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Hydrogeology and Water Chemistry of the Friar Tuck Abandoned Coal Mine Site, Indiana, USA

미국 인디아나주 Friar Tuck 폐탄광의 수리지질 및 수질

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Abstract : The Friar Tuck Abandoned Coal Mine site is one of the most complexly disturbed areas in the midwestern United States. The deposits of gob and tailings contain high concentrations of pyrite, whose oxidation contributes to the acidification of soil and water and prevents the growth of vegetation. In an effort to quantitatively evaluate the effects of reclamation techniques, detailed monitoring program was performed. Water samples were collected from surface water, groundwater, and pore water from the unsaturated zone during a period of five years. According to the results, The spoil deposits are a relatively minor source of contamination and gob piles are the source of severe contamination to surface water and groundwater. But, loess and till beneath the gob piles effectively prevent the contaminated water migration from the source. Surface layers of the gob piles and the tailing deposits are less toxic than the interior of the deposits as a consequence of weathering over several decades. Acid mine drainage is in a post-peak stage and acid formation potential is probably situated in the unsaturated zone of refuse.

요 약 : Friar Tuck 폐탄광은 미국 중서부의 가장 복잡하게 교란된 광산 중의 하나이다. 버럭 및 광미 속에는 고농도의 황철석이 함유되어 있고, 황철석의 산화작용에 의해 토양 및 물이 산성화되고 식물의 성장이 제한되고 있다. 복구기술들에 대한 효과를 정량적으로 평가하기 위한 노력으로, 상세한 관측프로그램이 수행되었다. 물 시료들은 지표수, 지하수 및 불포화대의 간극수에서 5년간에 걸쳐 채취되었다. 그 결과에 의하면, spoil은 미약한 물 오염원이고, 버럭 더미는 지표수 및 지하수를 심각하게 오염시키는 원천이다. 그러나 버럭 더미 하부에 분포하는 loess 및 till은 오염된 물이 이동하는 것을 효과적으로 억제하였다. 버럭 더미 및 광미 표면층들은 수십 년간에 걸쳐 풍화된 결과로 층 내부보다는 독성이 약하였다. 산성광산폐수의 생성은 정점에 달한 상태이며 잠재적인 산성층은 아마도 광산폐기물의 불포화대에 분포하는 것으로 사료된다.

INTRODUCTION

Water pollution problems created by coal refuse are very serious. Acid mine drainage usually contains elevated concentrations of metals such as iron, aluminum and manganese, and are quite corrosive. When AMD enters a stream, aquatic environments are greatly altered and desirable organisms are usually reduced or eliminated. When AMD infiltrates into the groundwater, aquifers can become polluted and drinking water obtained from these sources can cause health problems. Although a variety of water quality problems can be created by AMD, one of the most common types of pollution is water quality degradation.

Regulation of the concentration of certain chemical parameters in the acid mine drainage is now a fact of life for mine operators. Current new-source discharge guidelines were proposed in the January 13, 1981, Federal Register (Vol. 46, No. 8). Depending on the receiving stream's quality and flow, the limits may be further restricted by the state. However, to date, no regulations on acid mine drainage discharge from abandoned mine sites have been established. (U.S. EPA, 1983).

SITE GEOLOGY

Climate

Indiana has a continental climate and highly variable weather influenced by the interaction of cold polar air from the north and warm gulf air from the south. These air masses generally move from west to east across the State. Climatic data from the National Weather Service at Terre Haute were analyzed for the period from October 1955 to September 1982. Annual precipitation averaged 1,000 mm/yr and ranged from 710 to 1430 mm/yr. July is usually the wettest month (120 mm of precipitation), and February is usually the driest month (53 mm of

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Physiography

The site is located on the eastern flank of the Illinois Basin. Physiographically, the site lies within the Wabash Lowland, which is the largest of the southern Indiana physiographic units. The Wabash Lowland is a low lying area with wide, flat plains forming the most common feature. Most of the bedrock is composed of soft shales and siltstones of Pennsylvanian age, covered by glacial deposits of Illinoian age. Most major stream valleys were once narrow bedrock valleys, but these have been filled with glacial and lake deposits of the Pleistocene Epoch. The upland areas are broad, rolling plains with slight slopes. The Wabash Lowland has an average elevation of 150 m above sea level (Schneider, 1966).

Unconsolidated Deposits

Deposits of windblown sand or loess cover much of the upland surface of the Wabash Lowland and locally form the valley walls. In general, the thickness of the eolian sediments decreases eastward, away from the Wabash valley. At the Friar Tuck site, the bedrock is covered by about 3 to 9 m of Illinoian drift. Lying everywhere above the Illinoian is a layer of loess ranging from 2.7 to 3.6 m thick.

Bedrock Geology

Bedrock underlying the study site consists of the Pennsylvanian Petersburg, Dugger, and Shelburn Formations. These rocks are nearly flat-lying, dipping to the southwest at about 6 m per km toward the Illinoian Basin (Gray, 1979).

Repeated cyclic sequences of sandstone, coal, and limestone characterize the entire system, but subtle vertical distinctions may be perceived. In the lower group, sandstone is the predominant rock type, and beds of coal are thin and local. The middle group, in which shale is dominant, contains five major commercial beds of coal. The upper group also consists mainly of shale, but thin, scattered beds of coal are also present (Gray, 1979).

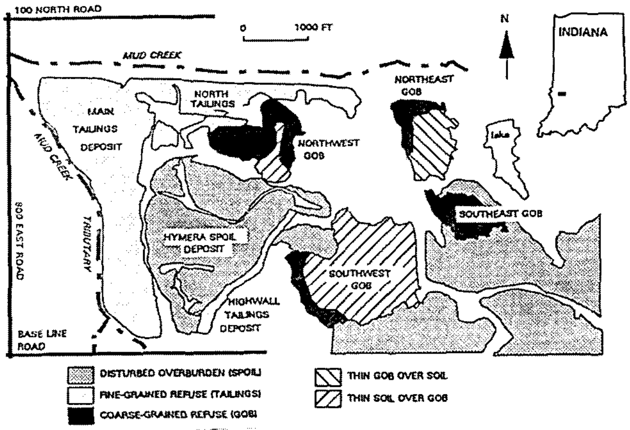

Figure 1. Distribution of refuse and spoil deposits at the Friar Tuck site.

Coal Refuse Piles

Extensive areal-type surface mining created steeply ridged deposits of disturbed overburden (spoil). A power plant and coal-preparation plant formerly operated within the site. Fine-grained refuse (tailings) from the preparation plants was deposited on floodplains and in a final-cut pit. Large mounded deposits of coarse-grained refuse (gob) from underground mines, form some of the highest topographic features in the area.

The distribution of deposits of gob, tailings, and spoil is shown in Figure 1.

MONITORING PROGRAM

In order to obtain data on groundwater quality and to monitor changes in the ground water quality following reclamation, a series of monitoring wells and suction lysimeters was installed at selected locations throughout the site (See Figure 2 and Table 1). The wells were used to monitor groundwater quality and flow for each of the different types of materials and at varying depths within and beneath the saturated zone. Suction lysimeters pull moisture from the materials above the water table in the unsaturated zone and provide information on quality where the groundwater is oxygen-rich. Wells were installed in undisturbed glacial till and alluvium, tailings, gob, spoil, and in the old mine workings.

Monitoring wells completed in the unconsolidated material were fitted with 50 mm Triloc PVC pipe and 0.25 mm PVC screen. 1.5 m-depth screen was used in almost all wells. Each well was finished by filling the annulus to 30 cm above the screen with medium-grained pure silica sand. A hole was back-

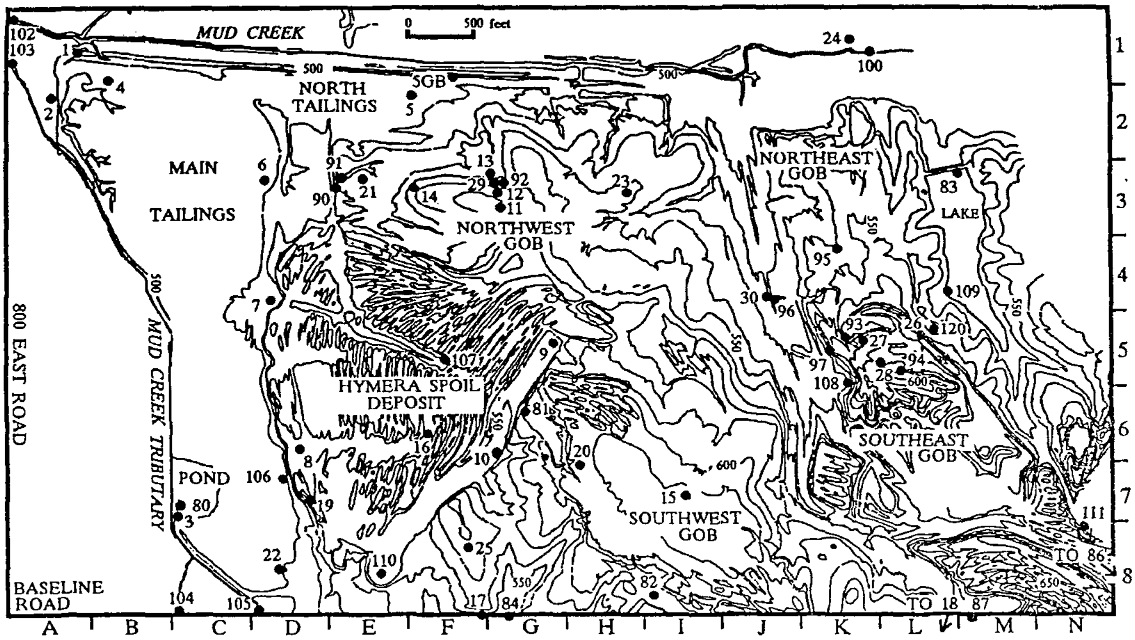

Figure 2. Topographic map of the Friar Tuck site showing the locations of numbered water-monitoring sites.

Table 1. Summary of information regarding numbered water monitoring sites

ID code	Type[1]	Location	Surface Elevation (m)[2]	Depth (m)[3]	Screen Length (m)	Material	Notes[4]
1	MW	A1	154.02	9.02	1.52	ALLUVIUM	
2	MW	A2	153.77	9.20	1.52	ALLUVIUM	X
3A	MW	C7	156.12	7.92	3.05	ALLUVIUM	
3B	MW	C7	156.18	2.19	1.52	LEVEE	
4	MW	B1	153.04	1.22	1.52	TAILINGS	
4SL-1.5	SL	A2	(153.01)	0.46		TAILINGS	X
5	MW	F2	155.66	2.10	1.52	TAILINGS	
5GB	MW	F1	(154.53)	13.72	1.52	ALLUVIUM	
5SL-1.5	SL	F2	(154.84)	0.46		TAILINGS	X
6	MW	D3	155.91	2.26	1.52	TAILINGS	
7	MW	D4	156.55	1.92	1.52	TAILINGS	X
7SL-1.5	SL	C4	(155.45)	0.46		TAILINGS	X
8A	MW	D6	163.80	5.94	1.52	TAILINGS	X
8B	MW	D6	163.80	1.89	1.52	TAILINGS	
9	MW	G5	169.04	1.77	1.52	TAILINGS	X
10A	MW	G6	166.85	7.16	1.52	TAILINGS	A, X
10B	MW	G6	167.00	0.67	1.52	TAILINGS	A, X
11	MW	G3	172.15	8.20	1.52	GOB	
11A	MW	G3	169.19	8.02	1.52	LOESS/TILL	
11B	MW	G3	172.21	5.12	1.52	GOB	
11SL-05	SL	G3	(172.21)	1.52		GOB	X
11SL-09	SL	G3	(172.21)	2.74		GOB	X
11SL-16	SL	G3	(172.21)	4.88		GOB	X
12	MW	G3	167.73	4.69	1.52	GOB	X
12SL-2	SL	G3	(167.64)	0.61		GOB	X
12SL-8	SL	G3	(167.64)	2.44		GOB	X
12SL-14	SL	G3	(167.64)	4.27		GOB	X
13A	MW	G3	(163.80)	4.02	1.52	LOESS/TILL	
13B	MW	G3	163.68	1.95	1.52	LOESS/TILL	
13SL-2	SL	G3	(163.68)	0.61		LOESS/TILL	X
13SL-7	SL	G3	(163.68)	2.13		LOESS/TILL	X
14	MW	F3	168.58	7.32	1.52	GOB	X
14SL-2	SL	F3	(168.55)	0.76		GOB	X

Table 1. Continued

ID code	Type[1]	Location	Surface Elevation (m)[2]	Depth (m)[3]	Screen Length (m)	Material	Notes[4]
14SL-8	SL	F3	(168.55)	2.44		GOB	X
14SL-16	SL	F3	(168.55)	4.88		GOB	X
15	MW	I7	188.61	13.29	3.05	SPOIL	C
16A	MW	F6	168.74	10.91	1.52	SPOIL	D
16B	MW	F6	168.62	7.62	1.52	SPOIL	D
16SL-2	SL	F6	(168.55)	0.76		SPOIL	D
16SL-8	SL	F6	(168.55)	2.44		SPOIL	D
16SL-20	SL	F6	(168.55)	6.10		SPOIL	D
17A	MW	F8	166.63	29.54	3.05	MINE VOID	F
17B	MW	F8	166.70	12.59	1.52	MINE PILLAR	H, X
18A	MW	L8	173.86	26.27	3.05	MINE VOID	F
18B	MW	L8	173.86	8.75	3.05	MINE VOID	G, X
19	MW	D7	168.37	10.15	1.52	SPOIL	E
20A	MW	H7	184.40	11.43	1.52	SPOIL	C
20B	MW	H7	184.46	6.49	1.52	GOB	
21	MW	E3	159.62	1.86	1.52	TAILINGS	
21SL-2	SL	E3	(159.41)	0.61		TAILINGS	X
21SL-4	SL	E3	(159.41)	1.22		TAILINGS	X
21SL-9	SL	E3	(159.41)	2.74		TAILINGS	X
22	MW	D8	156.12	1.80	1.52	TAILINGS	
22SL-1.5	SL	D8	(156.06)	0.46		TAILINGS	X
23	MW	H3	165.93	11.25	1.52	LOESS/TILL	
24	MW	K1	154.93	9.72	3.05	ALLUVIUM	
25	MW	F8	176.94	11.89	1.52	LOESS/TILL	X
26	MW	L5	180.72	16.15	1.52	SPOIL	
27	MW	K5	176.54	8.53	1.52	GOB	
27SL-3	SL	K5	(176.48)	0.91		GOB	
27SL-6	SL	K5	(176.48)	1.83		GOB	
27SL-17	SL	K5	(176.48)	5.18		GOB	
28	MW	L5	180.96	10.88	1.52	GOB	
28N	MW	L5	180.96	12.19	1.52	GOB	
28SL-1.5	SL	L5	(180.75)	0.46		GOB	
28SL-4.5	SL	L5	(180.75)	1.37		GOB	
28SL-18	SL	L5	(180.75)	5.49		GOB	
29A	MW	G3	165.20	1.83	0.91	LOESS/TILL	
29B	MW	G3	164.81	0.61	0.61	LOESS/TILL	X
29SL-1.5	SL	G3	(164.90)	0.46		?	
29SL-6	SL	G3	(164.90)	1.83		?	
30A	MW	J4	(159.11)	32.16	1.49	UNMINED COAL	J
30B	MW	J4	(159.11)	13.81	1.71	MINE POLAR	F
30C	MW	J4	(158.50)	10.36	2.83	MINE VOID	F
31A	MW		(167.64)	18.59	3.05	MINE PILLAR	F
31B	MW	170.65	21.64	3.05		MINE VOID	F
80	LK	C7	(154.23)			TAILINGS	
81	LK	G6	(174.35)			GOB	B
82	LK	I8	(174.04)			SPOIL	B
83	LK	M3	(162.76)			LOESS/TILL	I
84	LK	G8	(160.32)			SPOIL	A
86	LK	N8	(173.74)			SPOIL	A, B
87	LK	M8	(175.56)			SPOIL	
90	ST	E3	(158.50)			SPOIL	
91	ST	E3	(158.50)			GOB	
92	ST	G3	(161.54)			GOB	
93	ST	K5	(170.69)			GOB	
94	ST	L5	(179.83)			GOB	
95	ST	K4	(164.59)			GOB	
96	ST	J4	(157.89)			GOB	

Table 1. Continued

ID code	Type[1]	Location	Surface Elevation (m)[2]	Depth (m)[3]	Screen Length (m)	Material	Notes[4]
97	ST	K5	(164.59)			GOB	
100	ST	K1	(153.62)			ALLUVIUM	
101	LK		(149.66)			TAILINGS	
102	ST	A1	(148.74)			ALLUVIUM	
103	ST	A1	(149.35)			ALLUVIUM	
104	ST	C8	(153.62)			ALLUVIUM	
104N	ST	C8	(153.62)			ALLUVIUM	
105	ST	D8	(153.62)			ALLUVIUM	
106	SP	D7	(155.14)			TAILINGS	
106SL-1.5	SL	C6	(155.14)	0.46		TAILINGS	
107	SP	F5	(164.59)			SPOIL	
108	SE	K5	(162.46)			GOB	D
109	LK	L4	(162.46)			LOESS/TILL	I
110	LK	L4	(165.51)			TAILINGS	A
111	LK	N8	(169.77)			SPOIL	D
120	LK	L5	(167.34)			LOESS/TILL	

[1] Abbreviations: W, monitoring well; SL, pressure-vacuum (suction) lysimeter; S, stream; L, lake or pond; SP, spring; SE, seep.

[2] Elevation above mean sea level of the ground or lake surface; in parentheses, if approximate.

[3] Distance below the ground surface to the top of the screened portion of a monitoring well, or to the ceramic tip of a suction lysimeter.

[4] Notes: A, surface-mine highwall in Hymera coal; B, surface-mine highwall in Danville coal; C, surface-mine spoil of Danville coal; D, surface-mine spoil of Hymera coal; E, box-cut spoil of Hymera coal; F, underground mine in Springfield coal; G, underground mine in Hymera coal; H, emplaced in a narrow barrier between underground working and a surface-mine highwall in Hymera coal; I, reservoir (not a surface-mine lake); J, probably the Houchin Creek coal or an unmined split of the Survant coal; X, installation destroyed during reclamation or otherwise rendered inoperable before the end of investigations.

filled to within 60 cm of surface. The remaining hole was filled with granular bentonite and finally covered with concrete. The well heads are protected by 60 cm sections of 100 mm steel pipe with lockable cap (see Figure 3).

A different technique was required for installation of the mine wells. They were completed with the screen spanning the mine void and 50 mm PVC casing extending to the surface. A packer (inverted rubber cone) was installed immediately above the mine backfilled to within 60 cm of the surface. Granular bentonite pellets capped with concrete were used to seal the annulus to the surface.

Suction lysimeters are porous ceramic tips, connected at depth by polyethylene tubing to valves at the surface. When a vacuum is applied, the tip draws water from the surrounding vadose zone. Lysimeters were placed at two or three depths at given locations. Neutron probe access tubes cased in aluminum, were also placed and used to measure the soil moisture profile.

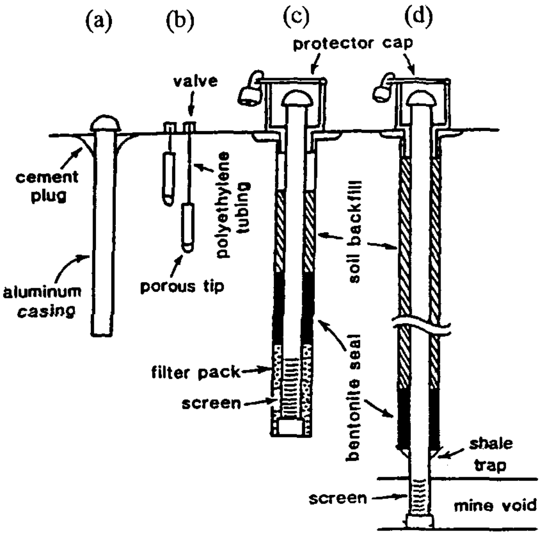

Figure 3. Cross-section of subsurface monitoring devices : (a) neutron probe, (b) suction lysimeter, (c) well into unconsolidated deposits and (d) well into mine.

Samples were collected from three different sources during a period of five years (from September, 1987 through December, 1992). Those samples included were surface water, groundwater, and pore water from the unsaturated zone. Surface water included streams, pond, seeps, springs, lakes, surface runoff, and precipitation. Precipitation samples were collected in a high-density polyethylene (HDPE) graduate cylinder. For surface runoff and high-flow stream discharge, collection vessels were strategically placed to catch water. Other surface water samples were collected using a grab technique in which a sample container is submerged into the water source, rinsed several times, and a portion is collected. Groundwater samples were obtained from monitoring wells that were first bailed out and allowed to recharge before obtaining a representative sample. The exception to this procedure was the monitoring wells installed in flooded mine voids, where complete purging by bailing was impractical. For these sites, three well volumes were bailed out prior to collecting a sample. Water for the unsaturated zone was collected using vacuum lysimeters. A vacuum was applied to the lysimeters 24 to 48 hours before sampling. All samples were collected in HDPE screwcap bottles.

A complete list of data for all samples collected from the Friar Tuck site can be found in Branam and Harper (1994).

ANALYTICAL PROCEDURE

Prior to December, 1989, samples were filtered in the field through a 0.45 μ membrane filter using a hand pump and one of the two aliquots preserved with concentrated hydrochloric acid (HCl). Both aliquots were placed in an ice chest and transported to the laboratory at the end of the day. Beginning in December, 1989, measurements of pH, Eh, specific conductance, and temperature, were conducted in the field and raw samples were collected and delivered to the laboratory at the end of the day where the measurements were completed within a 24 hour period and filtration, preservation and storage of sample aliquots were accomplished. Filtered aliquots remained in a refrigerator until anion and acidity and alkalinity analyses were completed. Prior to all chemical measurements, aliquots were allowed to equilibrate to room temperature before analysis (Branam and Harper, 1994).

SURFACE WATER

Mud Creek, a tributary of Busseron Creek, flows through the northern part of the Friar Tuck Mine. The Busseron Creek watershed, approximately 607 km^2, is contained in the Wabash Lowland physiographic division. The topography is characterized by level to gently rolling glacial till plains cut by a dendritic drainage system.

Mud Creek originates just west of the town of Midland, Indiana in the center of Section 21, Township 8N., Range 7W, at an elevation of approximately 202 m (USGS, 1980a). Mud Creek drainage is 30.5 km^2 and is highly affected by past mining. Annual runoff averages 419 mm/yr. The highest mean monthly flow for Mud Creek is in March, the lowest in October. Although the highest mean monthly flows are from March through May when spring rains occur, the highest peak flows typically are in July as a result of intense thunderstorm.

The largest tributary of Mud Creek originates just east of the town of Dugger, Indiana, in NE 1/4, Sec. 12, T. 7N., R. 7W., at an elevation of 166 m. This tributary flows immediately to the west of the Friar Tuck site and joins Mud Creek south of Road 100 North in the NE 1/4 Sec. 35, T. 8N., R. 8W., Dugger and Linton Quadrangles, at an elevation of 149 m (USGS,1980 and 1980a).

The drainage area of this tributary is about 7.5 km^2 (754 hectares) of which about 340 hectares (45 percent of the watershed) has been disturbed by surface mining. The tributary flows directly adjacent (on the west side) to the Main Tailing Pond of the Friar Tuck Mine for a distance of nearly one mile. This tributary receives acidic surface discharge from the Main Tailings Pond through drainage pipes at several locations along the embankment between the tributary and the pond. The southern Main tailing Pond in turn receives continuos discharge from a spring at the toe of the Hymera Spoil ridges.

Runoff from a total of 11 discharge points for different watersheds around the site was sampled for chemical analysis from January 29 to February 2, 1988, during a high-flow event (See Figure 4). The effects of drainage into Mud Creek from the Friar Tuck site can be seen in a comparison of pH, acidity, alkalinity, and sulfate at sites No. 100 (upstream of the Friar Tuck site) and No. 102 (downstream of Friar Tuck site). Acidity and sulfate concentrations increased downstream, whereas pH and alkalinity concentrations decreased. Contaminated water was flowing from all the watersheds that contain areas of gob (STR-4 through STR-7, STR-10, STR-11). In these areas, the mean values are as follows: pH (2.2 to 3.0), acidity (559 to 9,777 mg/l), alkalinity (0 mg/l), and sulfate (563 to 10,200 mg/l). Water flowing from the main tailings deposit (STR-1 and STR-3) was also severely contaminated: pH (2.6 to 2.9), acidity (194 to 2,974 mg/l), alkalinity (0 mg/l), and sulfate (318 to 3570 mg/l). Comparison of areas containing gob and tailings with areas unaffected by refuse disposal, such as sites No. STR-8 and No. STR-9, is remarkable: pH(6.0 to 6.1), acidity (0 mg/l), alkalinity (17 to 23 mg/l), and sulfate (14 to 239 mg/l). It should be noted that the area of STR-8 contains significant drainage from spoil areas to the south. Mud Creek Tributary was receiving moderately contaminated water from upstream (Sites No. 104 and No. 105), which was mixing with severely contaminated water from the Main Tailings Deposit (STR-1 through STR-3). The downstream analysis of Mud Creek Tributary (Site No. 103) indicates that the stream is also receiving significant quantities of relatively uncontaminated water from the west, which contains large areas of spoil.

GROUNDWATER

The shallow aquifer for Friar Tuck is composed of castover spoil, gob, tailings, and unmined, unconsolidated material. The unconsolidated overburden, prior to strip mining, was composed of loess, Illinoian glacial till, and alluvial deposits above the Pennsylvanian bedrock. The aquifer is unconfined, and is underlain by shale and by underclays lying below the coal seams. These shales and underclays prevent interconnection between the shallow aquifer and deeper groundwater system in bedrock. However, interconnection between the shallow aquifer and the deeper bedrock aquifers may occur at several places where old mine shafts or springs are located.

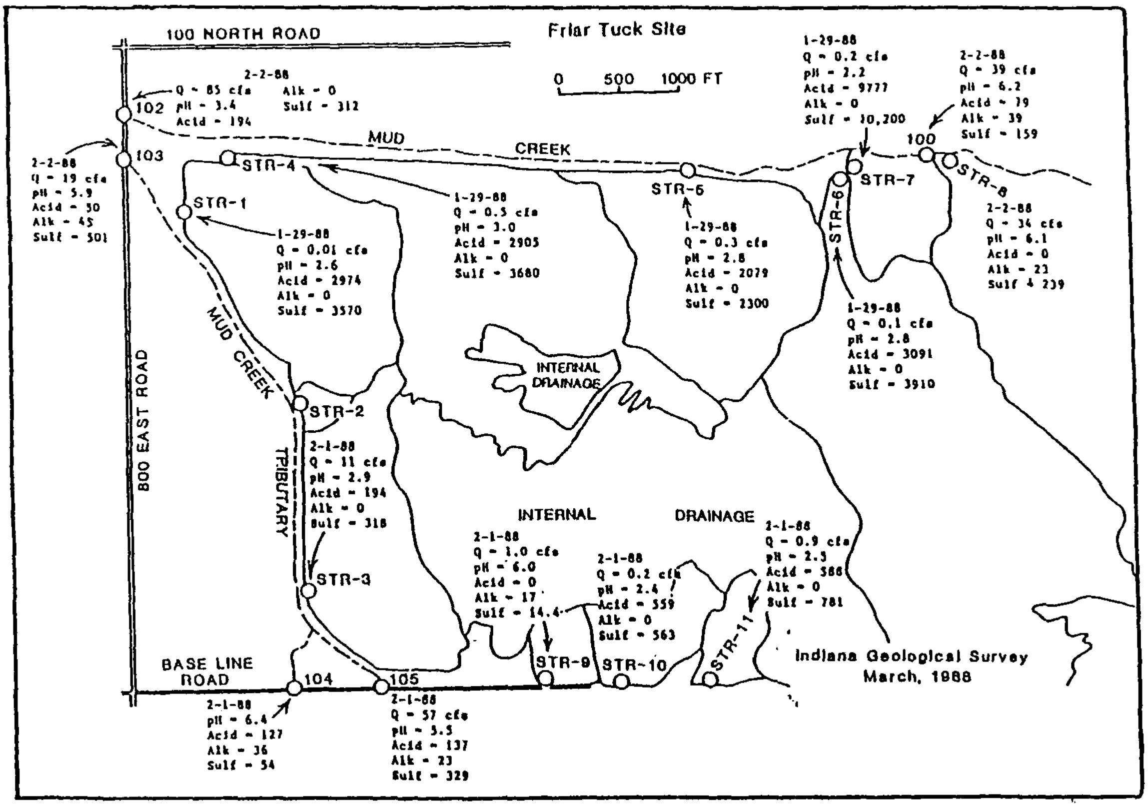

Figure 4. Sampling locations for surface water.

Hydraulic Conductivity Estimation

The most direct field method used to obtain hydraulic conductivity estimates is the single well (or piezometer) water-level response test, involving either bailing or addition of water in the well bore with subsequent water-level monitoring. Data were analyzed using the time lag method of Hvorslev (Fetter, 1988).

Kuo (1991) performed slug tests in some monitoring wells at the Friar Tuck site. The slug test conducted, the falling head test, begins with lowering of a 1.5 m solid pipe into the 50 mm diameter monitoring well to displace the water column from the initial steady water level. The displaced water rises 1.16 m in the annular space between the pipe and the casing of the monitoring well. A transducer connected to a data logger was installed at the lower end of the pipe to measure the pressure change due to the falling of water level in the monitoring well. The data logger was connected to a portable computer to record the water level changes. The transducer is measuring water-level changes in increments of 0.3 cm, from 0 to 1.5 m. Table 2 shows the hydraulic permeability for each well analyzed from slug test data performed by Kuo (1991).

Water-Level Fluctuation

Fluctuations in water level are the result of many factors such as aquifer characteristics, climate, precipitation, and groundwater seepage. Wells and ponds associated with the Southwest Gob Pile (Figure 2), which topographically is one of the highest features at the Friar Tuck site, showed the largest fluctuations in water level. Water levels in the Northwest (Figure 5 (a)) and Southeast Gob Piles (Figure 5(b)) exhibited seasonal variations. Water level declined steadily during summer and autumn and recovered rapidly during winter. The water level in the Highwall Tailing Deposit (Well 10A) has been almost constant, while water levels in monitoring wells in the Hymera Spoil Deposit have exhibited seasonal variations (Figure 5(c)). Water levels in the Main Tailings Deposits, till (Well 23), and alluvium (Well 24) show little change with water levels fluctuating only a few feet seasonally (Figures 5 (d) and 6 (a), (b), (c)). However, water levels in monitoring wells associated with abandoned underground

Table 2. Hydraulic conductivity analyzed from slug test

Well	Screened material	Confined or unconfined	Hydraulic conductivity (cm/sec)
1	alluvium	C	3×10^{-4}
2	alluvium	C	7×10^{-4}
3A	alluvium	C	3×10^{-4}
4	tailings	U	1×10^{-5}
8A	spoil	U	3×10^{-4}
10A	tailings	U	1×10^{-4}
11A	gob	U	1×10^{-4}
13A	till	C	1×10^{4}
13B	till	C	4×10^{5}

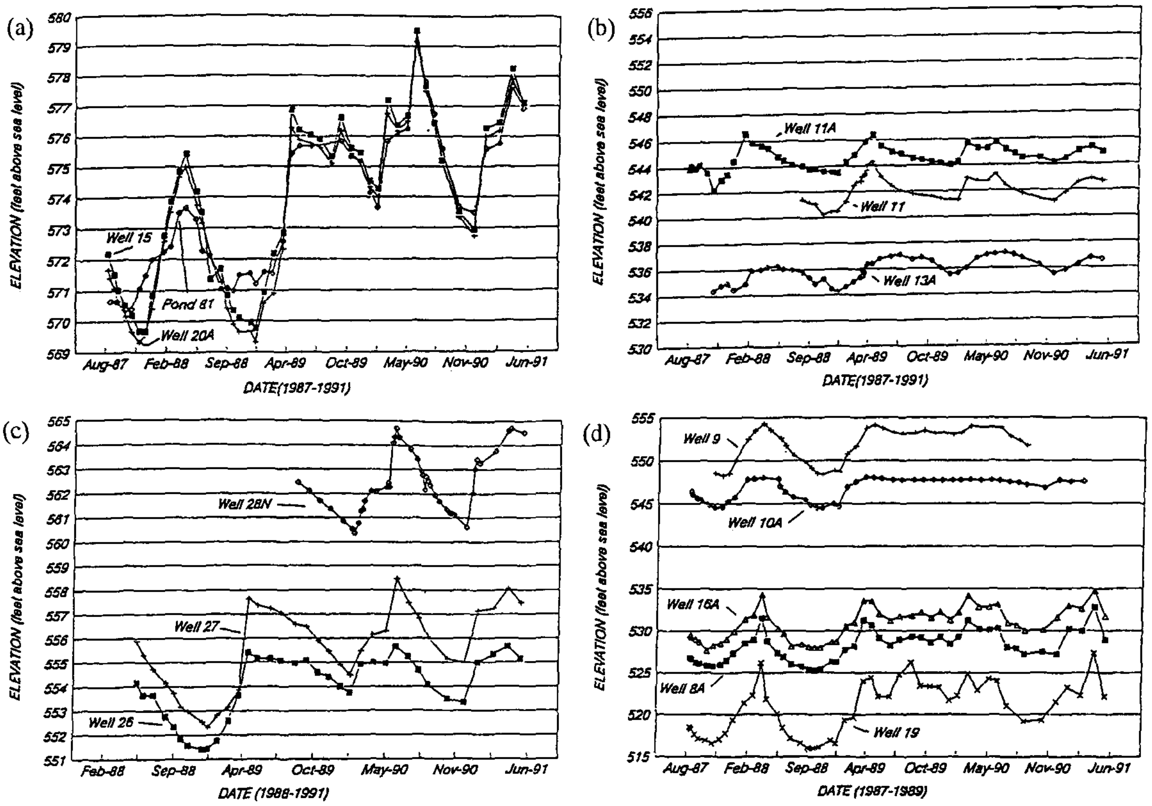

Figure 5. Water level fluctuation in wells and pond associated with : (a) the Southwest Gob Pile, (b) the Northwest Gob Pile, (c) the Southeast Gob Pile, and (d) the Hymera Spoil Deposit and the Highwall Tailings Deposit.

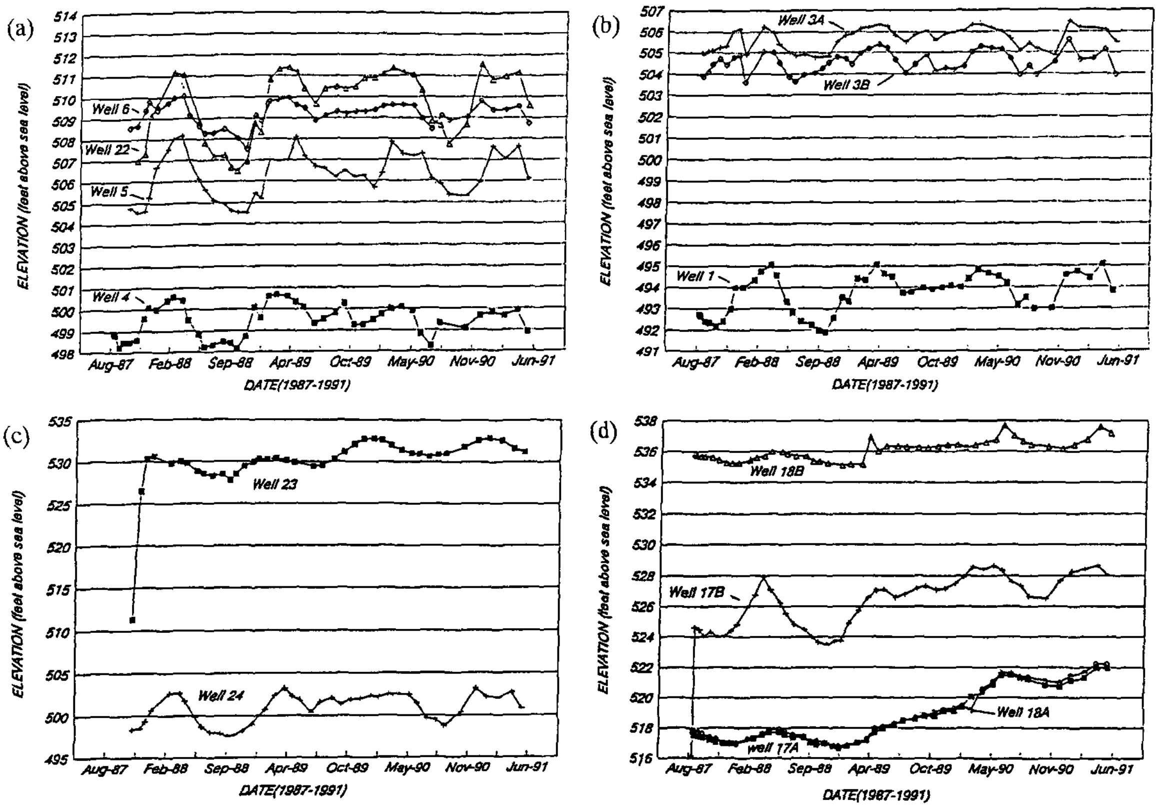

Figure 6. Water level fluctuation in wells associated with : (a) the Main Tailings Deposit, (b) levee that bounds the Main Tailings Deposit, (c) areas composed of undisturbed materials, and (d) abandoned underground mines.

mines have continued to rise (Figure 6 (d)).

Water Chemistry

The major inorganic constituents in most natural waters occur mainly in ionic form, and are commonly referred to as major ions. These are sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and sulfate (SO_4^{2-}).

The major cations in groundwater samples are calcium and magnesium. These cations probably originated from dissolution of carbonate minerals in limestone or dolomite. The dominant cations in most groundwater samples at the Friar Tuck Mine in order of their abundance are calcium>magnesium>sodium>potassium.

The water samples from Wells (#1, #2, #3A and #24) installed in the alluvium aquifer beneath the Main Tailing Deposits and along the Mud Creek, show mean pH values ranging from 5.8 to 6.3, sulfate concentrations from 652.0 mg/l to 2001.4 mg/l, Fe concentrations ranging from 66.3 mg/l to 237.0 mg/l and Al concentrations from 0.3 mg/l to 8.0 mg/l.

The water samples from Wells (#11, #29A #29B) installed in loess or till beneath the Northwest Gob Pile, indicate severe contamination due to infiltration of AMD from this gob pile. Water samples had mean pH values ranging from 1.7 to 4.4, sulfate concentrations ranging from 8996.3 mg/l to 13,650.0 mg/l, Fe con-

Table 3. Summary of selected chemical analyses of water samples

UNSATURATED ZONE					
	Main Tilings	*North Tailings*	*Hymera Spoil*	*Northwest Gob*	*Southeast Gob*
n	42	6	18	183	249
pH					
average	3.3	2.4	6.2	2.2	2.0
range	1.6-6.7	2.0-2.7	5.5-7.1	0.7-4.2	1.3-3.2
ACIDITY (mg L^{-1}, $CaCO_3$ equivalent)					
average	4,300	2,2800	41	41,000	7,300
range	0-58,000	790-4,700	0-350	9,000-160,000	1,400-23,000
SULFATE (mg L^{-1})					
average	5,00	2,500	3,600	43,000	7,900
range	200-58,000	600-5,600	180-7,100	8,900-160,000	2.600-25,000
TOTAL IRON (mg L^{-1})					
average	1,200	460	5	15,000	840
range	1-18,000	40-1,000	0-29	2,000-55,000	49-7,100
TOTAL DISSOLVED SOLIDS (mg L^{-1})					
average	7,800	4,300	5,400	60,00	9,900
range	310-79,000	2,200-7,100	610-9,800	12,000-220,000	3,600-33,000
SATURATED ZONE					
	Main Tilings	*North Tailings*	*Hymera Spoil*	*Northwest Gob*	*Southeast Gob*
n	47	15	15	32	66
pH					
average	5.4	3.8	5.9	4.0	1.8
range	2.7-6.7	3.1-4.3	4.6-6.7	1.8-5.9	1.4-2.5
ACIDITY (mg L^{-1}, $CaCO_3$ equivalent)					
average	790	1,800	730	24,000	22,000
range	0-3,500	590-4,400	60-1,800	1,200-110,000	13,00-35,000
SULFATE (mg L^{-1})					
average	1,800	1,700	3,400	23,000	23,000
range	1,000-2,800	430-4,900	2,700-5,400	5,600-40,000	13,000-31,000
TOTAL IRON (mg L^{-1})					
average	240	600	890	9,400	3,800
range	5-840	110-1,800	81-10,000	500-19,000	2,200-7,000
TOTAL DISSOLVED SOLIDS (mg L^{-1})					
average	2,800	2,700	5,000	35,000	30,000
range	1,600-4,100	640-7,500	4,200-6,700	7,800-60,000	18,000-43,000

centration ranging from 8996.3 mg/l to 13,650.0 mg/l and Al concentrations ranging from 310.7 mg/l to 1452.9 mg/l. However, wells (#13A, #13B and #23) installed in loess or till deposits, located some distance from the Northwest Gob Pile show little affect of AMD from this gob pile. Water samples had pH values ranging from 6.4 to 7.1, sulfate concentrations from 138.2 mg/l to 483.1 mg/l, Fe concentrations ranging from 0.6 mg/l to 19.6 mg/l and Al concentrations ranging from 0.1 mg/l to 0.8 mg/l.

Table 3 shows a summary of selected chemical analyses of water samples for tailings, spoil and gob. The spoil deposits are a relatively minor source of contamination. It is apparent that the spoil material contains carbonate minerals. These carbonates (calcite and dolomite) are moderately soluble in acidic waters. In this process, hydrogen ions combine with the carbonate ($HCO3^-$), thereby raising the alkalinity of the water. The bicarbonate, calcium and magnesium ions resulting from dissolution of calcite and dolomite raise the total dissolved solids in the water.

Acidity is greatest in the shallow unsaturated zone of the Northwest Gob Pile and decreases with depth, whereas shallow waters are least acidic in the Southeast Gob Pile and acidity increases with depth. However, the acidities of saturated-zone waters in both piles are similar. These differences are a consequence of the different histories for the piles. The Southeast Gob Pile has remained undisturbed since its construction in the 1940s, promoting development of a deep zone of weathering (pyrite depleted in upper 90 cm). In contrast, the failed reclamation attempt that was made on the Northwest Gob Pile in the early 1970s resulted in the exposure of fresh pyrite to the surface when the weathered layer was removed.

SUMMARY AND CONCLUSION

Coal refuse from surface mining operation, the old coal-fired power plant, and coal processing plants was indiscriminately across an area of over 5 km^2 at the Friar Tuck site.

Six major gob piles, hundreds of hectares of spoil ridges, and tailing ponds of various dimensions were formed.

A primary environmental concern at the site is acid mine drainage (AMD) resulting from oxidation of pyrite in the refuse piles. Pyrite oxidation occurs in the presence of water and oxygen, producing ferrous iron and sulfuric acid. Mud Creek and its tributary, which flow directly through the site, have been polluted by acidic groundwater seepage.

In an effort to quantitatively evaluate the effects of reclamation techniques, detailed monitoring program was performed. Water samples were collected from surface water, groundwater, and pore water from the unsaturated zone during a period of five years.

According to the results, acidity and sulfate concentrations increased downstream, whereas pH and alkalinity concentrations decreased. The spoil deposits are relatively minor sources of contamination and gob piles are the source of severe contamination to surface water and groundwater. But, loess and till beneath the gob piles effectively prevent the contaminated water migration from the source. Surface layers of the gob piles and the tailing deposits are a consequence of weathering over several decades and therefore they are less toxic than the interior of the deposits. Acid mine drainage is in a post-peak stage and acid formation potential is probably situated in the unsaturated zone of refuse.

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