Average Precipitation

The GLM Procedure

Number of observations 43

The GLM Procedure

Dependent Variable: AvgMeasAcid	AvgMeasAcid				
		Sum of			
Source	DF	Squares	Mean Square	F Value	Pr > F
Model	3	1794040.014	598013.338	2.93	0.0457
Error	39	7969804.265	204353.956		
Corrected Total	42	9763844.279			

R-Square	Coeff Var	Root MSE	AvgMeasAcid Mean
0.183743	34.91840	452.0553	1294.605

Source	DF	Type I SS	Mean Square	F Value	Pr > F
AvgPrecip	1	954170.1898	954170.1898	4.67	0.0369
AvgFlowA	1	532122.3546	532122.3546	2.60	0.1147
AvgPrecip*AvgFlowA	1	307747.4697	307747.4697	1.51	0.2271

Source	DF	Type III SS	Mean Square	F Value	Pr > F
AvgPrecip	1	4546.8421	4546.8421	0.02	0.8822
AvgFlowA	1	63030.3663	63030.3663	0.31	0.5818
AvgPrecip*AvgFlowA	1	307747.4697	307747.4697	1.51	0.2271