WATER QUALITY FROM ABOVE-DRAINAGE UNDERGROUND MINES OVER A 35-YEAR PERIOD[1]

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Abstract: The duration of acid mine drainage (AMD) flowing out of underground mines is important in watershed restoration and abandoned mine land reclamation projects. Past studies report that AMD flows from underground mines for hundreds of years with little change, while others find that poor drainage quality only lasts 20 to 40 years. In northern West Virginia, 20 above-drainage underground mines with AMD discharges were located and sampled during 1968, 1980, 2000, and 2005. Water flow, pH, acidity, Fe, Al, and sulfate were measured at all sampling times. From earlier work, 33 out of 44 sites (77%) were found to improve in drainage quality between 1968 and 2000. The results of the 2005 water sampling period confirmed these earlier findings. Out of 20 sites in the present study, only nine sites gave sufficient flow for water samples to be taken again in 2005. Of these nine discharges sampled in 2005, two showed a 22% and 32% increase of acidity, while the other seven sites (78%) decreased in acidity between 64 to 93%. Further sampling will quantify acidity changes of the original 44 above-drainage underground mine sites and more water samples will be collected during all four seasons of the year, which will represent both wet and dry periods. In this way, quantification of the effects of flow on underground mine chemistry may be evaluated.

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Introduction

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 Pennsylvania, Maryland, Ohio, and West Virginia (USEPA, 1995). Many mines currently discharging AMD were operated and abandoned before enactment of the Surface Mining Control and Reclamation Act (SMCRA) of 1977 (US Government, 1977). 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).

Two distinct types of underground mines exist. Above-drainage mines removed coal along coal outcrops and these coal seams were located above the regional water table. Water infiltrating into the underground mine usually drained out to the down-dip side of the mine at the portal and did not accumulate in the mine. Water that infiltrates into the mine continually flows out without fully flooding the mine. Therefore, mine voids and acid-generating materials are continually exposed to high and low water levels depending on the season, creating an ideal situation for acid generation where neither O_2 nor water limit pyrite oxidation and transport of reaction products. Under these optimized oxidizing and flushing situations, it is possible that mine discharges from above-drainage mines could be contaminated for decades or centuries depending on the pyrite supply, coatings, and flushing events (Younger, 2000; Younger et al., 2002).

Below-drainage underground mines are located below the regional water table and must be pumped to remove infiltrating water so as to allow mining to continue. Once mining ceases, pumping stops and the infiltrating water fills the mine voids thereby forming a mine pool. As the mine pool forms, the water deprives the pyrite in coal and associated rocks of O_2. Once flooded and after several complete flushing periods where the volume of water in the mine pool is turned over, the underground mine's water chemistry often changes to net alkaline water or at least to water with very low acid and metal concentrations (Donovan et al., 2000).

Several researchers have suggested that above-drainage underground mines give very different patterns of water chemistry over time than below-drainage underground mines of the same coal beds (Demchak et al., 2004). For example, Lambert and Dzombak (2000) located three underground discharges in the Uniontown Syncline of Pennsylvania with distinct flooding histories, and water quality measurements had been taken in 1974 and 1999 in each mine. A flooded below-drainage mine closed in 1934 (40 and 65 yr had passed since closure when sampling in 1974 and 1999 had occurred) had a pH of 6.0 in 1974 and 6.4 in 1999, Fe decreased from 45 to 25 mg L^{-1}, and SO_4^{-2} decreased from 1700 to 1000 mg L^{-1} (net alkaline water). In a flooded below-drainage mine that was closed in 1970 (instead of 1934), water pH increased from 3.1 in 1974 to 5.9 in 1999, Fe decreased from 140 to 70 mg L^{-1}, while SO_4^{-2} decreased from 2000 to 900 mg L^{-1}. The water essentially changed from strongly acidic water to slightly acidic water. The researchers concluded that underground mine water quality changed from acidic to alkaline within 30 yr after closure and flooding in their geologic setting.

Lambert and Dzombak (2000) then reported that 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^{-1} in 1974 to <2 in 1999 and SO_4^{-2} declined from 800 mg L^{-1} in 1974 to 600 mg L^{-1} in 1999. Water in all cases was net acidic from the unflooded mine. So, unflooded above-drainage mines improved in drainage quality, but still remained net acidic.

The objective of this paper was to determine the trend of water quality change from above-drainage mines in northern West Virginia. Using data from 1968, 1980, 2000, and 2005, changes in water quality were assessed.

Materials and Methods

Twenty sites were selected because of the availability of data from previous studies (Demchak et al., 2004) and their accessibility for further water sampling (Table 1). The sites were located in Preston and Monongalia counties of West Virginia (Fig. 1). All mines removed coal from either the Upper Freeport or Pittsburgh coal seams.

Table 1. Characteristics of discharge points used in this study of underground mines in northern West Virginia. Numbers correspond to locations on the map in Fig. 1.

Sample ID#	**Discharge point**	**Mine name**	**Time Since Closure**	**Coal Seam**	**Size (ha)**
1	Bull Run 4	Sherrey	50	Freeport	282
2	Cheat River 4	Morgantown North	65	Pittsburgh	44
3	Cheat River 5	Canyon	65	Pittsburgh	448
4	Fickey Run 3	Valley Point F	60	Freeport	62
5	Fickey Run 5	Valley Point K	55	Freeport	38
6	Fickey Run 6	Valley Point L	55	Freeport	75
7	Fickey Run 8	Tri State	53	Freeport	78
8	Glade Run 4	Valley Point A	55	Freeport	156
9	Glade Run 5	Valley Point A	55	Freeport	156
10	Greens Run 1	Pleasant	65	Freeport	33
11	Greens Run 3	Lowery	55	Freeport	88
12	Lake Lynn 1	Hollow	52	Pittsburgh	34
13	Lake Lynn 2	Canyon	70	Pittsburgh	448
14	Lake Lynn 3	Canyon	70	Pittsburgh	448
15	Martin Ck 2	Me	55	Freeport	11
16	Middle River 1	Mountain Run	58	Freeport	310
17	Muddy Ck 2	Cuzzart C	65	Freeport	72
18	Muddy Ck 3	Shermike	70	Freeport	278
19	Muddy Ck 9	Tri State	53	Freeport	78
20	Muddy Ck 11	Ruthbell 3	57	Freeport	35

The Pittsburgh coal seam is the lowest stratum of the Monongahela Group in the Pennsylvanian System. The seam has 1.5 to 2% S 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. Therefore, the water quality emanating from above-drainage mines in this coal bed is usually of very poor quality with high acidity and metal concentrations.

The Upper Freeport coal seam is the topmost stratum of the Allegheny Formation in the Pennsylvanian System. Upper Freeport coal contains <1.5% S, and an ash content from 8 to 12%. It is a multiple-bedded seam that is divided into a top coal and a 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). This coal bed also produces water with poor quality.

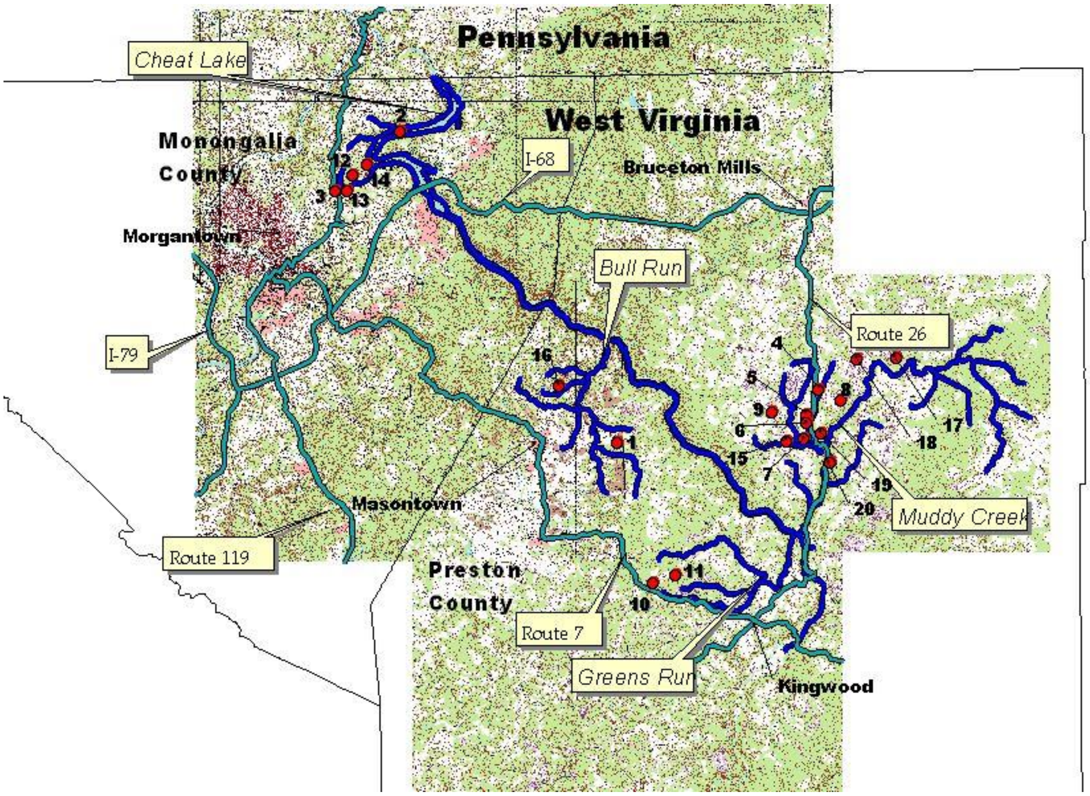

Figure 1. Location of the 20 above-drainage underground mines in Preston and Monongalia counties of northern West Virginia. Most are located in the Muddy Creek drainage area.

<u>1968 Sampling</u>

A previous research project was conducted during June-September of 1968–1970 to sample all mine discharges in the Monongahela River basin. Maps and field sheets were completed for each site. Flow rates were measured with a bucket and stopwatch, or for larger flows the workers installed V-notch weirs. Two water samples were taken at each discharge in this early study: (i) a 1-L bottle was filled with water, put on ice, and then analyzed in the laboratory for acidity, alkalinity, conductivity, SO_4^{-2}, and pH; and (ii) a 50-mL glass bottle was filled, treated with acid, and then analyzed in the laboratory for metals (total Fe, Mn, Al). 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 (G. Bryant, personal communication, 1999).

1980 Sampling

The West Virginia Division of Water Resources also conducted periodic sampling and analyses of underground mine discharges in this area (West Virginia Division of Water Resources, 1985). We accessed their data and found that 20 of their sample sites matched the discharges sampled in 1968. 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.

2000 and 2005 Sampling

Using maps and field sheets from the 1968 study, the underground mine discharge sites were located in 2000 and 2005. Where water flowed out of the ground at each site, flow was determined by placing a pipe to capture the water and measuring the flow with a bucket and stopwatch. Two water samples were taken at each sample point: (i) a 250-mL unfiltered sample was taken for general water chemistry (pH, total acidity and alkalinity by titration, and SO_4^{-2}); and (ii) a 25-mL filtered sample was acidified to pH of <2 with 0.5 mL concentrated HNO_3 and used to determine metal concentrations.

Water pH, acidity and alkalinity were determined by a Metrohm pH Stat Titrino System (Brinkman Instruments, Westbury, NY). Metal analysis was preformed using a Plasma 400 inductively coupled spectrophotometer (PerkinElmer, Wellesley, MA). Sulfate was measured turbidimetrically by flow injection analysis (Latchat Instruments, Milwaukee, WI). Analyses were performed at West Virginia University's National Research Center for Coal and Energy analytical laboratory. The data results from 2005 were compared to the data from previous sampling periods.

Results and Discussion

Changes in water infiltration and flow out of the mine have been shown to influence above-drainage mine water chemistry (Lopez and Stoertz, 2001; Pigati and Lopez, 1999). Therefore, precipitation amounts were determined for each year since sampling began in 1968. Precipitation records at Albright, WV, which is a station very near to the sites in Preston County, showed that most of the years since the 1968 sampling were within 30% of the average long-term annual precipitation in the region (Fig. 2). The notable exceptions were 1972 and 1975 with around 145 cm, 1989 with 158 cm, and 2003 with 160 cm, all of which were well above the long-term precipitation average of 105 cm. However, none of these years of high precipitation were close to our water sampling years.

During the sampling years of 1968 and 1980, rainfall was above the average with around 120 to 140 cm of rainfall. Rainfall was 98 cm in 2000, and this followed three years of below average precipitation (~90 cm). Some evidence suggests that years with below normal rainfall may allow storage of salts within an underground mine during dry periods, which are then flushed out with higher precipitation, resulting in high concentrations of acidity and metals during high flows (Pigati and Lopez, 1999). If true, the acidity and metal concentrations during the 2000 water sampling may show improved water quality since these salts may have remained in the mine. The 2005 rainfall was much higher, similar to 1968 and 1980 rainfall, and therefore the water flow from these mines in 2005 may be more similar to 1968 and 1980 sampling years.

The most surprising finding of this 2005 sampling period was that 10 of the 20 sites had no flow when visited in the summer and early fall of 2005 (Tables 2 and 3). While evidence of flowing water in the past could be seen at all of these dry sites, insufficient water was available to determine a flow or to extract a water sample. All 20 sites will be visited again in the spring of 2006. It is anticipated that in the spring most if not all of these sites will provide sufficient quantities of water for measurable flows and for water samples to be collected.

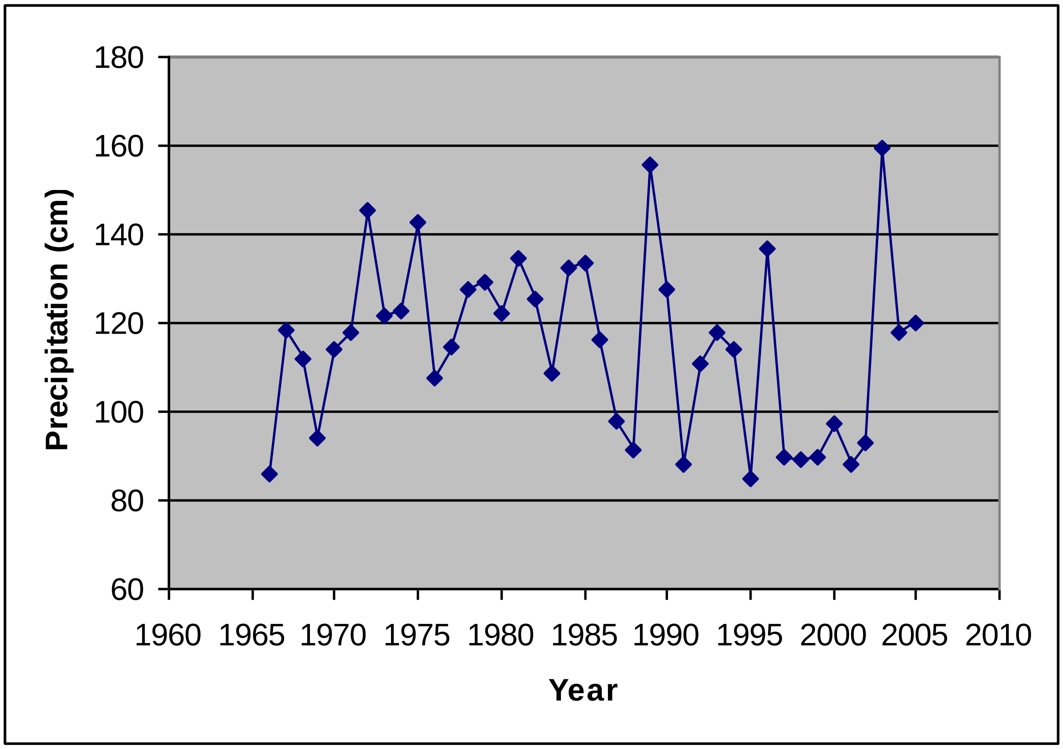

Figure 2. Annual precipitation for Albright, WV, from 1966 to 2004. The average rainfall of Albright, WV is 105 cm. The rainfall of 2005 is estimated to be around 120 cm, very similar to the 2004 data. Sampling of water from underground mines was done in 1968, 1980 and 2000. Rainfall data provide an estimate of the general wetness conditions during the sampling periods: 1967 = 119 cm, 1968 = 112, 1979 = 129, 1980 = 122, 1999 = 90, 2000 = 97, 2004 = 118, 2005 = 120.

Five of the previous 20 sites were from Pittsburgh underground mines (Table 2). Only one of these five sites was flowing for a water sample to be collected in the 2005 sampling, Lake Lynn 1. This site had an acid reduction of 92% between 1968 and 2000 (1368 to 102 mg/L), but acidity in the water increased slightly to 245 mg/L in 2005, which equated to an 82% reduction in acidity from 1968 to 2005 (1368 to 245 mg/L). During 1968 to 2000, the other Lake Lynn and Cheat River sites also improved dramatically showing an 84 to 95% decrease in acidity. It is unclear why these sites had no flow in 2005 since there had been substantial amounts of water at previous sampling times. As mentioned, further visits to these sites during wetter periods should provide answers to these questions.

Table 2. Water quality in 1968, 1980, 2000, and 2005 for five discharges flowing from Pittsburgh Coal above-drainage underground mines in northern West Virginia.

Discharge	Year	pH	Flow	Acidity	Iron	Aluminum	Sulfate
		s.u.	L/min	------------------	mmol/L	------------------	
Cheat River 4	1968	3.1	72	3603	824	65	4238
	1980	2.0	83	1000	160	55	1800
	2000	2.7	15	431	19	41	917
	2005		No Flow				
Cheat River 5	1968	2.6	19	1825	458	101	2392
	1980	2.6	8	210	25	19	1100
	2000	3.5	38	104	24	11	379
	2005		No Flow				
Lake Lynn 1	1968	2.8	38	1368	495	100	8861
	1980	2.4	1	405	90	26	1000
	2000	3.5	6	102	4	9	240
	2005	3.4	38	245	67	16	811
Lake Lynn 2	1968	3.2	144	2690	131	302	1105
	1980	2.0	208	605	90	48	1000
	2000	2.8	140	434	49	33	745
	2005		No Flow				
Lake Lynn 3	1968	3.1	1840	4988	477	532	2593
	1980	2.4	850	1075	180	122	920
	2000	2.9	120	237	7	33	619
	2005		No Flow				

Fifteen of the 20 sites were from Freeport underground mines (Table 3). Previous results showed that four of these 15 Freeport sites showed an acidity increase of 13 to 52% between 1968 and 2000. For the same time period of 1968 to 2000, the other 11 Freeport sites improved in quality with acidity decreases of 17 to 94% (Demchak et al., 2004).

Table 3. Water quality in 1968, 1980, 2000, and 2005 for 15 discharges flowing from Freeport above-drainage underground mines in northern West Virginia.

Discharge	Year	pH	Flow	Acidity	Iron	Aluminum	Sulfate
		s.u.	L/min	-------------------	mmol/L	------------------	
Bull Run 4	1968	3.3	41	250	82	1	556
	1980	2.2	242	360	85	3	800
	2000	3.0	181	530	48	44	1199
	2005	3.0	83	371	73	22	578
Ficky Run 3	1968	2.9	117	420	82	7	1456
	1980	2.5	32	460	42	19	800
	2000	3.1	144	912	107	66	1240
	2005		No Flow				
Ficky Run 5	1968	3.1	34	515	88	24	585
	1980	2.5	5	460	42	29	500
	2000	3.8	571	697	43	67	620
	2005		No Flow				
Ficky Run 6	1968	2.4	4	1300	288	112	1456
	1980	2.3	302	425	44	34	900
	2000	3.6	42	118	13	1	849
	2005	3.0	370	325	24	52	1180
Ficky Run 8	1968	3.0	185	1505	288	84	1872
	1980	2.2	5	1225	81	55	2200
	2000	3.5	14	390	17	34	996
	2005		No Flow				
Glade Run 4	1968	2.9	72	1660	395	28	2150
	1980	2.1	945	1250	120	43	1800
	2000	3.7	30	230	37	35	2385
	2005		No Flow				
Glade Run 5	1968	2.4	49	1765	158	150	2184
	1980	2.2	170	1330	160	135	2400
	2000	3.6	30	383	44	33	790
	2005	Treated by WVDEP					
Greens Run 1	1968	2.7	22	945	215	53	1600
	1980	2.9	8	455	130	27	1440
	2000	2.2	18	702	117	42	1320
	2005	4.1	11	268	69	15	680

Greens Run 3	1968	2.5	21	1504	288	108	1508
	1980	3.0	35	830	180	51	700
	2000	2.4	30	1732	203	121	1521
	2005	2.8	2	1935	319	175	2140
Martin Ck 2	1968	2.7	215	2315	640	161	990
	1980	2.7	151	385	60	16	560
	2000	4.2	144	135	10	4	587
	2005	3.0	17	166	24	9	580
Middle River1	1968	2.7	1262	917	165	46	2405
	1980	2.3	253	515	125	30	800
	2000	3.2	150	291	23	30	578
	2005		No Flow				
Muddy Ck 2	1968	2.8	1198	687	116	14	1878
	1980	2.1	12	410	120	10	1000
	2000	5.0	15	86	7	1	462
	2005	3.3	19	178	25	14	750
Muddy Ck 3	1968	3.3	14	170	25	6	377
	1980	3.4	302	110	20	3	400
	2000	5.3	113	45	0	1	111
	2005		No Flow				
Muddy Ck 9	1968	2.9	385	3515	422	301	1951
	1980	2.4	711	634	84	21	1200
	2000	2.3	359	2916	223	206	2400
	2005	2.6	168	1260	179	118	1930
Muddy Ck 11	1968	2.6	4286	2140	430	108	2704
	1980	2.4	5670	543	80	68	1100
	2000	3.1	926	550	102	29	1343
	2005	3.0	3302	450	93	27	790

One Freeport site, Glade Run 5, was reclaimed as part of the WV Division of Environmental Protection's Special Reclamation Program between the 2000 and 2005 samplings. The location of the water outflow now has an Aquafix system installed over it, which is treating the AMD. No untreated water could be sampled before treatment. Even before the installation of the Aquafix system, the acidity had declined about 78% between 1968 and 2000 (Table 3).

Eight of the 15 Freeport sites had water flowing at the site in 2005 so that water samples could be taken. The Bull Run 4 and Greens Run 3 sites showed acidity increases of 32 and 22% acidity between 1968 and 2005, supporting the 2000 sampling, which also found an increased amount of acidity in the water.

An increase of acidity over time from abandoned underground mines is difficult to explain, especially since the explanations are based on assumptions. One reason may be that the underground mine is still changing, with periodic roof falls and coal pillars continuing to degrade and deposit fresh pyritic materials into the flow paths of the mine. These fresh surfaces can react quickly, generating more acidity and allowing more metals to be dissolved into the low pH water. These falls can influence mine hydrology by impeding water flow in the mine and forming small cells of water or diverting water flow to different paths. Any of these changes would provide contact with different materials and perhaps change the water chemistry.

Another way to develop increased acidity in water from abandoned underground mines is to have an influx of water from adjacent active or abandoned underground mines through barrier breakage, which can introduce new acidic water into the mine. Another reason may involve cracks or openings to the surface, which could allow more water into the mine, which can then dissolve and remove stored acid salts in the mine.

The remaining six Freeport sites with 2005 data showed acidity decreases of 64 to 93% between 1968 and 2005. The Greens Run 1 site decreased in acidity by 71%, while the Greens Run 3 site remained about the same throughout the 35-year period. In 2005, water quality at Greens Run 3 has worsened and presented the highest acidity and metal concentrations of all sampling times.

Between 1968 and 2000, the Martin Creek, Middle River, and most Muddy Creek sites have improved in water quality over time, showing a decrease in acidity of between 68 to 94%. The notable exception was the Muddy Creek 9 site that showed only a slight decrease of 17% in acidity. These same sites showed a 64 to 93% decrease in acidity between 1968 and 2005, and the Muddy Creek 9 site improved to a 64% reduction in acidity.

Summary and Conclusions

The results of the 2005 water sampling support the original findings that the majority of above-drainage underground mines in the northern West Virginia coal field have improved in drainage quality over time. Demchak et al. (2004) reported that 33 out of 44 sites (77%) improved in drainage quality between 1968 and 2000. Out of 20 sites in the present study, nine sites provided sufficient flow for water samples to again be taken in 2005. Of these nine sites sampled in 2005, two (22%) showed a 22% and 32% increase of acidity (Bull Run 4 and Greens Run 3); while the other seven sites (78%) gave decreases of between 64 and 93%.

Further work will continue to quantify these acidity changes of the original 44 above-drainage underground mine sites from our original work reported in Demchak et al. (2004) and more water samples will be collected during all four seasons of the year, which will represent both wet and dry periods. In this way, quantification of the effects of flow on underground mine chemistry may be evaluated.

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