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Groundwater Contamination Problems Resulting from Coal Refuse Disposal

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ABSTRACT

An inherent problem in the disposal of solid waste on land is the possibility of groundwater contamination by leachates from the waste. In the few studies conducted on the effects of coal refuse disposal on groundwater quality, significant impacts have been observed. Based on past and present rates of coal refuse disposal and current knowledge of water chemistry of runoff and seeps from refuse piles, significant groundwater contamination may be occurring in the eastern and midwestern United States.

Following a review of previous studies and a discussion of water quality problems related to coal refuse disposal, results from a three-year investigation of an orphan disposal site in southwestern Illinois are discussed. Although the coal refuse lay unreclaimed at the site for over 50 years, contamination of groundwater from acid leachate extended less than 200 m from the gob pile in the underlying calcareous, silty-clay till. Reclamation of the site in 1977 did not have immediate effects upon groundwater quality, but long-term changes are likely to occur. Slightly increased infiltration into the gob pile is causing greater flows of acid

seeps from the base of the pile, which may be hindering plant growth and increasing erosion of soil cover around the base. Further hydrologic and geochemical research is needed to assess the full magnitude of groundwater contamination problems related to coal refuse disposal at other sites and to develop disposal and reclamation criteria that are practical and effective in preserving long-term water quality at disposal sites.

COAL REFUSE AND ITS DISPOSAL

Because coal often contains a considerable amount of rock and mineral matter, a significant proportion of coal mined in the United States is cleaned prior to use. Thinner seams, higher pyrite and shale content, and greater percentage of underground mining of eastern and midwestern U.S. coals require more of this coal to be cleaned than in the West. In 1974, about 574 million metric tons (574 Mt) of coal were produced in the U.S. Of that amount, approximately 60% (330 Mt) underwent mechanical cleaning, resulting in 89 Mt of coal refuse (1). In 1975, about 97.2 Mt of refuse were created (2).

Coarse refuse is separated from coal at preparation facilities by some form of density separation and consists primarily of carbonaceous shale, pyritic coal, pyrite lenses and nodules, claystone, and some sandstone and limestone. Until recent enactment of state and federal coal waste disposal regulations and guidelines, selections of disposal methods and sites were usually determined by convenience and economic considerations, with little or no thought given to long-term environmental consequences (3). Dumping usually occurred adjacent to preparation plants, which often was down the nearest hillside or into the nearest stream valley. Refuse piles can cover areas from less than 1 ha to more than 400 ha, range from 3 m to more than 100 m in height or depth, and occupy a volume up to 1,200,000 m^3 (4).

The fine coal and mineral matter suspended in the washwater slurry is pumped from coal cleaning facilities into impoundments where the sediment is allowed to settle; the clarified water is then decanted or pumped from the ponds. There are two common types of slurry impoundments: a) large shallow ponds enclosed by low levees and ground irregularities, and usually located in level to gently rolling terrain, and b) deep impoundments located behind relatively high dams constructed across stream valleys and ravines in hilly country. Slurry material can contain significant quantities of fine coal, with the remainder generally consisting of sand, shale fragments, silt, clay, and some pyrite. When abandoned, the dams or berms of the ponds gradually erode, are often breached, and erosion of the slurry materials can ensue.

The number of sizable active or abandoned waste piles and impoundments in the eastern U.S. alone is conservatively estimated to be 3000 to 5000, containing over 3000 Mt of refuse (5). The U.S. Bureau of Mines (6) has estimated that over 80,000 ha in the U.S. have been used for the disposal of coal-processing wastes during the period 1930-1971, with only 10,700 ha having been reclaimed. More than 1050 ha of gob and 660 ha of slurry material in Indiana (7) and approximately 2480 ha of gob and 1630 ha of slurry material in Illinois (8,9) presently lie unreclaimed. Past coal refuse disposal sites, in most cases, were neither properly designed nor reclaimed because state and federal requirements governing such activities were lacking.

The environmental problems associated with coal refuse disposal sites are many: sliding, dam failures, burning piles, acid water, siltation of streams and reservoirs, and land property devaluation. Because of pyrite oxidation and dissolution, acid water formation is ubiquitous and difficult to control at most refuse disposal sites in the eastern and midwestern U.S. Rainfall and snowmelt on the refuse areas result in continuous or intermittent effluents due to direct surface runoff and percolation of water through the refuse. Table I is a summary of water quality data collected by several investigators at coal refuse sites throughout the East and Midwest. The pH is generally low and values of most listed parameters are quite high. The differences between surface water quality (ponds, surface runoff, and seeps combined) and seep water quality are not significant. The acidic discharges from unreclaimed disposal sites usually are a serious detriment to water quality and aquatic biota in receiving streams, and numerous reports and papers document these impacts.

Table No. I
Water Quality of Runoff and Seeps from Coal Refuse Piles in the Eastern and Midwestern U.S.

Location	Refuse Type[a]	Water Type[b]	No. of Samples	pH[c]	Acidity	Specific Conductance	$SO_4^=$	Fe	Mn	Al	Zn	Source of Data
Illinois	G	Su	41	2.6	3500	4200	3900	430	17	200		(8)
Illinois	S	Su	21	2.4	2600	4400	3500	510	14	170		(8)
Macoupin Co., Ill.	G,S	Su Su	36 7-11	2.8	11475		9465	3310	 41		 41.7	(10) (10)
New Kathleen Mine, Ill.	G	Su	>200	2.2	13520	12740	14340	3860				(11)
Pennsylvania	G,S	Su	7	2.9	13294	7516	15535	2304	103	515		(12)
West Virginia	G,S	Su	4	3.1		8550	6328	1367	43	73	0.2	(13)
Kentucky	G	Su	3	2.5		3947	4715	1344	34	231	3.8	(13)
Indiana		Su	8	2.5		6263	8720	2129	35	112	4.4	(13)
Macoupin Co., Ill.	G,S	Sp	5	3.1	6280		2891	3757				(10)
New Kathleen Mine, Ill.	G	Sp	>120	2.5	19062	16158	20641	5991				(11)
Pana, Ill.	G	Sp	3-6	3.7			5787	1867	703	260	4.3	(14)
Pennsylvania	G	Sp	2	3.0,4.1		3700	2300	15.3	70	68	2.6	(13)
West Virginia	G	Sp	1	4.9		5000	3800	260	9	3.6	0.2	(13)
Kentucky	G	Sp	2	3.8,6.9		1080	878	4.3	5.8	35.9	0.6	(13)
Indiana	G	Sp	1	2.3		1200	15000	4500	56			(13)

[a] G -- gob; S -- slurry material

[b] Su -- surface water (runoff, ponds, and seeps combined); Sp -- seeps and springs only

[c] Median pH in standard units; mean specific conductance in µmhos/cm at 25°C; other parameters are mean values in mg/L.

With ponded water commonly found at disposal sites (8) and moderate permeabilities in coal refuse, substantial amounts of acid water could be seeping into the subsurface. At the New Kathleen site in Illinois, it was determined that about 20% to 60% of rainfall infiltrated into the unreclaimed coal refuse (15,16). Thus, there exists a definite potential for groundwater contamination near coal refuse disposal sites, but no studies as yet have seriously addressed this possibility in the U.S.

Libicki (17) has reported on two disposal sites in Poland. Approximately 1500 m^3 of gob and fly ash were disposed of at the first site overlying a shallow sand aquifer, and 11 monitoring wells were installed within and around the disposal area. At the second disposal site, a total of 500,000 m^3 of gob were placed in a pit at a rate of 20,000 to 30,000 m^3/month, and fourteen monitoring wells were installed in sand and gravel around the pit. Total dissolved minerals in the shallow aquifer beneath the first site began to increase two months after disposal operations began. Initially, increases in pollutant concentration were related to intensity of precipitation, indicating episodic pulses of water percolating down through the disposal pit. Migration of dissolved constituents down-gradient of the pit was clearly evident after seven months. The following parameters were seen to increase in water down-gradient of the first site as compared to ambient water quality: specific conductance, total dissolved solids, chloride, sulfate, sodium, potassium, calcium, magnesium, ammonium, phosphate, cyanide, phenols, cadmium, strontium, copper, molybdenum, and boron. No noticeable increases in iron, manganese, aluminum, or chromium occurred, nor were there any apparent changes in pH. Observed impacts to groundwater quality at the second site, where only gob was dumped, were similar. Increases in molybdenum, strontium, and cyanide did not occur, but increased concentrations of aluminum, chromium, and iron were observed.

In the Yorkshire coalfield of England, Nicholls (18) reported the steady gradual decline of water quality in a public water supply well about 700 m from an active colliery gob pile and slurry pond. The very extensive gob pile was deposited across an outcrop of the Bunter Sandstone aquifer and onto sand and gravel deposits overlying the sandstone, thus enabling seepage water to easily percolate into the aquifer from which the well obtained its water. Table II shows water quality in the slurry pond, seeps from gob, and the well water over a period of nearly 50 years.

Table No. II
Effects of Coal Refuse Disposal on a
Well in Yorkshire Coalfield, England (18)

	Slurry Pond Water	Gob Seepage	Well Water			
			1919	1925	1933	1965
Total Hardness[a]	1090	--	126	163	414	2060
Sodium	1200	1750-3400	--	--	--	--
Chloride	2550	1300-3000	12.9	25.7	337	2925
Sulfate	480	2600-5500	--	--	--	--

[a] All values in mg/L.

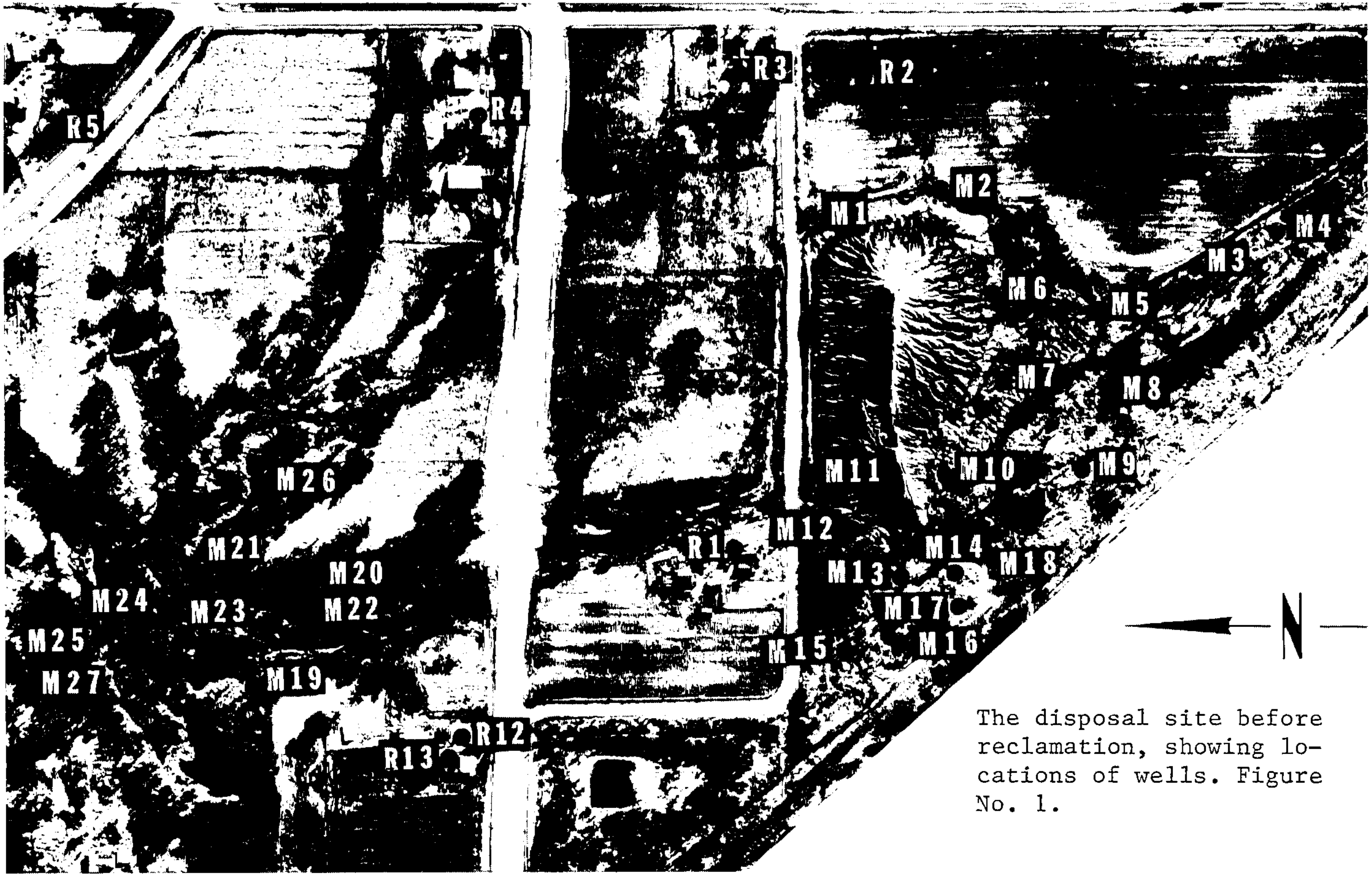
Judging by the seepage water chemistry (e.g., near-neutral pH and relatively low concentrations of iron and manganese) of these European examples, the coal refuse at those disposal sites probably had very low pyrite content. In Canada and the western U.S., however, there are examples where seepage waters from sulfide-ore mineral wastes are extremely low in pH; in some of these cases, contamination of groundwater quality has been documented (19,20,21,22,23,24,25,26).

In 1975, the Illinois General Assembly created the Abandoned Mined Lands Reclamation Council to designate high-priority abandoned mined lands to be acquired and reclaimed by the state and to establish priorities to guide the selection process. Pennsylvania and other states have taken similar steps to reclaim abandoned lands where mining companies are not held responsible for environmental problems (e.g., Operation Scarlift Projects in Pennsylvania). With the enactment of the Surface Mining Control and Reclamation Act of 1977 (P.L. 95-87) by the federal government, funding and administration for the reclamation of abandoned lands has been delegated to the Abandoned Mine Land Reclamation Program and Rural Abandoned Mine Program of the Office of Surface Mining. Because acid drainage is a major problem at many disposal sites, reclamation techniques are needed to effectively control water movement and quality in pyritic mine spoils and coal refuse. To date, however, very little field research has been conducted to determine moisture movement, percolation, subsurface pyrite oxidation, leaching processes, or groundwater pollutant transport and attenuation mechanisms relative to this particular problem.

To assess the nature and magnitude of water quality problems resulting from an abandoned unreclaimed coal refuse disposal area, hydrologic and water quality monitoring began in November 1975 at a site near Staunton, Illinois, approximately 66 km northeast of St. Louis, Missouri. Six months after the investigation was initiated, reconstruction and reclamation of the site was begun in accordance with design and engineering plans developed by Argonne National Laboratory's Land Reclamation Program. This work included grading and liming of the coal refuse, covering with a calcareous, silty-clay till, and fertilizing and seeding the project area (27,28). Thus, it was possible to study not only the groundwater quality problems attributable to an unreclaimed "orphan" refuse disposal area, but also any modifications to the hydrologic system and changes in water quality (both surface water and groundwater) brought about by the reclamation activities. Only the groundwater aspects of the research program will be discussed in this paper.

DESCRIPTION OF DISPOSAL SITE

The Consolidated Coal Company Mine No. 14 opened in 1904 and operated until about 1924. Underground mining of the 1.8-m-thick Herrin (No. 6) coal, and crude cleaning operations near the mine mouth resulted in the accumulation of a large gob pile (about 25 m high and 1.8 ha in area) and 4.5 ha of slurry material north of the pile (Fig. 1). Extreme erosion occurred on the site in the 50 years following mine closure; the gob pile had deep gulleys cut into its steep sides and a large quantity of sediment had washed into adjoining lowland areas. The impoundment dam was breached by erosion, and runoff water from the entire site gradually wore down the low point in the dam, resulting in cliffs of exposed slurry material as much as 4.5 m in height. During rainstorms a portion of runoff water from the gob pile flowed into lowland areas surrounding the pile and underwent extended periods of evaporation and infiltration.



The disposal site before reclamation, showing locations of wells. Figure No. 1.

Between September 1976 and April 1977, the coal refuse was graded to gentle slopes. Ground agricultural limestone (175 t of $CaCO_3$ equivalent/ ha) was then disked into the gob material and a mixture of limestone and quicklime (175 t of $CaCO_3$ equivalent/ha) was disked into the slurry material. A 0.3-m layer of calcareous, silty-clay till was then placed over the regraded refuse material and the area was fertilized and seeded (Fig. 2). The earth dam of the slurry impoundment was reconstructed and a 0.5 ha pond was excavated at the north end of the disposal site, primarily to reduce peak runoff flow and sediment transport from the site. Additional details of the reclamation project are described by Zellmer (27) and Wilkey and Zellmer (28).

PRE-RECLAMATION GROUNDWATER QUALITY

Light rainfalls produced little or no runoff at the Staunton site prior to reclamation and intermittent seeps were observed at the base of the gob pile and slurry material. Thus, clear evidence was available that some

View of the reclaimed disposal site looking north.
Figure No. 2.

degree of saturated conditions existed at the base of the refuse materials. Heavy incrustations of metal sulfate and oxyhydroxide minerals formed where seep waters evaporated.

Twenty-two shallow (< 4.6 m) monitoring wells were installed in the glacial till surrounding the refuse pile and slurry area, and five wells were placed in the saturated slurry material (Fig. 1). Within 0.6 km of the refuse site, residents rely on shallow, hand dug wells and one drilled well for their water supplies. In addition to the 27 wells installed at the refuse site, 13 residential wells were monitored during the prereclamation study.

Pumping tests are planned for the future, but is is already apparent that the permeability of the till is low throughout most of the site area. All monitoring wells were bailed prior to sampling and recovery rates were low. In some cases, several weeks were required for a well to recover two to three meters. Most of the residential wells also had low specific capacities and poor recovery rates after heavy use. A few wells, however, exhibited greater permeability (e.g., M19) and the reasons for this are to be investigated further. A few thin, discontinuous sand lenses in the till were found in the north part of the site and may serve as zones of increased permeability. Jointing and fractures in the till may also provide avenues of increased groundwater flow (29). The water table in the till was generally less than 3 m below the land surface near the refuse pile and sloped gently away from the pile in all directions. For the entire area, however, the water table in the glacial material sloped toward the north and northwest (30).

Chemical analyses of water samples collected from monitoring and residential wells during 1976 before site reclamation are summarized in Table III. The wells are grouped in the table according to similarity of location and water chemistry. In an area less than 30 m from the north, west, and south sides of the gob pile (well group A), the median groundwater pH was 3.10 and ranged from 6.38 down to 2.27; the average acidity was 4000 mg/L. Concentrations of sulfate and most dissolved metals were extremely high and some parameters exceeded recommended drinking water standards by several orders of magnitude.

Table No. III

Average[a] Pre-Reclamation Groundwater Quality

Well Group	A	B	C	D	E	F	G	H
No. of Samples	10	7	5	15	3	3	3	16
Spec. Cond[b]	19921	2489	2847	4249	2956	3954	8373	1696
Median pH	3.10	6.40	5.60	6.50	6.80	4.35	6.85	7.64
Min. pH	2.30	6.20	3.20	4.00	6.70	4.00	6.84	7.10
Acidity	4076	37.3	207	67.8	77.0	1784	76	22.3
Max. Acidity	31400	62	660	372	124	2604	105	59.8
Alkalinity	142	131	64	135	376	4.4	435	268
Bicarbonate	173	160	78.4	165	459	5.3	531	327
Sulfate	6330	329	1255	1064	856	3596	1719	433
Calcium[c]	490	88.5	438	249	304	435	500	137
Magnesium	246	41.9	80.4	108	69.5	149	279	70.1
Sodium	263	61	26.3	120	235	91	117	53.6
Potassium	15.9	0.3	4.0	1.3	14.1	17.2	0.8	3.88
Strontium	1.5	<.5	0.7	0.5	2.9	5.3	0.6	<.5
Aluminum	414	<.02	19.4	2.57	<.1	61.7	.06	<.5
Cadmium	1.00	<.01	.09	.01	<.01	.01	<.01	<.01
Chromium	.46	<.02	<.02	<.02	<.02	<.02	<.02	<.02
Copper	1.22	<.01	.05	<.02	<.02	<.02	<.02	<.02
Iron	1367	.24	119	2.61	6.89	933	.21	.039
Max. Iron	6010	.77	560	24.9	12.9	1840	.35	.20
Manganese	24.2	.45	9.28	7.26	.55	16.9	.16	.26
Max. Mn	62	.74	18.6	51	.80	41.0	.29	1.26
Nickel	1.52	<.02	.25	.094	.03	.81	.03	<.02
Zinc	59.0	.02	6.64	.734	.096	28.4	.097	.192
Max. Zinc	252	.05	23	10.4	.115	40.5	.104	1.95

[a] All chemical parameters are reported as mean concentrations, except pH which is a median; minimum pH and maximum acidity, iron, manganese, and zinc are also reported for most well groups.

[b] Specific conductance is reported as mhos/cm at 25°C, pH in standard units, acidity and alkalinity as mg/L $CaCO_3$ equivalence, and other parameters are reported in mg/L.

[c] Dissolved cations were analyzed from filtered, acidified samples.

Well Group Locations - Pre-Reclamation Monitoring

A. < 30 m from N, S, and W side of gob pile (M6,M7,M11,M12,M13).

B. < 30 m from E side of gob pile (M1,M2).

C. 30-60 m SW and W of gob pile (M10,M14,M15,M16,M17,M18).

D. 60-190 m S of gob pile (M3,M4,M5,M8,M9).

E. In saturated slurry material away from main drainage channel (M24,M26).

F. In saturated slurry material near main drainage channel (M22,M23).

G. Located in alluvium downstream of disposal site (M27).

H. All residential wells (R1 through R13).

Of particular concern were the concentrations of aluminum, cadmium, chromium, iron, manganese, and zinc. At distances of 30 to 60 m south and west of the gob pile (well group C), the groundwater had a median pH of 5.60, average acidity of 207 mg/L, and lower levels of most major and minor constituents relative to group A wells. Concentrations of aluminum, iron, cadmium, manganese, and zinc, however, were still much higher than the residential wells of the area (group H). Groundwater on the southeast, south, and west sides of the pile could have been contaminated by groundwater migration from the pile (subsurface transport) and surface water running off the pile and ponding in lowland areas (surface transport) with subsequent infiltration. Both processes were occurring, but the relative importance of each has not yet been quantified.

At distances greater than 60 m southeast, south, and west of the pile (well group D), concentrations of acidity and most dissolved metals were greatly reduced. However, moderately high specific conductance, acidity, sulfate, aluminum, iron, manganese, and zinc persisted in a few wells at distances up to 200 m from the pile. Water quality in the field east of the pile (well group B and well R2) was alkaline with low concentrations of sulfate and most metals (iron and manganese were slightly high). Based on data from the pre-reclamation monitoring wells, shallow groundwater quality was not significantly affected at distances greater than 200 m south and west of the gob pile and 30 m east of the pile. The till underlying the gob pile had a low permeability and the hydraulic gradient of the water table was also low; therefore, flow velocity of groundwater was low and transport distance of contaminants was not great. As the acid leachate flowed through the calcareous till, neutralization of the water took place and precipitation of metals probably occurred. An insufficient number of wells were located north of the pile to determine groundwater quality patterns in this direction.

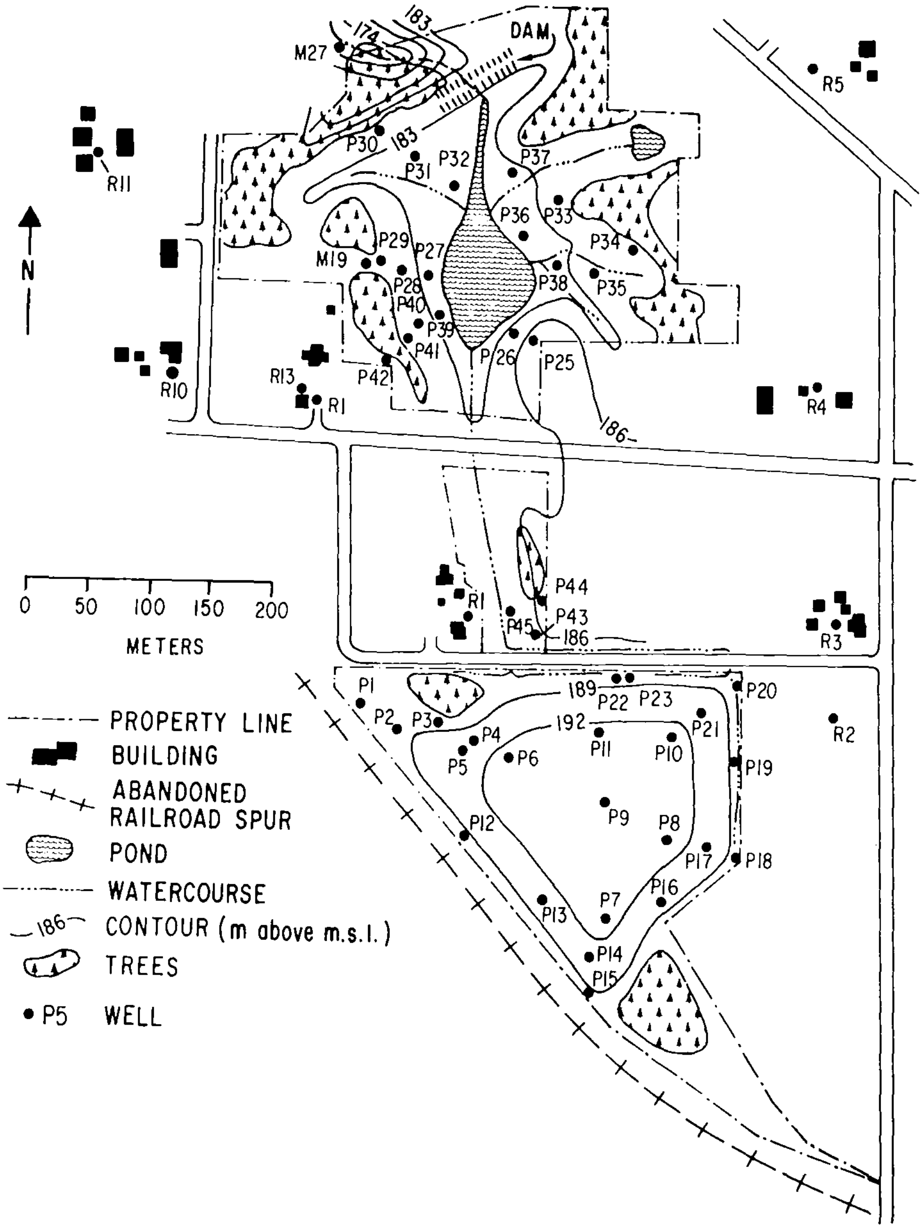
Groundwater in the saturated slurry material exhibited diverse chemistries. Water in slurry material adjacent to the drainage channel leading away from the gob pile (well group F) had concentrations of acidity, metals, and sulfate similar to acid surface drainage from the pile. Monitoring wells in slurry material located farther away from the main drainage channel (group E) had water with much lower specific conductance, sulfate, and metal concentrations, and a net alkalinity. This suggests that surface water draining from the gob pile area was recharging the slurry material along the main channel. Well M27 (group G), located in the alluvium of the drainage channel leading away from the site (see Fig. 1), had water with a high specific conductance, high alkalinity, and high concentrations of calcium and magnesium relative to residential wells and relative to the surface drainage water. This indicates groundwater discharge, rather than recharge, along the streambed, thus causing dilution and neutralization of acid water in the stream (30).

Water in residential wells (group H) within 0.6 km of the disposal site contained primarily calcium, magnesium, sodium, sulfate, and bicarbonate ions (a normal assemblage for this area) and low concentrations of transition and heavy metals. The presence of zinc in some wells was probably due to the use of galvanized steel pipes in the wells.

POST-RECLAMATION GROUNDWATER QUALITY

All of the pre-reclamation monitoring wells except M19 and M27 were destroyed during the reclamation activities. In 1977, 45 new monitoring wells were drilled in the study area: 10 in the reclaimed gob pile, 16 in the till surrounding the gob pile, 12 in the slurry material, and 7 in the till surrounding the slurry area (Fig. 3). The wells range in depth from 2 m to 12 m. Monitoring of water levels and collection of samples from the 45 new monitoring wells, 2 pre-reclamation monitoring wells, and 15 residential wells was performed twice in 1978 (spring and fall) and once in 1979 (winter). More monitoring wells and a better distribution of wells allowed for a more complete study of the groundwater system following reclamation. Chemical analyses of 1978 well samples are summarized in Table IV.

Ten monitoring wells (group I) were drilled to the base of the reclaimed gob pile and showed a saturated zone of 0.4 to 4.7 m. Originally, it was assumed that grading the pile and reducing the steep slopes would greatly increase infiltration rates into the pile, but no significant changes in the basal saturated zone have yet been observed. The saturated basal zone has a large



Locations of wells after reclamation. Figure No. 3.

Table No. IV
Average[a] Post-Reclamation Groundwater Quality

Well Group	I	J	K	L	M	N	O	P	Q
No. of Samples	20	12	15	6	19	17	2	1	29
Spec. Cond[b]	16559	9172	4825	3054	2793	2869	7526	2447	1362
Median pH	4.30	4.94	6.50	6.88	6.93	6.90	5.05	6.90	7.09
Min. pH	2.56	3.22	4.26	6.70	6.38	6.51	—	—	6.32
Acidity	15209	9290	1373	67.7	156	168	3820	74.4	44.2
Max. Acidity	89775	68040	12380	108	443	402	—	—	114
Alkalinity	42	203	186	212	498	539	88	484	212
Bicarbonate	51	248	227	259	607	658	108	590	259
Boron	3.86	2.37	.74	.24	1.04	.42	2.87	.80	.68
Chloride	39	24	53	22	59	37	40	69	26
Sulfate	21745	8012	3946	1414	853	1303	5800	475	600
Silica	226	64.4	27.3	21.6	18.3	18.7	36.1	10.2	17.9
Calcium[c]	421	477	411	376	233	339	468	202	202
Magnesium	919	646	575	205	129	263	469	123	104
Sodium	630	363	192	229	262	172	327	209	80
Potassium	51.3	18.7	3.2	2.79	5.71	5.30	8.03	<.5	3.27
Strontium	1.47	.66	.84	.72	1.37	.79	.50	<.3	.68
Aluminum	2104	873	14.6	<.05	.041	.77	62.5	.20	<.10
Arsenic	.631	.369	.0047	.0030	.0020	.0008	.018	.0008	<.002
Barium	.169	.0477	.0182	.0190	.0265	.0240	.0132	.0215	.0178
Cadmium	3.06	.904	.051	.006	<.005	.006	.021	.008	<.010
Cobalt	1.90	1.06	1.17	.027	.025	.038	.360	.040	.034
Chromium	.817	.336	.012	<.01	<.02	<.02	.01	.02	.04
Copper	.189	.119	.030	.010	.006	.013	.052	<.01	<.01
Iron	4172	1940	444	.613	6.39	1.74	937	.60	1.20
Max. Iron	14170	11100	4800	2.03	30.1	11.27	—	—	12.0
Manganese	82.7	60.1	90.6	2.11	4.59	3.14	30.0	.20	.20
Max. Mn	329	194	645	2.34	10.8	12.6	—	—	1.68
Nickel	6.56	3.39	1.26	.04	.02	.06	.97	.06	.01
Lead	.393	.254	.125	.070	.045	.093	.130	.030	.042
Zinc	322	136	22.5	.020	.019	.105	34.6	.230	.083
Max. Zinc	1465	825	245	.044	.073	.700	—	—	.590

[a] All chemical parameters are reported as mean concentrations, except pH which is a median; minimum pH and maximum acidity, iron, manganese, and zinc are also reported for most well groups.

[b] Specific conductance is reported as mhos/cm at 25°C, pH in standard units, acidity and alkalinity as mg/L $CaCO_3$ equivalence, and other parameters are reported in mg/L.

[c] Dissolved cations were analyzed from filtered, acidified samples.

Well Group Locations - Post-Reclamation Monitoring

I. In base of gob material (P5-P11,P14,P21,P23).

J. In till beneath or < 5 m from gob pile (P4,P13,P16,P17,P22,P24).

K. 5-30 m from gob pile (P3,P12,P15,P18,P19,P20,P43).

L. > 30 m W and N of gob pile (P1,P2,P44).

M. In saturated slurry material (P27,P28,P31,P32,P36-P41).

N. In till around slurry material (P25,P26,P29,P30,P33-35,P42,M19).

O. In saturated slurry material < 5 m from main drainage channel (P45).

P. In alluvium downstream of disposal site (M27).

Q. All residential wells (R1 through R15).

diversity of water quality characteristics, with pH varying between 2.56 and 6.46 and specific conductance between 2700 and 36,900 µmhos/cm. In general, the basal water has a low pH (< 4.30) and very high concentrations of acidity, boron, sulfate, silica, and dissolved cations. Particularly high are magnesium, sodium, aluminum, cadmium, cobalt, chromium, iron, manganese, nickel, and zinc. Also found in high concentrations are lead and arsenic, which were not analyzed during pre-reclamation studies. Groundwater in till beneath the pile or less than 5 m from the pile (well group J) has slightly higher pH, lower acidity, lower specific conductance, and concentrations of most ionic constituents of about one-half that found in the refuse leachate. At distances of 5 m to 30 m from the pile (well group K), a marked improvement in water quality is noticeable. At distances greater than 30 m west and north of the pile (well group L), groundwater in the till approaches the average residential well quality (well group Q) with the exception of sulfate, sodium, and manganese, which are moderately higher.

During grading of the pile at the beginning of the reclamation phase, the refuse was spread over a larger area, thereby covering most of the area southeast, south, and west of the former pile where groundwater was contaminated. Post-reclamation wells P15 and P18 (within 30 m south of the new pile edge) are in an area that formerly had relatively good water quality, but now show preliminary signs of acidification since the reclamation project. It is likely that the groundwater quality in this area will take several years to readjust to the new physical and hydrological conditions.

Since the reconstruction of the dam and the filling of the new pond with low-acidity water, groundwater levels in the slurry material (well group M) have risen and groundwater quality has greatly improved, with only boron, sodium, iron, and manganese slightly elevated above ambient levels (residential wells). The average water quality for these wells is very similar to that of the group E pre-reclamation slurry wells. The exception is well P45 (group O), located near the center of the site next to the drainage channel. As in some of the pre-reclamation slurry wells (group F), the water quality of this well reflects the acid water chemistry in the channel leading from the pile and indicates that the slurry material is being recharged to some extent from the channel.

Downstream of the dam in the channel alluvium, monitoring well M27 (group P) has lower concentrations of most constituents relative to pre-reclamation conditions (group G). This may be due either to seasonal effects and time of the single sample collection or to the large reduction of total dissolved solids in the site discharge which is mixing with groundwater in the alluvium downstream of the site.

Water quality of residential wells (group Q) has not changed significantly since reclamation of the disposal site. Although quite hard and high in sulfate in some cases, the residential wells do not appear to have been affected by either coal refuse disposal or site reclamation. Residential well R1 is closest to the disposal site (Fig. 3) and has only slightly higher concentrations of acidity, boron, sulfate, and calcium relative to other residential wells.

SUMMARY OF SITE INVESTIGATION

Groundwater quality within 60 m of the gob pile has not improved since reclamation and, in some cases, has declined because the pile was spread over a larger area. Although not yet quantified, it also appears that an increased amount of water infiltrating into the top and side terraces of the pile is causing greater flow of acid water seeping from the base of the pile and probably increased recharge of groundwater by the leachate. Concentrations of acidity and most metals in groundwater decrease with distance away from the pile and approach ambient levels at a distance of less than 200 m. Surface flow of acidic water to lowland areas around the pile may have been a significant transport mechanism in the spread of contaminants to the groundwater system.

Groundwater quality has greatly improved in the reclaimed slurry area (north part of site) because the acid drainage from the gob pile is now diluted and partially neutralized in the pond to create improved surface water quality. Interchange of water between the pond and the saturated slurry material, therefore, may be improving the groundwater quality. Also, with creation of the pond, water levels have risen in the slurry material and may be reducing the subsurface oxidation rate of pyrite by the exclusion of atmospheric oxygen.

It appears that neither coal refuse disposal at the site in the early 1900's nor the recent reclamation project have altered the relatively good water quality in residential wells within 0.6 km of the site. Well R1, located closest to the site, may have slightly higher concentrations of acidity, boron, sulfate, and calcium than the "average" residential well, but further investigation is necessary to determine if the well intercepts groundwater from the disposal site.

NEEDS FOR FURTHER RESEARCH

Water samples collected from the saturated base of a coal refuse (gob) pile can be extremely acidic and contain very high concentrations of boron, sulfate, and transition and heavy metals. Although the coal refuse lay unreclaimed at the Staunton site for over 50 years, the spread of contaminants in the shallow groundwater system occurred only in an area within 200 m from the pile and adjacent to the channel that carried surface water from the gob pile. However, at other sites in the country where coal refuse has been deposited on sand and gravel (e.g., glacial outwash material or alluvium) or in areas where bedrock aquifers are exposed at the surface, the greater permeabilities of these materials could permit impacts to groundwater systems much greater than those observed at the Staunton site. Such cases are of concern and should be investigated further.

The mechanisms of retardation or attenuation of contaminants as coal refuse leachate travels through the groundwater system are important processes that must be better understood. The mobility of the contaminants may be controlled by a variety of adsorption processes (e.g., cation exchange and adsorption by colloids, amorphous hydrous metal oxides, and organic matter), precipitation, and coprecipitation. These processes have been investigated for nuclear waste disposal sites (29,31) and municipal refuse disposal sites (32,33,34). A study of reactions between acid coal mine water and a variety of soils in Pennsylvania showed that higher values of base saturation, cation exchange capacity, pH, and $CaCO_3$

equivalent of the soils resulted in greater amounts of acidity, iron, zinc, aluminum, copper, and manganese being removed from the mine water (35). In addition, specific conductance of the water was reduced by reactions with the soil, indicating that precipitation of dissolved species, as well as cation exchange and adsorption phenomena, was occurring. With a better understanding of these processes, future disposal sites can be chosen with sufficient carbonate content and adsorption capacity to adequately retard contaminant migration.

Studies involving the movement of water within the piles are also recommended. Future plans for this research project include investigation of infiltration, moisture movement, and percolation of water through unreclaimed and reclaimed refuse material. It is apparent that water is perching on the gob-soil cover interface within the reclaimed gob pile at Staunton. Chemical bonding by the ground limestone or a textural discontinuity at that interface may be the cause. Subsurface movement of water along the interface on the sides of the gob pile may have contributed to sloughing, piping failure, and increased erosion of the soil cover on some areas of the hillsides.

One question that arises and may take many years to answer is whether the covering of coal refuse with a soil layer will control the subsurface oxidation and leaching of pyrite. At present, substantial amounts of soluble sulfate salts are present within the Staunton refuse pile and will produce an acid leachate for a considerable length of time. Theoretically, if pyrite oxidation is eliminated by reclamation, then the acidity of the leachate will gradually diminish as the salts are flushed from the pile. However, if the oxidation process is continuing, then the leaching of acid, metals, and sulfate from the refuse will persist. At some active coal refuse disposal sites, where concurrent reclamation is taking place, seeps from the refuse have been reported to be neutral to slightly alkaline. Whether this is common and whether reclamation techniques can effectively prevent acid leachate formation under long-term situations should receive further scrutiny.

The projected growth of coal production and cleaning will result in an estimated 155 Mt of coal refuse being produced annually by 1985 (36). Present and future disposal sites will be regulated through the Office of Surface Mining and state agencies. In addition, the possible classification of coal refuse as a hazardous or special waste under provisions of the Resource Conservation and Recovery Act of 1976 could lead to additional disposal regulations by the U.S. EPA. Also, the Office of Surface Mining, together with state organizations, will undertake numerous reclamation projects, costing millions of dollars, to correct hazards and environmental problems associated with abandoned disposal sites. With additional research into the hydrology and geochemistry of these disposal sites, valuable information may be used to develop reclamation techniques that will reduce infiltration, pyrite oxidation, and acid leachate formation, as well as identify siting criteria that will maximize retardation of contaminants as they travel through groundwater flow systems. From the research currently being conducted at the Staunton research site, it appears that future coal refuse disposal will not present significant groundwater problems if located on a calcareous, low to moderately permeable material, and if reclamation is carried out according to current regulations.

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