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Design, Construction, and Monitoring of the Ground-Water Resources of a Large Mine-Spoil Area: Star Fire Tract, Eastern Kentucky

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Donald C. Haney, State Geologist and Director
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DESIGN, CONSTRUCTION, AND MONITORING OF THE GROUND–WATER RESOURCES OF A LARGE MINE–SPOIL AREA: STAR FIRE TRACT, EASTERN KENTUCKY

David R. Wunsch, James S. Dinger, and Page B. Taylor

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COVER

Drill rig used for installation of a 240-foot-deep monitoring well in mine spoil at the Star Fire tract. Part of the 35-acre experimental goose lake constructed on the reclaimed spoil is visible in the foreground.

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David R. Wunsch, James S. Dinger, and Page B. Taylor

ABSTRACT

By the year 2010, the Star Fire mining operation in Knott, Breathitt, and Perry Counties in eastern Kentucky, which uses mountaintop-removal and hollow-fill mining techniques, will have created approximately 5,000 acres of gently rolling terrain that could support alternative land uses. The present research is centered on approximately 1,000 acres of spoil created since mining began in 1981. An aquifer fed by both ground and surface water will be created within the spoil. Spoil-handling techniques such as cast blasting, dragline placement, end dumping by trucks, and surface grading have created porous coarse-rock zones within the spoil through which ground water can move. A vertical rubble chimney in the spoil has been constructed of durable rock to enhance infiltration to the ground-water reservoir through a surface infiltration basin.

Fourteen monitoring wells have been installed along with flumes to gage surface-water discharge and monitor water quantity and quality at the site. Dye-tracing studies have identified ground-water flow paths and flow velocities. A preliminary assessment of the water resources at the site indicates that a stable water table has been created at the mined site. Based on an average saturated thickness of 21 feet for the entire site and an estimated porosity of 20 percent, the spoil stores approximately 4,200 acre-feet (1.37 billion gallons) of water.

Dye-tracing data, hydraulic gradients, and water-quality data indicate that ground water moves more slowly in the spoil's interior; from there it flows down into the hollow fills before discharging as springs along the bottom of the spoil. The springs discharge approximately 1 million gallons per day under normal flow conditions, and discharges of approximately 5 million gallons per day have been measured a week after rainfall events.

Chemical analyses of water samples taken from wells and springs in the spoil indicate that the water is a calcium-magnesium-sulfate type. All but one of the samples had pH measurements between 6 and 7, indicating that the spoil does not produce highly acidic water. Total dissolved solids typically range between 618 and 3,042 mg/L, with a median value of 2,162 mg/L.

INTRODUCTION

The Eastern Kentucky Coal Field is an intricately dissected upland characterized by narrow, crooked valleys and narrow, irregular, steep-sided ridges. Local relief ranges from 300 feet along the Ohio border to 2,500 feet near the Tennessee border.

Like much of Appalachia stretching from New York state to Alabama, the Eastern Kentucky Coal Field is characterized by insufficient water supplies to support large-scale urban and industrial development. Where development has occurred, it has predominantly taken place in the floodplains along major streams, which provide both water and flat land. Most of this preferential land in eastern Kentucky was settled decades ago, leaving for future development areas highly susceptible to flooding or having steep hillsides. Apart from the few rivers that cross the region, water supplies are available primarily through the use of cisterns, which often go dry in the summer months, and ground water from springs and wells, which generally produce less than several gallons a minute. These obstacles greatly inhibit future economic growth in the region.

The Kentucky Geological Survey is directing a research program to study the factors important to the development of water supplies at large surface-mined areas. The research is being conducted at the Star Fire Mine operated by Cyprus Mountain Coal Company, located in Knott, Breathitt, and Perry Counties in eastern Kentucky.

This paper discusses the concepts of defining and developing a water supply in the spoil generated by mountaintop-removal and hollow-fill coal mining. It documents the initial planning, construction, and recharging of a man-made aquifer in mine spoil. It reviews monitoring methods employed at the site, initial ground-water quantity and quality, and data from the aquifer gathered from 1987 through September 1991. Knowledge gained from this investigation will provide a water-resource assessment for post-mining land uses, and, it is hoped, provide for divergent economic development at the large-scale surface mining sites in Kentucky and the rest of the Appalachian coal region.

In 1990, Kentucky produced more than 170 million tons of coal, ranking number two in the Nation. However, due to more efficient mining techniques, the work force generating this production has been reduced approximately 30 percent since 1980, and unemployment among the general work force is estimated to be 10 to 20 percent. A principal cause for this high unemployment rate is the lack of economic diversification. Among other things, economic diversification is hampered by the lack of water supplies and suitable land because of the rugged topography. Water supplies sufficient to support economic development are restricted to the larger streams, and even these supplies must be enhanced by construction of expensive reservoirs. Rugged terrain also makes pumping water from the source of treatment to outlying areas difficult.

The Star Fire Mine encompasses parts of Breathitt, Perry, and Knott Counties and is located approximately 5 miles northeast of Hazard, Kentucky, near the Daniel Boone Parkway (Kentucky Highway 80) (Fig. 1). Regional geology of the site is mapped on the Noble (Hinrichs, 1978) and Vest (Danilchik and Waldrop, 1978) 7.5-minute geologic quadrangle maps. The coal zones being mined include the Hazard Nos. 7, 8, 9, and 10 beds (Fig. 2), all of which are part of the Breathitt Formation of Pennsylvanian age. These beds range in thickness from 3 to 7 feet, and several of the zones contain rider coals that are also mined. The overburden at the site consists of calcareous sandstones and shales, and mine-permit data indicate that the potential for acid-mine drainage is low because of the high net neutralization potential of the overburden lithologies at the site.

Figure 3 shows the major drainages and the sequence of mining to be completed by the years 1989, 1995, 2002, and 2007 for jobs 5 and 7 at the Star Fire Mine. The total area of approximately 17,000 acres is expected to be mined. Dinger and others (1987) used the computer model Sediment, Erosion, Discharge by Computer Aided Design (SEDCAD+) (Schwab, 1987; Schwab and Warner, 1987) to estimate annual total

Figure 1. Location of the Star Fire Mine.

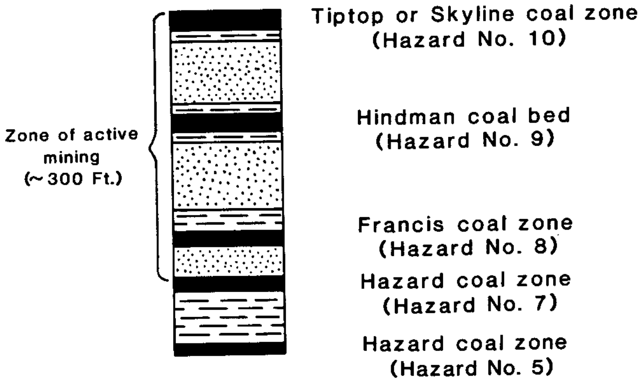

Figure 2. Schematic geologic column showing near-surface coals in the study area. All units are part of the Breathitt Formation of Pennsylvanian age.

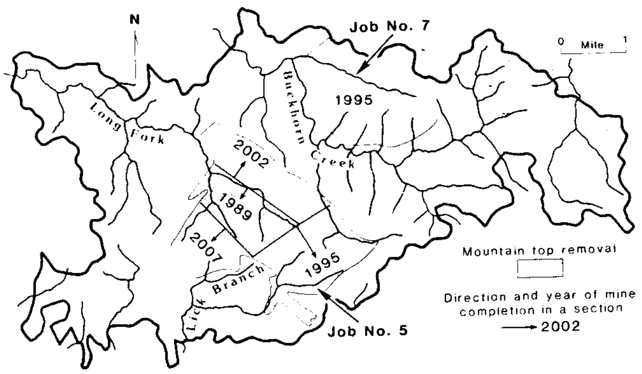

Figure 3. Drainage basins and sequence for mining job 5.

runoff for the site in 1995 and 2007, which is when major sections at both job sites will be completed. The model estimated that an upper limit of 2,770 and 2,960 acre-feet of annual runoff would be generated in 1995 and 2007, respectively. Mountaintop-removal mining methods are being used at each job site, with primary emphasis presently being placed at job 5. At job 5, truck-and-shovel techniques are recovering the Hazard No. 9 and No. 10 coals, and a 64-cubic-yard bucket dragline is employed to mine the No. 7 and No. 8 seams. In the process of mining, a 100- to 300-foot thick spoil backfill is being created over the site.

Three major watersheds drain the 17,000-acre site: Buckhorn Creek (8,019 acres), Long Fork (5,129 acres), and Lick Branch (2,049 acres) (Fig. 3). Field observations indicate that these streams react quickly to precipitation events and have low flows during the summer months. These characteristics do not lend themselves to a reliable long-term condition upon which significant economic development can depend. Therefore, the present research has been established to measure the effects of mining on the hydrologic system at the site, and it is anticipated that mine spoil has the potential, with advanced planning and development, to significantly increase ground-water availability and baseflow conditions in the streams.

SPOIL AND AQUIFER CONSTRUCTION

Several facets of the spoil have been studied at job 5 since August 1987 in the section of the mine completed between 1981 and June 1989 (Fig. 3). These facets are: (1) the distribution of coarse-rock zones within the spoil that allow recharge and movement of ground water (i.e., the creation of an aquifer framework), (2) design and construction of infiltration basins to enhance recharge to the ground-water reservoir, and (3) design and installation of a monitoring-well network to characterize ground-water quality and quantity in the spoil material.

Discussions with mine personnel and direct observation of the mining process indicate that selected spoil-handling techniques have produced a rock framework important to the development of an aquifer within the spoil (Fig. 4). Where the mine has crossed tributaries of the surface drainage system, selected durable rock hollow fills were sometimes created to provide subsurface drainage for the mine (see Fig. 4, feature A). These hollow fills should provide for storage and rapid movement of ground water at the base of the spoil material. These fills are not continuous throughout the 1989 section of spoil, however, so ground water migrating to these fills may be restricted in movement down gradient, where finer size spoil material was placed into the hollow fill. In the future, hollow fills in other sections of job 5 will be designed to retain ground water in general but also to provide selected points of subsurface drainage from the spoil to streams as base flow. This design should provide continuous flow to surface reservoirs; the reservoirs will probably be constructed in the lower reaches of Buckhorn Creek and Long Fork. Providing subsurface drainage points will allow the dams creating the reservoirs to be downsized, which will reduce costs, and water level for each reservoir can be stabilized.

A second type of coarse boulder zone exists continuously on top of the pavement rock for the Hazard No. 7 coal seam *(see* Fig. 4, feature B). This zone ranges from 15 to approximately 30 feet in thickness, and is created when part of the under burden of the No. 9 seam is cast blasted into the open pit after the No. 7

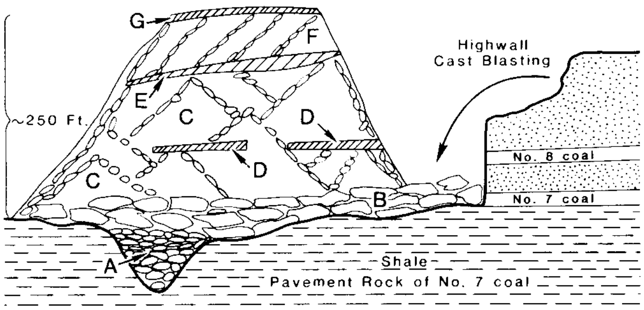

Figure 4. Schematic cross section showing components of spoil significant to the development of an aquifer framework. A = hollow fill, B = cast-blasted rubble, C = dragline spoil, D = dragline pad, E = temporary haul road, F = end-dumped spoil, and G = final graded land surface.

seam is removed. This zone, like the hollow fill, should permit the storage and rapid movement of ground water. Because of its thick and continuous nature, it is anticipated to be the preferred zone from which to pump ground water for a water supply.

The spoil material cast by the dragline also produced numerous inclined layers of coarse aggregate (see Fig. 4, feature C). These layers are created by gravity sorting of the spoil material when the material is dumped from the dragline bucket. In this process the larger, heavier rock fragments separate from the finer material and accumulate from the bottom up along the outer edge of each spoil cone. As mining continues, the spoil cones, and therefore the coarse layers, coalesce to create interconnected pathways for ground-water movement. These pathways should act as recharge routes from the land surface to the boulder zone at the base of the fill, whereas the finer material within the spoil cones may behave as extensive storage reservoirs for ground water if the spoil cones become saturated at some point.

Another sequence of coarse inclined layers are also found in the upper 30 feet of the spoil material, where spoil has been end-dumped by truck hauling (see Fig. 4, feature F). In some instances, this sequence occurs in double layers of spoil, or lifts, but the lifts are not continuous over the entire surface of the mine. The coarse rock layers occur in the same sorting pattern as cast dragline spoil (see Fig. 4, B-C), but are not as thick or as extensive. These sequences should function as ground-water recharge paths from the land surface of the mine into the spoil.

Figures 5 through 7 illustrate the features discussed above. Figure 8 is a schematic diagram of the distribution of these coarse zones within the spoil and the orientation and potential connectivity among the coarse rock layers.

In contrast to the coarse zones, compacted zones are also produced by mining within and on top of the spoil (see Fig. 4, features D, E, and G). A pad for the dragline is built with bulldozers, and the subsequent operation of the dragline from this pad compacts the spoil (Fig. 7). Although this compacted pad is fairly continuous parallel to each mine panel, breaks occur between pads of successive panels and along any panel where the dragline has not been stationed to operate.

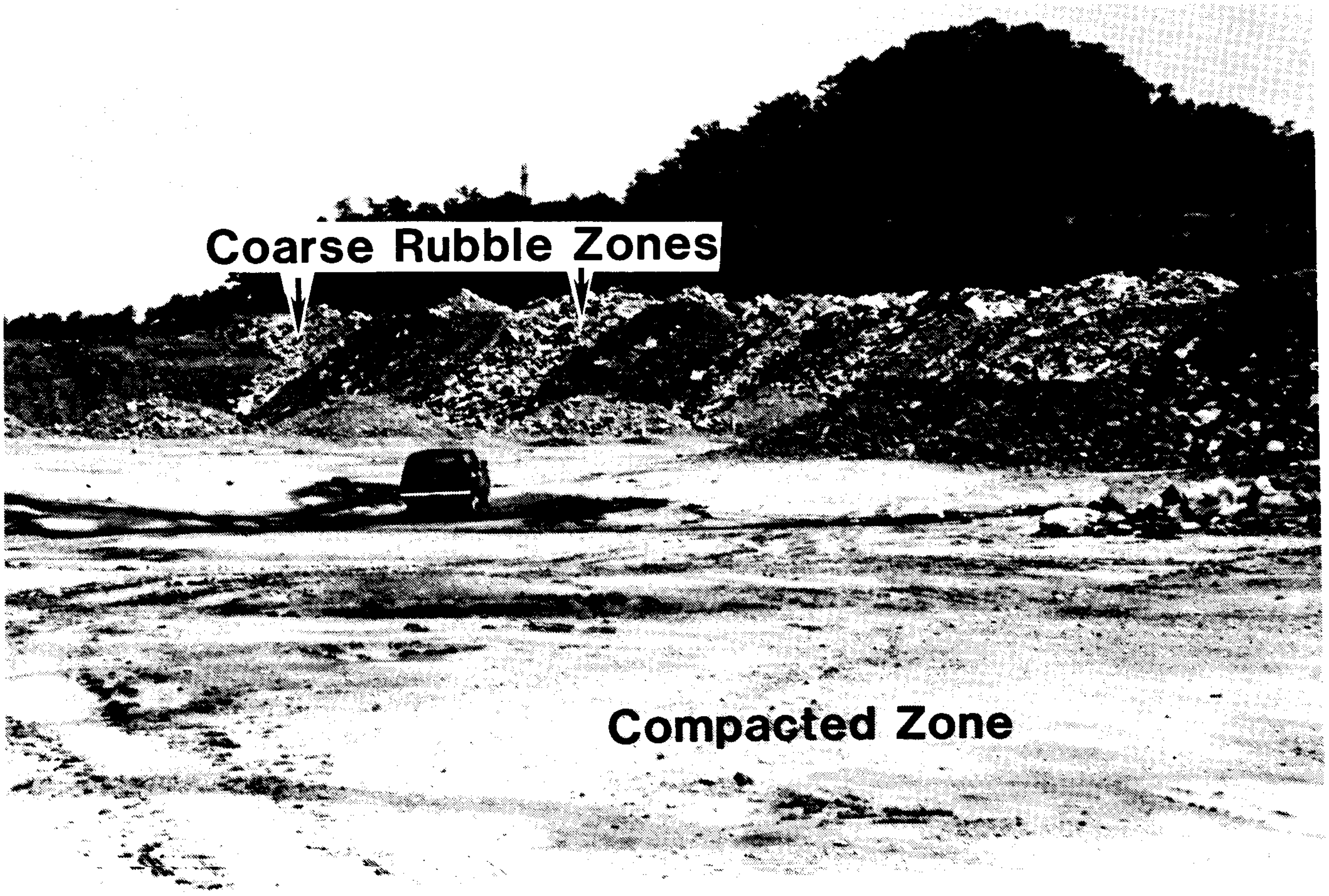

Figure 5. End-dumped spoil on top of temporary haul-road surface.

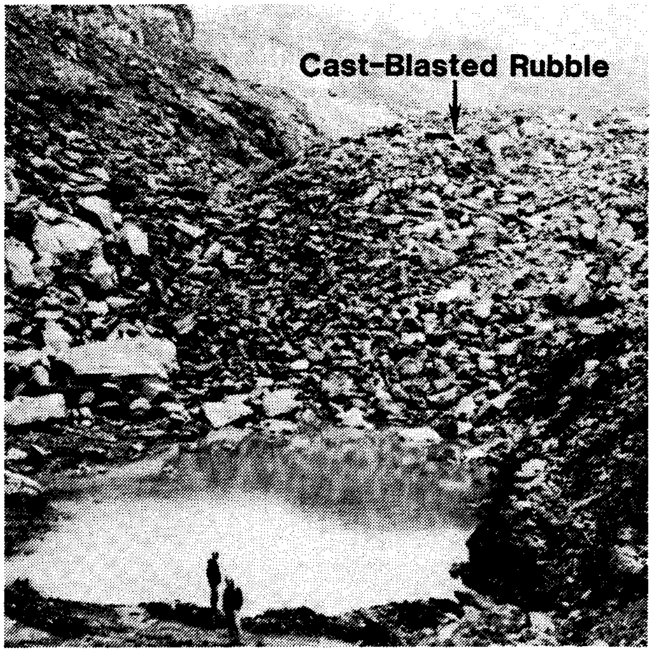

Figure 6. Cast-blasted rubble.

In addition, the pad is constructed on coarse material at the top of the previously placed spoil cones and castblasted material. It is anticipated that this coarse material will retain considerable permeability despite construction activity and use of the pad by the dragline.

Two other compacted zones are created by bulldozers, motor graders, and haul trucks in the process of providing access roads to the active pit and in end-dumping operations. This compaction takes place in the upper 5 feet of the surface being traveled upon. However, the compacted zones on the temporary haul roads (*see* Fig. 4, feature E) are not continuous across the mine surface, which allows subsurface water to move through non-compacted spoil.

The final graded land surface is continuous (*see* Fig. 4, feature G) and could readily prohibit surface water from infiltrating into the spoil material. Upon completion of mining, surface infiltration will be the only mechanism for recharge to the ground-water system. Therefore, the construction of infiltration basins that will capture surface runoff from the land surface and recharge the ground-water system within the spoil is being investigated.

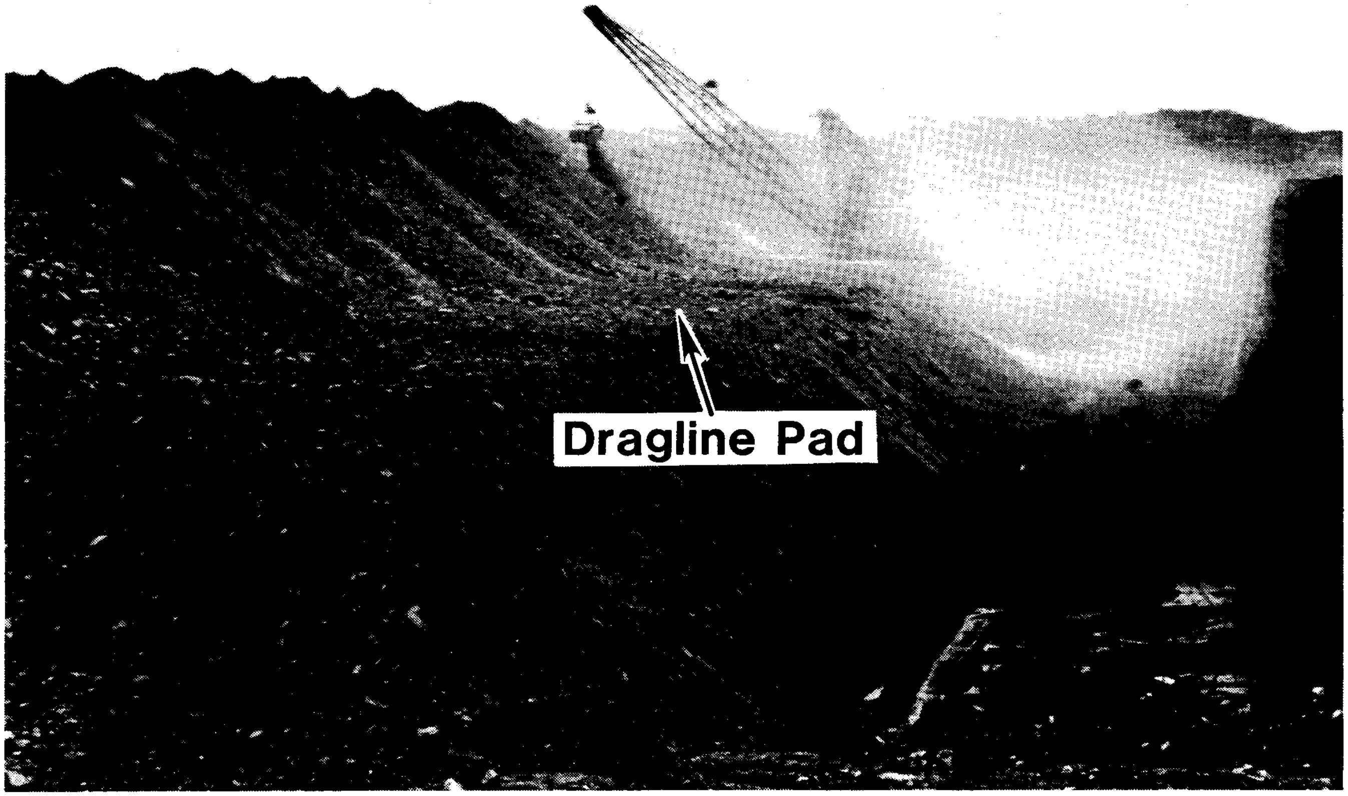

Figure 7. Dragline pad built on spoil.

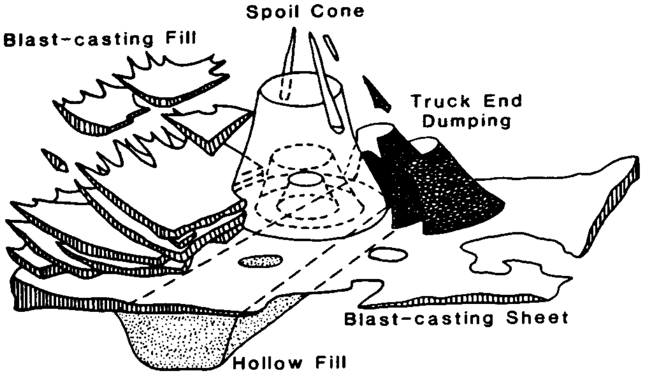

Figure 8. Schematic diagram showing spoil cones and possible connectivity among zones composed of coarse rock spoil.

INFILTRATION BASINS

In addition to the relatively impermeable surface of the graded spoil area, future construction of impervious structures such as paved roads, parking lots, and buildings would substantially hinder recharge to the groundwater system. Therefore, infiltration basins constructed in the spoil may be the best way to facilitate groundwater recharge. To this end, special techniques are being pursued to capture surface runoff from the land surface to recharge the ground-water system within the spoil material.

Two alternative infiltration-basin depths were proposed for the Star Fire project (Dinger and others, 1988): approximately 70 feet and approximately 250 feet. The shallow alternative was based upon the open space approximately 70 feet deep between spoil cones produced by the dragline (Fig. 9). A selectively filled rock chimney 70 feet deep may be deep enough to bypass the potential near-surface confining layer within the spoil (Fig. 10, features E and G).

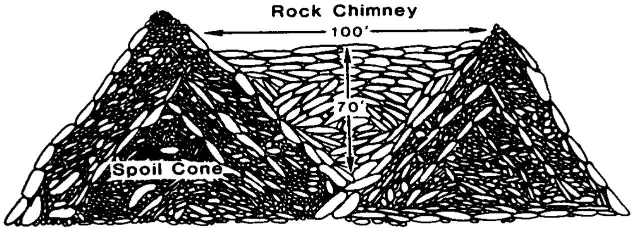

Figure 9. Schematic cross section of 70-foot-deep, V-shaped rock chimney for infiltration basin.

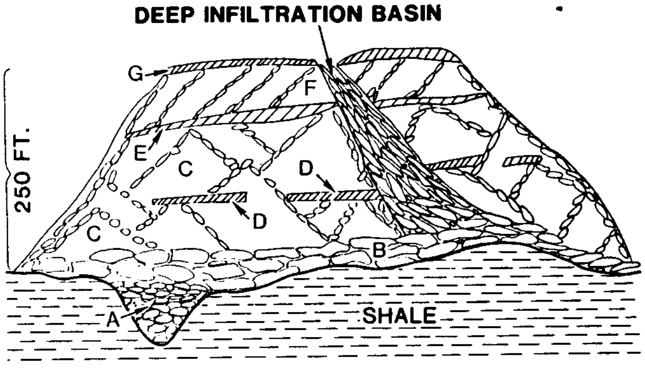

Figure 10. Schematic cross section showing deep infiltration basin and components of spoil significant to the development of an aquifer framework. A = hollow fill, B = cast-blasted rubble, C = dragline spoil, D = dragline pad, E = temporary haul road, F = end-dumped spoil, and G = final graded land surface.

Although the 70-foot alternative may prove to be as effective in recharging the spoil as the deeper option and more economical to construct, only one 250-footdeep chimney has been installed so far. The deep option was designed to function as a direct connection to the rubble zone resting on top of the No. 7 coal underburden (Fig. 10). This rubble zone is created by cast blasting the interburden rock from the highwall into the pit from which the No. 7 coal has been removed. The extensive rock chimney constructed to this zone bypasses all intermediate compacted zones within the spoil that might perch percolating ground water.

Analysis of ground-water data from the Star Fire project will permit an objective evaluation of the benefits of recharge capability versus the costs of aquifer construction. Continued monitoring of the ground water in the man-made aquifer over the next several years will result in greater knowledge of ground-water recharge rates, discharge rates, and quality. Continued monitoring of this site will also allow specific relationships to be determined between aquifer recharge, watershed area, number and location of infiltration basins, and costs of aquifer construction. Detailed knowledge about these relationships is essential for the successful completion of similar projects elsewhere in Appalachia.

SPOIL HYDROLOGY

Methods

In order to characterize the hydrogeology of the spoil aquifer, several research methods were utilized, including (1)precipitation measurements, (2) discharge measurement of streams and springs, (3) monitoring wells in spoil, (4) dye tracing in spoil, and (5) water-quality analysis.

Daily precipitation data from the gage at the Robinson Forest Camp were provided by the University of Kentucky Department of Forestry at the beginning of this study. The camp gage is a standard 8-inch non-recording gage located 3.5 miles from the study area. Subsequently, a tipping bucket precipitation gage was installed near the infiltration basin in May 1990.

Instantaneous discharge measurements were made at three springs discharging from the spoil (S 1, S 2, and S 3) and where Chestnut Gap Branch flows into the base of the spoil (swallet) in a manner similar to a disappearing stream in karst areas (Fig. 11). These springs were monitored to characterize the variability of discharge in relation to recharge events, determine the sources of recharge to the spoil, and determine the nature of ground-water flow through the spoil. Chestnut Gap Branch was monitored to determine the amount of recharge it contributes to the spoil aquifer.

Fourteen monitoring wells have been installed in the spoil to study the development and fluctuations (if the water table in the spoil, characterize the ground-water quality, determine the effectiveness of the deep infiltration basin, and determine the hydraulic properties of the spoil. Presently seven wells are equipped with TELOG continuous water-level recorders[1]. The location of each well and other features of interest are shown on Figure 12.

Two dye traces using Rhodamine WT were conducted: one at the Chestnut Gap Branch swallet and the other at monitoring well (MW) 1 (Fig. 11).

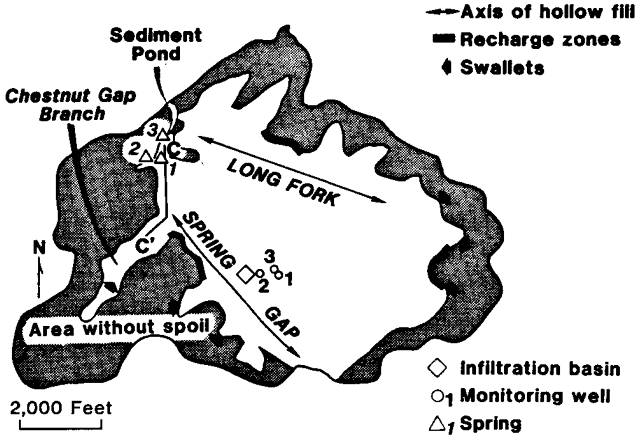

Figure 11. Locations of ground-water-related features.

Charcoal detectors were used to monitor the three springs. An additional detector was placed in Chestnut Gap Branch upstream from the dye introduction point In order to test for interference from organics. The elutriant from the detectors was analyzed with a Turner Model 10 filter fluorometer.

Water samples from the springs, monitoring wells, streams, and the deep infiltration basin were collected to establish water quality and determine changes in water quality that occur between recharge and discharge points. Samples have been collected on a monthly basis since May 1989 from springs and sporadically from wells since the summer of 1989. Some samples were taken from springs and wells to study recharge events. Temperature, specific electrical conductance, pH, sulfate, chloride, bicarbonate, calcium, magnesium, sodium, potassium, manganese, and iron were determined in most samples. In some cases nitrate was measured.

Recharge

Field reconnaissance of the study area revealed numerous places where streams and storm runoff recharge the spoil aquifer (Fig. 13). Several streams flowed directly into swallets at the toe of spoil slopes. The largest of these streams is Chestnut Gap Branch, a first-order stream with a watershed area of 0.32 square miles.

A number of recharge zones and specific points of recharge were observed on the spoil during storm runoff events (*see* Fig. 11). These zones occur at places where the spoil adjoins highwalls or natural bedrock slopes, or in places where boulder zones are exposed at the surface. The largest of this latter type of recharge zone is located in the northeastern portion of the spoil, where a depression approximately 150 feet deep has been left open since 1982. Storm runoff flowed into this pit and then rapidly disappeared into the spoil. Likewise, the deep infiltration basin has been partially functional in this regard, although its present watershed is limited.

Recharge also occurs when precipitation falls directly on ungraded dragline-cast spoil cones. The area of recharge varies depending on the amount of grading that has occurred, but an extensive area, often 2 million square feet or larger, is always present.

In addition to these major points of recharge, numerous small cracks and fissures in the spoil surface captured lesser amounts of storm runoff. Another source of

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[1] The brand names of products are included for informational purposes only. The Kentucky Geological Survey does riot endorse or promote the use of specific equipment.

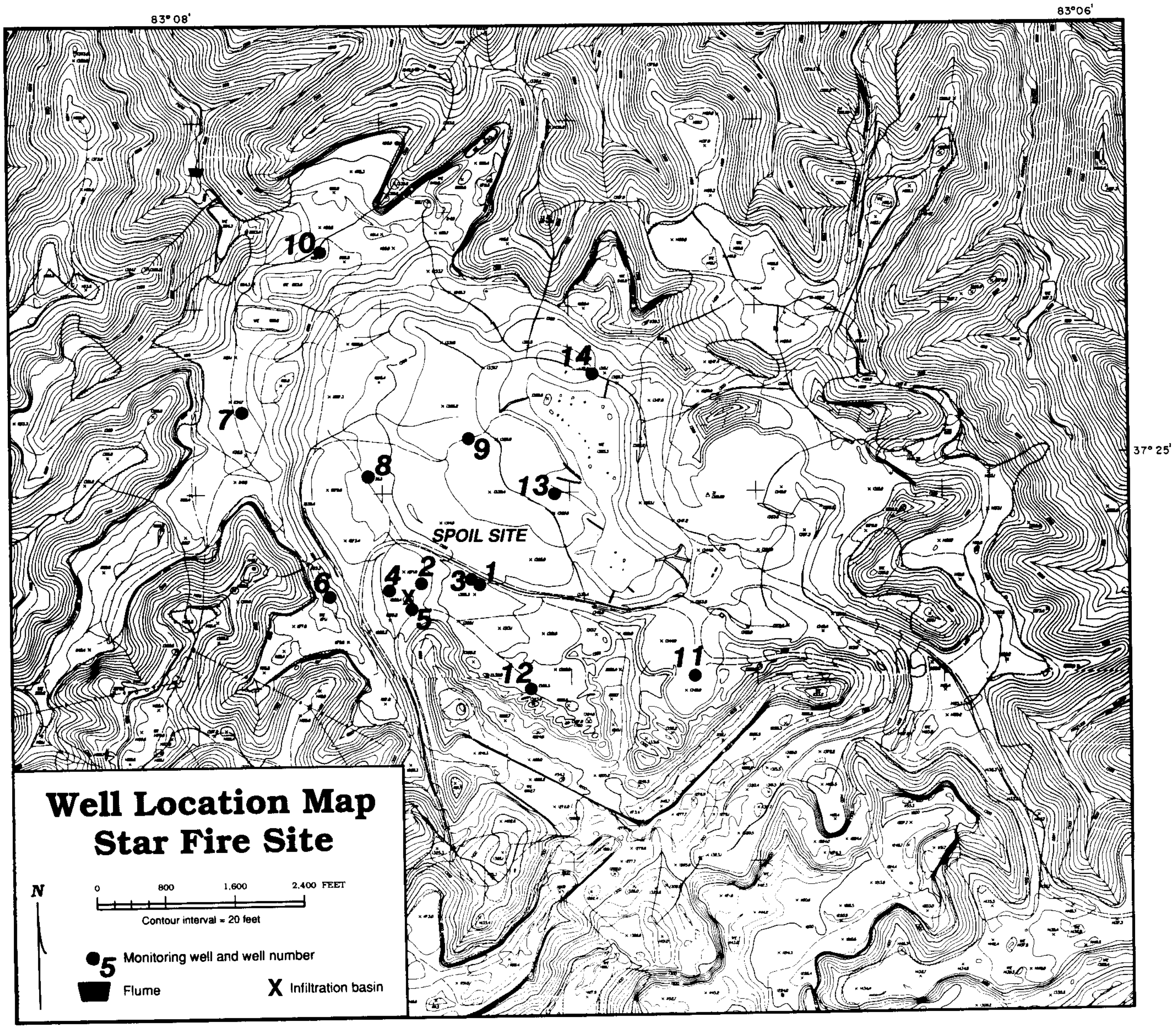

Figure 12. Location of monitoring wells, flume, and infiltration basin at the spoil site.

recharge to the spoil aquifer is the bedrock aquifer where it is in contact with spoil.

Infiltration through the spoil surface is not thought to account for a significant amount of recharge because of the compaction of the graded spoil. Drilling and excavation have shown that the spoil is dry within a few inches of the surface, and a thin sheet of mud forms quickly on the surface during storms, which indicates that rainfall does not easily infiltrate the spoil. This situation may change as vegetation re-establishes itself and aids in the development of soil profiles, resulting in a more porous surface structure.

Ground-Water Movement

Ground-water movement has been studied by examining discharge hydrographs and dye tracing to the springs, through water-level measurements in the spoil monitoring wells, and through ground-water-quality determinations made at both the springs and wells.

Spring Discharge

The most significant area of observed discharge is a group of three springs located at the northern toe of the Spring Gap Branch hollow fill (Fig. 13). This area has remained swampy throughout the time of field investigation. Spring 1 (S 1) is the largest of the three springs, and discharges at an approximate elevation of 1,040 feet. The discharge point is at the toe of a 130-footthick lift of end-dumped sandstone spoil that adjoins a 45-foot-thick lift of end-dumped shale with a lower permeability than the sandstone spoil (Fig. 11). During times of extremely high discharge, a number of small springs have emerged along the toe of this lift at the same elevation as S 1. Spring 2 boils up from a small hole in the middle of the 45-foot lift, about 200 feet from S 1 (Fig. 13), at an approximate elevation of 1,030 feet. Spring 3 discharges from a boulder zone along the outslope of the 45-foot lift at an approximate elevation of 1,010 feet (Fig. 13).

In contrast to the Spring Gap Branch hollow fill, discharge was not observed from the toe of the Long Fork hollow fill. Ground water is believed to be flowing through this hollow fill, but it discharges directly into the sediment pond at a point below the water level of the pond (Fig. 13).

Ground water also discharges from the spoil into the active dragline pit when the pit is at the level of the Hazard No. 7 coal bed. During the past 6 years, ground water has been discharging from the spoil into the active pit at a rate high enough to require daily pumping. On occasion, pumping rates have reached 360,000 gallons per day (gpd). Discharge measurements range from 1. 10 to 6.05 cubic feet per second (cfs) for S 1, 0. 13 to 0.41 cfs for S 2, and 0.58 to 1.37 cfs for S 3 (approximately 1 to 5 million gpd) (Fig. 14). Spring 1 is by far the largest of the three springs; its daily discharge is approximately equal to the volume of water used each day by the nearby town of Hazard, Kentucky.

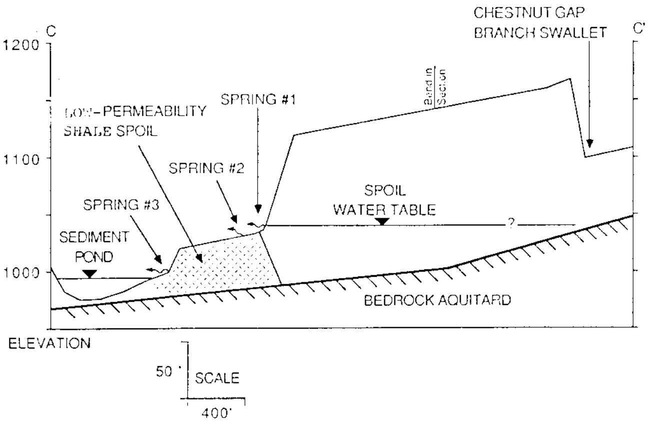

Figure 13. Cross section C–C' showing the configuration of the springs, spoil, and bedrock along the axis of the Spring Gap Branch hollow fill.

Flow at S 3 seems to correspond to flow at S 1, whereas S 2 generally flows at a steady rate, independent of recharge events. The rapid response of S 1 and S 3 to precipitation and their location at the base of the mine spoil are good indicators that these springs are discharge points for ground water moving through permeable spoil. Because of its location close to the bedrock valley wall and its steady flow, we can infer that S 2 is fed by ground water coming primarily from the bedrock through the low-permeability shale spoil that was dumped in this general location in 1982 (Fig. 13).

The difference in discharge between S 1 and S 3 also indicates the effectiveness of the low-permeability shale fill in reducing ground-water discharge from S 3. S 3 is at a lower elevation than S 2, but has a lower rate of discharge. If a flow barrier did not exist, and assuming that the spoil has a nearly uniform vertical hydraulic conductivity, the majority of discharge would be expected to occur at S 3 instead of S 1.

Spring 1 responded within an hour after the beginning of a storm that produced 1.37 inches of rainfall,

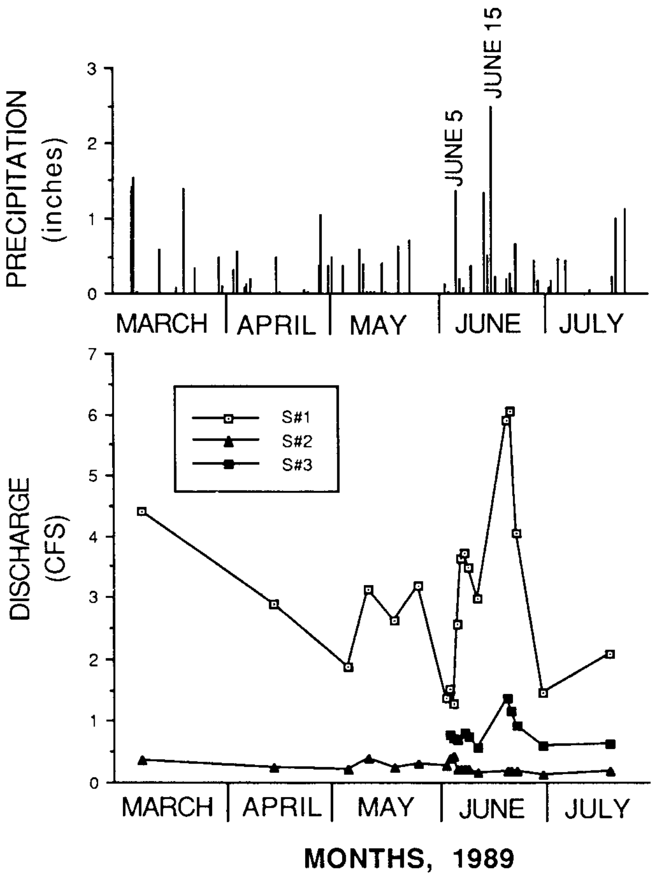

Figure 14. Precipitation and discharge hydrographs for springs 1, 2, and 3, March 1–July 25, 1989.

and after only 5 hours its discharge was measured at 70 percent of peak flow (Fig. 15). The peak discharge occurred between 29 and 50 hours after the storm began. This profile indicates that the spring responds quickly to recharge from a storm event. Such rapid flow through the aquifer suggests that the storm pulse moves along discrete high-porosity conduits composed of loose boulders (Caruccio and Geidel, 1984).

Figure 15 also indicates that the discharge recession for the 1.37-inch rainfall was slow and extended, in contrast to the rapid rise and peak in discharge. Measurements recorded on June 11, 1989, 4 days after the peak discharge, showed that S 1 was discharging at 80 percent of the peak. Because the spring does not recede as fast as it rises, the spoil must have the ability to store a significant amount of ground water and release it over an extended period of time. A similar hydrograph response was observed at S 1 after a three-storm event that began on June 13, 1989 (Fig. 14).

The source of recharge to the spoil aquifer can be determined by studying the relationship between S 1 and Chestnut Gap Branch, the largest stream recharging the aquifer. Figure 16 shows that two storms in June 1989 produced similar hydrographs at both gaging locations, reflecting the close relationship between recharge from surface runoff and peaks in spring discharge. However, the volume of water discharged from S 1 consistently exceeds the input from Chestnut Gap Branch, indicating that Chestnut Gap Branch is not the sole source of recharge to the spring.

It was determined that 90 percent of the flow at S 1 can be accounted for by ground-water recharge from Chestnut Gap Branch and Spring Gap Branch basins, based on hydrograph separation and recharge-to-area ratios. Thus, the large area of mine spoil to the east is not contributing significantly to the spring's discharge.

Ground-Water Levels

Table 1 lists the water levels of the spoil wells collected at approximately monthly intervals. Table 2 shows the elevation, depth, and water-level fluctuation exhibited by the monitoring wells. Water levels have varied from as little as 1.0 foot in MW 10 to as much as 9.0 feet in MW 6 (*see* Table 2).

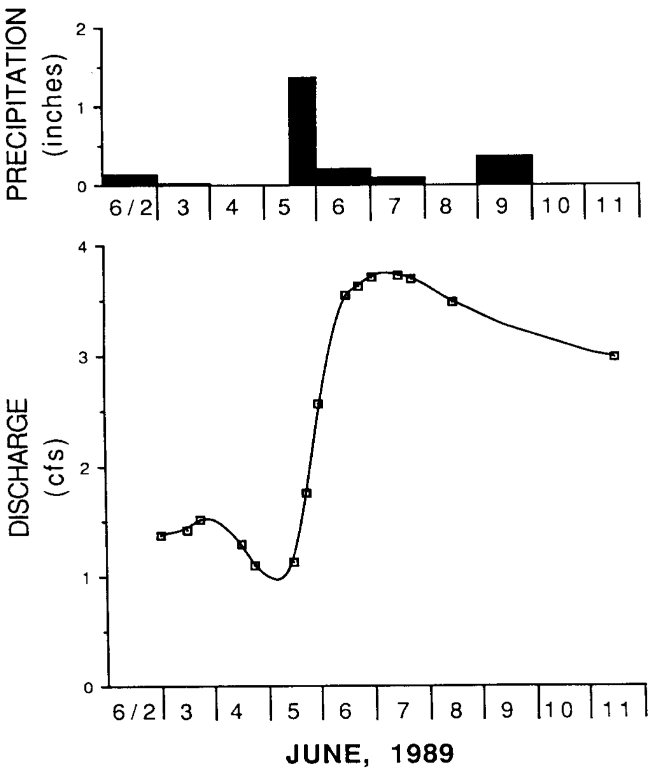

Figure 15. Precipitation and discharge hydrograph for spring 1, June 2–11, 1989.

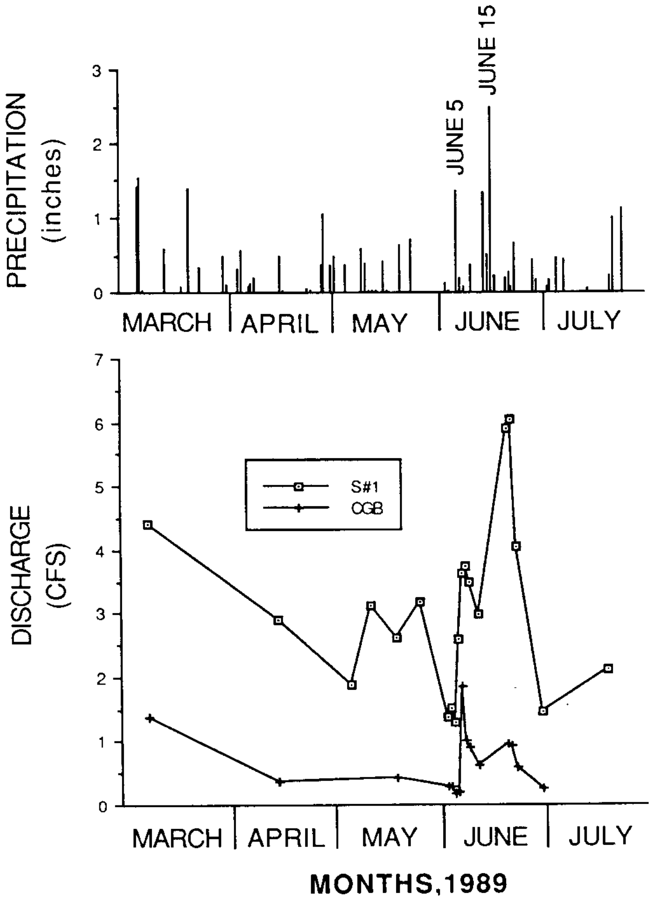

Figure 16. Precipitation and discharge hydrograph for spring 1 and Chestnut Gap Branch, March 1–July 25, 1989.

Table 1.—Water Levels in Spoil Monitoring Wells. Measured Water Level in Feet Above Mean Sea Level.

Date	*MW 1*	*MW 2*	*MW 3*	*MW 4*	*MW 5*	*MW 6*	*MW 7*	*MW 8*	*MW 9*	*MW 10*	*MW 11*	*MW 12*	*MW 13*	*MW 14*
9/20/90	1127.1	1127.4	1127.2	1126.7	1126.2	1123.2	1056.1	1127.5	1130.0	1049.2	1129.5	1133.4	1129.0	1121.0
10/24/90	1127.5	1127.6	1127.3	1126.0	1127.7	1129.2	1055.5	1127.7	1129.1	1049.6	1129.3	1126.5	1126.7	1121.4
2/26/91	1131.0	1131.2	1130.9	1126.1	1131.7	1124.0	1060.9	1130.5	1130.4	1049.6	1133.9	1132.2	1131.4	1123.9
3/13/91	1131.3	1132.5	1131.3	1126.4	1131.9	1125.1	1060.2	1130.9	1131.6	1049.2	1133.9	1132.5	1133.2	1126.6
5/30/91	1131.4	**	1131.4	1126.3	1132.8	1130.6	1060.4	1131.8	1129.7	1049.4	1135.0	1133.4	1130.6	1122.5
6/20/91	1131.7	1132.0	1131.6	1128.4	1132.4	1121.6	1049.5	1131.1	1130.4	1048.8	1135.3	1133.1	1131.5	1123.0
7/17/91	1132.5	1132.7	1132.4	1126.6	1133.3	1122.2	1059.8	1131.8	1131.1	1046.7	1136.7	1133.8	1132.4	1123.3
8/13/91	1132.6	1132.9	1132.5	1126.8	1133.4	1122.9	1059.0	1132.0	1131.1	1046.6	1137.6	1134.0	1132.2	1122.7

** defective data logger

Table 2.—Data for Spoil Monitoring Wells. All Values in Feet.

MW	*Casing Elev.*	*Depth to H_2O*	*Well Bottom Depth*	*Saturated Thickness 9/16/90*	*Fluctuation in H_2O Level 9/16/90 to 8/13/91*
1	1310.60	178.6	191.3	12.7	5.2
2	1275.70	143.3	165.2	21.9	5.6
3	1309.50	177.5	188.5	11.0	4.3
4	1272.71	147.0	168.8	21.8	3.1
5	1274.15	145.9	164.8	18.9	5.7
6	1179.91	54.7	80.0	25.3	9.0
7	1139.34	83.2	107.0	23.8	5.4
8	1290.54	163.0	170.0	7.0	4.5
9	1331.84	201.8	211.0	10.0	2.5
10	1166.69	117.5	155.0	37.5	1.0
11	1362.09	232.6	244.0	11.4	8.3
12	1312.92	179.5	196.5	17.0	5.5
13	1331.84	202.9	215.0	12.1	4.5
14	1324.00	203.1	239.0	35.9	7.8

Overall, the mean water-level fluctuation for all wells is 5.2 feet. The greatest fluctuation in water level was found in wells located in hollow-fill spoils on the fringe of the main spoil body (e.g., MW 6 and MW 14). Although located in the main spoil body, well 11 exhibited 8.3 feet of fluctuation for the record period. This well is the closest well to the active mining pit; thus, the changes in water level are most likely caused by mining-related activities such as pumping to remove water from the area of mining. It is estimated that 250,000 gallons per day have been pumped from the pit for several weeks at times during the monitoring period.

Hydrographs for the monitoring wells reveal some important behavior of the ground-water system (Fig. 17). Daily water-level averages for monitoring wells 4, 6, 9, 11, and 14 were calculated using software supplied along with the TELOG data loggers. Figure 17 shows a gradual increase in water level in each well from May 5,1991, till June 19,1991. Wells 4, 9, 11, and 14 exhibit a steady, gradual rise in water level, with well 6 showing an erratic hydrograph that closely parallels the precipitation pattern for the same period. The net rise in water level for well 6 is similar to the approximately 1 -foot increase exhibited by the other wells.

Well 6 is located near the bedrock wall that resulted from contour-cut mining that occurred in Spring Gap in the 1950's. Its rapid response to precipitation events is most likely caused by surface water quickly entering the spoil at the contact of the hollow fill and the valley walls by way of disappearing intermittent streams, drainage pits, and shallow ground water from the bedrock that is in contact with the spoil.

Based on an average saturated thickness of 21 feet and a porosity of 20 percent, an estimated 4,200 acre-feet (1.37 billion gallons) of water is stored in the 1,000 acres of spoil at the Star Fire site.

Dye Tracing

Two dye traces have been conducted at the site: at the Chestnut Gap Branch swallet (trace 1) and MW I (trace 2). In both traces the springs were monitored for dye discharge. Visual confirmation of dye discharge was overshadowed in the elutriant by a tea-colored interference fluid. Similar coloration has been reported in the literature, and is attributed to the presence of organic matter (Quinlan, 1986). Although visual inspection was unsuccessful, subsequent analysis of the elutriant with a fluorometer produced positive readings. These readings were reviewed with the knowledge

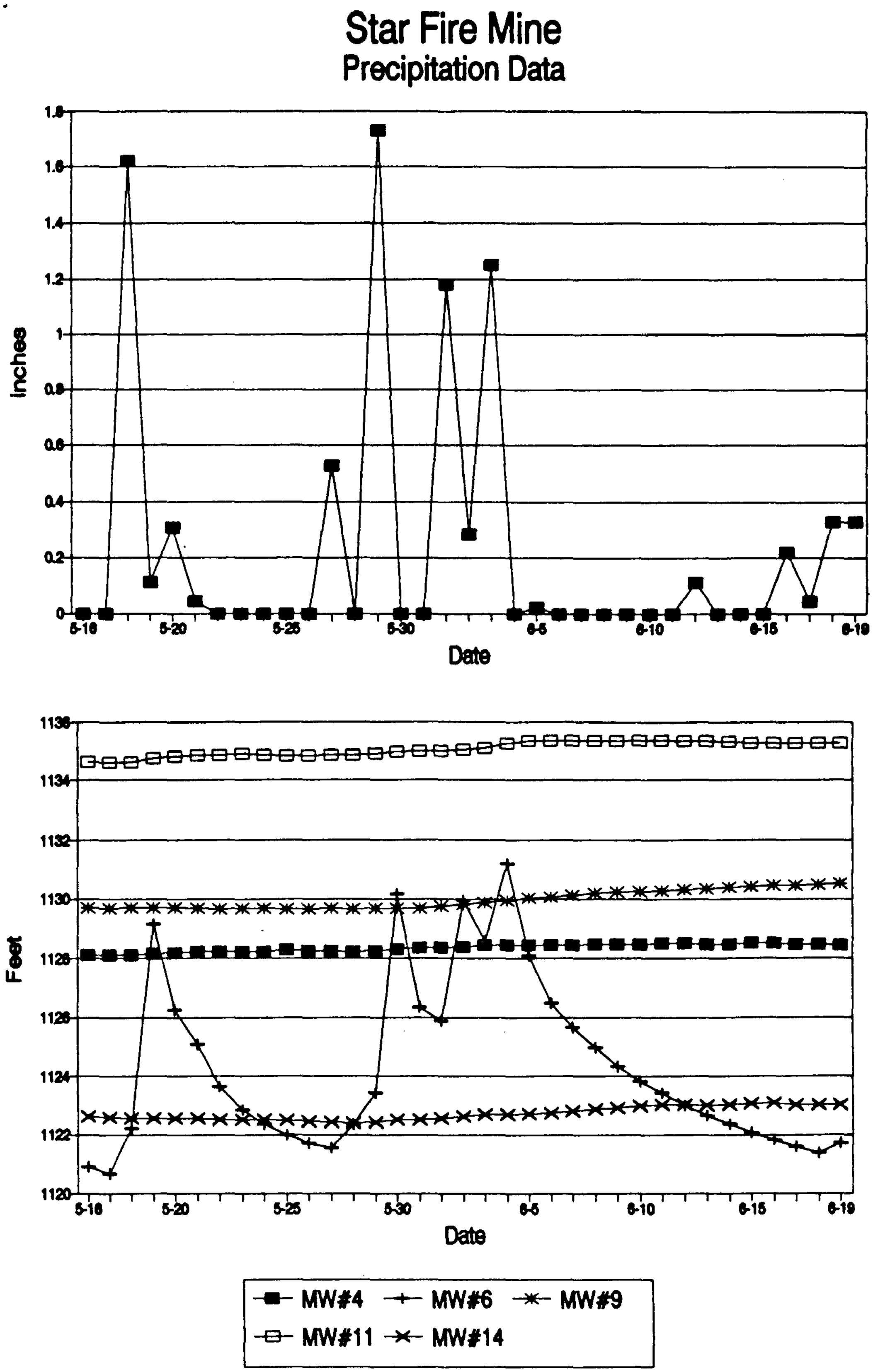
Star Fire Mine
Precipitation Data

Figure 17. Precipitation and well hydrographs for May 16–June 19, 1991.

that the intensity could be affected by the interference fluid, which fluoresces at a wavelength close to Rhodamine WT (Smart and Laidlaw, 1977). Dye concentrations at S 2 indicate that dye definitely arrived at the spring 49 to 93 hours after injection (Table 3).

Table 3.—Dye Concentrations for Trace 1.

Date Start	*Hours After*	*Dye Concentration* (µg/L)		
		S 1	*S 2*	*S 3*
2/22 to 2/27	–118–0	0.00	0.00	0.00
2/27 to 3/1	0–49	0.35	0.00	0.00
3/1 to 3/2	49–74	29.00	0.55	1.75
3/2 to 3/3	74–93	40.00	2.80	3.20
3/3 to 3/13	93–334	2.10	0.45	1.30
3/13 to 3/16	334–411	1.80	0.20	0.30
5/11 to 5/18	1749–1917	0.00	0.00	–

Breakthrough time (first appearance of dye) for trace 1 was used to calculate an apparent velocity, which ranged from 0.014 to 0.009 foot/second based on a straight-line travel distance of 2,400 feet and a travel time between 49 and 73 hours. This range is close to the flow velocity of 0.002 foot/second reported by Ladwig and Campion (1985), who used an unidentified tracer in spoil at a mountaintop-removal operation in Pennsylvania.

Dye injected at MW 1 was not recovered at any of the springs. Three months after dye injection, water samples from MW I showed high concentration of Rhodamine WT, indicating that ground water in the vicinity of the well is flowing slowly through saturated, porous media. This result is in contrast to the result of trace 1, in which flow was rapid through boulder zones in the hollow fill at Chestnut Gap Branch. This slower movement of ground water in this portion of the mine spoil and the lack of dye emerging from the springs also suggest that a low-permeability barrier exists between this area and the lower elevation hollow fill in the Spring and Chestnut Gap Branches; or the water in this area may discharge at some site other than the springs.

Water Quality

Chemical data for the water samples measured in the field are presented in Table 4. Figure 18 is a trilinear diagram showing the major cation and anion distribution of each water sample collected from wells in April 1990. The plotted position of each sample is a function of the relative percentage of the sample's major cations and anions normalized to 100 percent. All of the samples plot on the top left edge of the diamond-shaped field of the diagram, indicating that all of the samples have calcium or magnesium as the major cations, and sulfate as the dominant anion. One sample, taken from MW 14, is somewhat anomalous. Its distribution of cations (mainly calcium and magnesium) is consistent with the other samples, but its distribution of anions is different. The sample from well 14 has an extremely low bicarbonate content (2.99 mg/L), lower than the other water samples by approximately two orders of magnitude (the range of bicarbonate for all other samples is from 195 to 805 mg/L). The sample from well 14 also had a pH measurement of 4.18, which is the lowest pH encountered on the site. This well apparently bottoms in an area of "hot" spoil, where significant amounts of sulfide-bearing minerals are located and conditions are favorable for their oxidation. This setting produces acid-mine water, where the potential acidity exceeds the neutralization potential of the surrounding rock, resulting in acidic waters. Although a net neutralization potential for the entire site was predicted, well 14 indicates the existence of localized areas capable of acid production.

The neutralization of acid-mine waters by the calcium carbonate contained in the overburden is the dominant geochemical process affecting ground water at the site. This process is evidenced by the predominance of calcium-sulfate water with a near-neutral pH in monitoring wells spaced across the site. Overall, the pH of ground water *(see* Table 4) shows that the vast majority of the mine spoil does not produce highly acidic water. All of the ground-water samples, with the

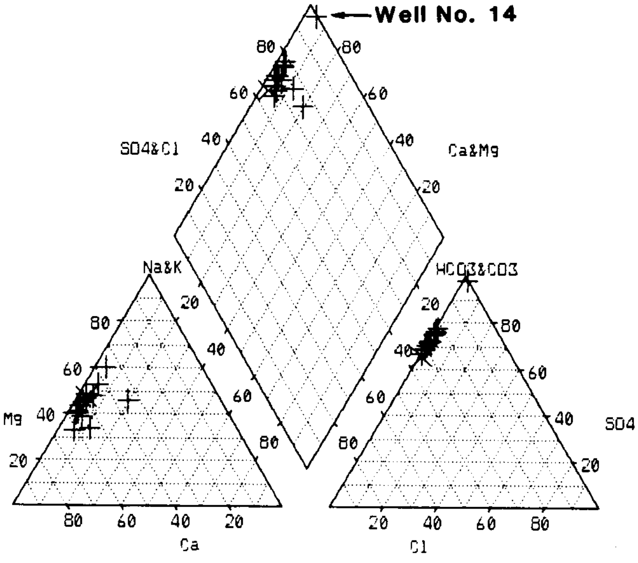

Figure 18. Trilinear diagram showing water types of ground-water samples from wells 2 through 14.

exception of that from well 14, have pH values greater than 6.0.

Dissolved iron content in the samples ranged from 0.35 to 31.3 mg/L. The two samples with the highest iron content came from wells 4 and 7, both of which are influenced by direct influx of surface water. Well 7 is directly downgradient from where Chestnut Branch disappears into the spoil. Well 4 is downgradient from where surface-water recharge enters the spoil through the infiltration basin. More data are needed (and are presently being collected) to ascertain the exact geochemical relationships that may exist between well location, surface-water recharge, and chemical characteristics.

The calculated total dissolved solids (TDS) for all samples indicates that ground water derived from wells located in the interior section of the spoil (monitoring wells, 2, 3, 5, 8, 9, 11, 12, and 13) have significantly higher TDS (mean = 2485.2 mg/L than ground water from the hollow fill areas (wells 4, 6, 7, 10, 14, and spring 1; mean = 1127.7 mg/L. This difference most likely results from the hollow-fill wells being closer to the highwall/spoil contact where less mineralized surface water can more easily recharge the spoil; also, the hollow fills are apparently separated from direct flow of the more mineralized ground water from the spoil interior.

Only one sample of water has been taken from the intermittent flow that descends into the infiltration basin (Table 4). This sample had a relatively low TDS value (177.8 mg/L) and a pH of 7.67. It is reasonable to assume that the majority of surface water entering the basin is similar in chemistry to this sample. Unless disturbed, the spoil exposed at the surface will become less and less reactive because of leaching by subsequent precipitation. The low TDS value of the sample from well 4 (776.41 mg/L) probably results from the mixing of recharge water from the infiltration basin with more mineralized ground water from the saturated

Table 4.—Chemical Constituents of Ground-Water Samples, April 16–17, 1989.

Ground-Water Chemistry (mg/L)

Well ID/ Sample Location	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Fe	T (C)	SC (uS)	pH	TDS
MW 2	366.0	171.0	19.40	14.10	584.0	1230.0	3.96	0.09	2.87	16.5	2361	6.26	2118.41
MW 3	441.0	189.0	40.90	22.00	763.0	1330.0	7.18	1.00	1.37	16.3	2680	6.05	2412.27
MW 4	75.6	60.8	45.80	4.29	195.0	470.0	4.22	0.09	16.90	15.5	1083	6.05	776.61
MW 5	395.0	170.0	17.50	12.40	618.0	1160.0	4.56	0.91	1.46	18.0	2372	6.10	2071.47
MW 6	106.0	62.2	4.41	5.80	214.0	327.0	3.23	0.09	2.36	16.8	1022	6.19	618.59
MW 7	266.0	292.0	30.60	16.50	805.0	1440.0	5.50	0.92	31.30	18.0	3107	6.50	2502.17
MW 8	539.0	199.0	118.00	25.00	727.0	1780.0	11.90	0.09	7.89	18.2	3285	6.09	3042.30
MW 9	441.0	233.0	20.30	17.50	580.0	1510.0	8/75	0.09	1.24	19.5	3155	6.20	2518.84
MW 10	316.0	190.0	12.80	12.70	519.0	1060.0	4.70	3.03	0.35	15.8	2413	6.20	1857.10
MW 11	567.0	321.0	32.50	21.70	739.0	1900.0	8.57	8.09	5.33	20.0	3993	6.33	3231.84
MW 12	463.0	151.0	43.20	19.10	729.0	1160.0	5.17	0.09	2.97	18.0	2827	6.38	2206.76
MW 13	413.0	205.0	19.30	11.90	483.0	1370.0	6.11	2.53	11.30	16.8	2760	6.23	2279.91
MW 14	111.0	83.8	12.10	3.64	2.9	695.0	7.18	0.09	8.81	18.0	1326	4.18	928.28
SP 1	197.0	123.0	20.90	9.59	372.0	779.0	5.64	4.81	1.16	14.0	1744	6.35	1327.03

Surface-Water Chemistry (mg/L)

Sample Location	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Fe	T (C)	SC (uS)	pH	TDS
IB	31.40	13.60	10.10	0.72	27.00	85.00	10.00	–	–	27.7	257	7.67	177.8
CB	64.00	46.60	6.67	5.11	179.00	246.00	3.17	1.51	0.14	19.0	768	7.21	552.2

MW = monitoring well
SP = spring
IB = infiltration basin
CB = Chestnut Branch, before entering spoil

µS = microsiemens
pH values in standard units
TDS = total dissolved solids, calculated

zone. The TDS values for the two other wells surrounding the basin (MW 2 and MW 5) (*see* Fig. 12) are much higher than those for MW 4, but very similar to each other; their calculated TDS values are 2118.14 and 1071.47 mg/L, respectively.

The higher TDS values characteristic of the wells located in the interior of the spoil are most likely the result of longer contact time between the ground water and the spoil because of slow ground-water movement. The low gradient of the water table in the central spoil area, the low dye dispersion, and the long residence time (3 months) observed for the Rhodamine WT dye that was introduced into monitoring well 1 supports the conclusion that ground-water movement is sluggish in this area. The extended contact time allows for greater water/rock interaction and leaching of soluble and reactive rock materials, therefore increasing the concentration of the dissolved constituents.

Spoil Settlement

Visual inspection of the monitoring-well surface casings indicates that differential settlement is occurring within the mine spoil. Cement surface seals that were originally placed at the intersection of the well casing and the spoil surface are now suspended slightly above the present spoil surface. Two of the wells exhibit apparent settlement of as much as 2 inches. Some of the wells indicate no settling. The greatest settlement is at MW 11. This well is located in the most recently placed spoil, and is very near the active mining pit.

SUMMARY, CONCLUSIONS, AND FUTURE WORK

The Eastern Kentucky Coal Field, like much of Appalachia, would benefit from a diversified, broad-based economy. Because a work force is available in this region, the lack of flat land outside of flood plains and the scarcity of reliable sources of water are paramount problems that need to be overcome if economic diversification and revitalization are to take place. The Kentucky Geological Survey, in cooperation with Cyprus Mountain Coals, has initiated a study at the Star Fire Mine to assess these two issues.

Once a gently rolling topography is created by mountaintop-removal mining methods, the singular site characteristic that must be defined is water availability. Preliminary results from computer modeling indicate that the mountain streams may produce at most only 2,960 acre-feet of annual runoff. This low volume and the drought-prone nature of the mountain streams at the site indicate the need for developing ground-water resources.

The initial water-quality and -quantity data measured at the Star Fire Mine indicate that mining techniques can provide the physical framework to construct an aquifer in the extensive mine spoil. Selected spoil handling, such as cast blasting, dragline casting, and end-dumping by trucks, is creating rubble zones within the spoil that are characterized by material as large as boulders. These zones are found at the base of the spoil (the spoil being approximately 300 feet thick in places) and as inclined layers throughout its thickness. It is anticipated that these rubble zones will transmit subsurface water, whereas the finer material will act as a good storage reservoir, thereby providing a framework for an aquifer over the 5,000 acres to be mined by the year 2010.

Spoil handling also creates compacted zones within the spoil that must be breached if a ground-water reservoir is to be fully developed. Major recharge to the spoil appears to be limited to swallets in the border of the spoil, where spoil adjoins higher bedrock outcrops at highwalls and natural slopes, and areas where the spoil has not been graded and compacted. Local recharge can occur where areas of boulders crop out in the graded spoil and through the infiltration basin. Future land use may result in the creation of many structures, including roads and buildings, which could impede ground-water recharge. Therefore, a deep infiltration basin has been constructed in the spoil to assess the effectiveness of this type of structure in recharging the ground-water system.

Ground-water discharge has been observed at the spoil outslope in the form of springs. Discharge has varied from approximately 1 to 5 million gallons per day, and measurements indicate that the springs react quickly to precipitation. Recharge-area runoff estimates and dye tracing indicate that the springs are being fed primarily through the older hollow fills in Spring Gap and Chestnut Gap Branches. The extensive spoil created by the present mining, which began in 1981, does not appear to be contributing significant ground water to the springs. Ground-water discharge from this spoil may be taking place within a sediment pond downstream of the mined site. A flume was installed in December 1991 to measure this discharge, but data are not yet available.

Data from the monitoring wells and water levels measured in the active pit indicate that this more recent spoil (approximately 200 feet thick) has a water table approximately 90 feet above the springs and a saturated thickness ranging from 9.5 to 38 feet, depending on the structural contour of the underburden of the lowest coal bed being mined. Based on an average saturated thickness of 21 feet and a porosity of 20 percent, an estimated 4,200 acre-feet (1.37 billion gallons) are contained in the 1,000 acres of spoil at the Star Fire site.

Ground-water quality for both the springs emerging from the hollow fill and the monitoring wells in the upper spoil is classified as calcium-magnesium-sulfate type. The total-dissolved-solids concentrations contained in the water derived from the spoil's interior appear to be greater than in water derived from the hollow fills. The pH of all springs and most of the wells in the spoil falls within a favorable range of 6 to 7.

Future work at the site will include the monitoring of water-level response to short-term precipitation events as well as seasonal and climatic changes. Much of these data will be collected by digital data loggers installed on monitoring wells and other monitoring devices. Measurements of recharge from the infiltration basin and discharge from the streams will be monitored using flumes designed to gage surface-water flow. The surface-water data will aid in the estimation of a water budget for the site. Collectively, these data will be used to create and calibrate ground-water-flow models, which will be useful and necessary for the characterization of the spoil aquifer and prediction of its water-producing potential.

Water quality will be monitored by collecting water samples from wells and springs on a quarterly basis. These data will provide the necessary information for geochemical models used to define and predict the chemical evolution of water at the site.

Subsidence of the mine spoil is an important parameter that must be defined before construction of buildings can be considered for the site. Presently, methods for monitoring the settlement of the spoil are being reviewed. A series of monuments are proposed at the site in order to establish the rates of settlement and where settlement is most likely to occur. These monitoring schemes will provide important engineering and construction information for the future development on the land surface.

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One of the major goals of the Kentucky Geological Survey is to make the results of basic and applied research easily accessible to the public. This is accomplished through the publication of both technical and non-technical reports and maps, as well as providing information through open-file reports and public data bases.

SELECTED WATER-RESOURCES PUBLICATIONS AVAILABLE FROM THE KENTUCKY GEOLOGICAL SURVEY

KGS Information Circular 5: Quality of surface water in Bell County, Kentucky, by R. B. Cook, Jr., and R. E. Mallette, 1981, 11 p.	**$3.00**
KGS Information Circular 37: Water quality in the Kentucky River Basin, by D. I. Carey, 1992, 56 p.	**$4.00**
KGS Reprint 29: Ordinance for the control of urban development in sinkhole areas in the Blue Grass karst region, Lexington, Kentucky, by J. S. Dinger and J. R. Rebmann, 1991, 14 p.	**$2.50**
KGS Reprint 30: Stress-relief fracture control of ground-water movement in the Appalachian Plateaus, by J. A. Kipp and J. S. Dinger, 1991, 11 p.	**$2.50**
KGS Reprint 31: High barium concentrations in ground water in eastern Kentucky, by D. R. Wunsch, 1991, 14 p.	**$2.50**
KGS Special Publication 1: Bibliography of karst geology in Kentucky, by J. C. Currens and Preston McGrain, 1979, 59 p.	**$5.00**
KGS Special Publication 12: Caves and karst of Kentucky, ed. by P. H. Dougherty, 1985, 196 p.	**$12.50**
U.S. Geological Survey Open-File Report 80–685: A compilation of ground water quality data for Kentucky, by R. J. Faust, G. R. Banfield, and G. R. Willingers, 1980, 963 p.	**$12.00**
U.S. Geological Survey Hydrologic Atlases (consult KGS "List of Publications" for specific locations and prices)	**price varies**

Wunsch, Dinger, and Taylor—DESIGN, CONSTRUCTION, AND MONITORING OF GROUND-WATER RESOURCES, STAR FIRE TRACT—Ky. Geol. Survey, Rept. Inv. 6 Ser. XI, 1992