International Journal of Coal Geology 41 (1999) 73–106

Predicting ground-water movement in large mine spoil areas in the Appalachian Plateau

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Abstract

Spoil created by surface mining can accumulate large quantities of ground-water, which can create geotechnical or regulatory problems, as well as flood active mine pits. A current study at a large (4.1 km^2), thick, (up to 90 m) spoil body in eastern Kentucky reveals important factors that control the storage and movement of water. Ground-water recharge occurs along the periphery of the spoil body where surface-water drainage is blocked, as well as from infiltration along the spoil–bedrock contact, recharge from adjacent bedrock, and to a minor extent, through macropores at the spoil's surface. Based on an average saturated thickness of 6.4 m for all spoil wells, and assuming an estimated porosity of 20%, approximately 5.2×10^6 m^3 of water is stored within the existing 4.1 km^2 of reclaimed spoil. A conceptual model of ground-water flow, based on data from monitoring wells, dye-tracing data, discharge from springs and ponds, hydraulic gradients, chemical data, field reconnaissance, and aerial photographs indicate that three distinct but interconnected saturated zones have been established: one in the spoil's interior, and others in the valley fills that surround the main spoil body at lower elevations. Ground-water movement is sluggish in the spoil's interior, but moves quickly through the valley fills. The conceptual model shows that a prediction of ground-water occurrence, movement, and quality can be made for active or abandoned spoil areas if all or some of the following data are available: structural contour of the base of the lowest coal seam being mined, pre-mining topography, documentation of mining methods employed throughout the mine, overburden characteristics, and aerial photographs of mine progression. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: mine spoil; groundwater; hydrogeology; methods; conceptual model; mine drainage

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PII: S0166-5162(99)00012-9

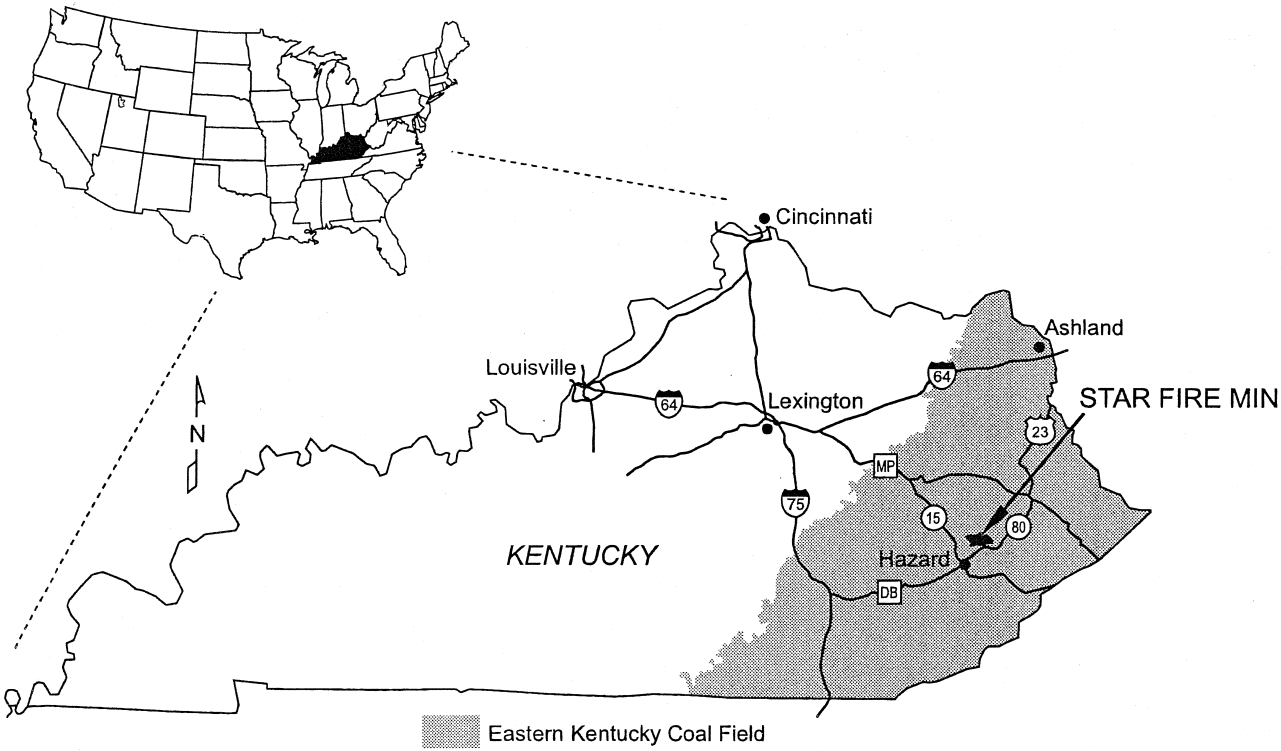

Fig. 1. Location of the Star Fire Mine. DB = Daniel Boone Parkway. MP = Mountain Parkway.

1. Introduction

Approximately 8100 km^2 of mined lands have been reclaimed by the US coal industry since 1974. Economic diversification in depressed mining areas such as Appalachia can be enhanced by planning and utilization of reclaimed lands. Although significant areas of relatively flat land are continuously being created by surface-mining operations throughout this area, the availability of water resources to sustain industrial development or agriculture remains questionable. However, mines in areas where the geologic conditions are conducive to good water quality, and where selective spoil placement or engineering practices have been employed to maximize water storage and retrieval, there exists the potential to utilize the spoil water for industrial or agricultural applications.

The increased permeability and porosity of the broken rock materials (spoil) replaced during mining significantly increase the water-storing potential of the spoil compared to the solid rock from which it was derived. However, ground-water stored in mine spoil can create geotechnical problems such as slope instability, or regulatory problems related to acid mine drainage. In addition, active mining can be impeded when water floods adjacent, active mine pits.

This study evaluates the potential development of water resources in a thick and extensive spoil at the reclaimed site to define the hydrogeology of the site, and describes the dynamics of the spoil–water flow system. This results of this study will contribute to baseline data and technology transfer that may be applicable to other reclaimed mine areas in maturely dissected landscapes such as the coal fields in the Appalachian Plateau.

A conceptual model will be presented that suggests that a prediction of ground-water occurrence, movement, and quality can be made for active or abandoned spoil areas if all or some of the following data are available: structural contour of the base of the lowest coal seam being mined, pre-mining topography, documentation of mining methods employed throughout the mine, overburden characteristics, and aerial photographs of mine progression. Examples of methods utilizing these types of data for hydrogeologic characterization of the reclaimed mine will be shown, as well as their integration toward the creation of a conceptual model for ground-water occurrence and movement.

2. Geologic and hydrogeologic setting

The Star Fire Mine encompasses parts of Breathitt, Perry, and Knott Counties and is located approximately 8 km northeast of Hazard, KY, off the Daniel Boone Parkway (KY Highway 80) (Fig. 1). Regional geology of the site is mapped on the Noble (Hinrichs, 1978) and Vest (Danilchik and Waldrop, 1978) 7.5-min geologic quadrangle maps. Fig. 2 is a generalized geologic column for the mine site. The coals being mined include the Hazard Nos. 7, 8, 9, and 10, all of which are part of the Breathitt Group of Pennsylvanian age (Chesnut, 1992). These coals are high volatile bituminous and range in thickness from 0.9 to 2.0 m. Several zones contain rider coals, thin coal beds adjacent

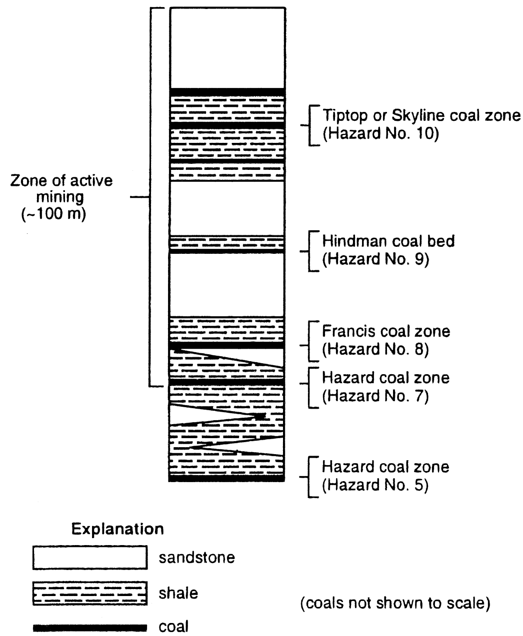

Fig. 2. Schematic geologic column showing near-surface coals in the study area. All units are part of the Breathitt Group of Pennsylvanian age. Modified from (Kemp, 1990).

to the major beds, which are also mined. The overburden consists of interbedded sandstones, shales, siltstones, and underclays. Some units are locally calcareous, or may contain lenticular calcareous concretions (Spengler, 1977). In the process of mining, backfill (spoil) up to 93 m thick is being created.

Weinheimer (1983) studied sandstone samples from four cores representing the Breathitt Group at a site approximately 4.8 km from the mine. Analyses revealed the following average component percentages (thus, the sum of the components does not equal 100%): quartz, 47.0%; feldspar (mainly potassium feldspar), 29.0%; rock fragments, 11.9%; mica, 5.4%; and heavy minerals (pyrite, siderite), 0.5%. The majority of the cement was determined to be ferroan calcite. Abundant authigenic kaolinite filled pore spaces and formed reaction rims around feldspar grains. The occurrence of dolomite in Breathitt rocks is rare. Shales and claystones in the Breathitt Group contain illite, kaolinite, and chlorite (Papp, 1976).

Analyses performed to obtain the initial mining permit (Soil and Material Engineers, 1982) predicted that the overburden should not produce acid–mine drainage problems because of the high net neutralization potential. The high neutralization potential was attributed to the abundance of carbonate cements in the overburden sandstones. All pre-mining overburden analyses show a potential acidity (PA) of less than 5. PA is the acidity, expressed as equivalents of calcium carbonate ($CaCO_3$), calculated from pyritic sulfur content. If PA is less than 5, the stratum is generally considered a non-acid producer, regardless of the neutralization potential (Sobek et al., 1978).

Ground-water is stored in the unmined bedrock that surrounds the mine. The dominant pathways for ground-water movement are coal seams, and near-surface and regional fracture systems (Kipp and Dinger, 1991; Wunsch, 1992).

3. Ground-water considerations

3.1. Aquifer framework

Discussions with mine personnel and direct observation of the mining process demonstrated that selected spoil-handling techniques have produced a rock framework conducive to the development of an aquifer within the spoil. Several previous papers have described, in detail, blasting effects, gravity settling and sorting, selective dumping, and compaction of the spoil and the implications of these factors in controlling the movement and storage of ground-water at the site (Dinger et al., 1988, 1990; Wunsch et al., 1992). Therefore, these factors will be discussed only briefly here.

Fig. 3 illustrates the transformation from the pre-mining bedrock topography to the landscape resulting from the extraction of the Hazard Nos. 7, 8, and 9 coal beds. Overburden is removed by alternating episodes of cast blasting and spoil removal by a 49 m^3 bucket dragline (cast blasting is a process in which explosives are placed in holes drilled along the highwall, and the rock is directionally blasted and ‘cast’ into the bottom of the pit; large boulders (>1 m) of rock typically accumulate at the bottom of the spoil as a result). The lowest coal being mined is the Hazard No. 7. The shale bedrock remaining in place after the removal of the coal creates a pavement that forms a relatively impermeable lower boundary for any water that accumulates in the spoil. Fig. 3b shows the continuous, coarse boulder zone created by cast blasting the adjoining bedrock. Spoil covering the boulder layer is placed by the dragline, electric shovels, and dumping of large rocks by dump trucks (Kemp, 1990).

Fig. 4 is a detailed schematic cross section of the spoil illustrating the spoil structure in which various mining methods and spoil placements are being used. Unmined valleys are sometimes filled with durable boulder drains, creating a zone of higher hydraulic conductivity, which provides subsurface drainage for the mine (Fig. 4, feature A). The continuous coarse boulder zone on top of the unmined bedrock (Fig. 4, feature B) ranges from 4.6 to approximately 9.2 m in thickness and usually consists of the underburden of the Hazard No. 9 coal. This spoil is cast-blasted into the open pit after the Hazard No. 7 coal is removed. This zone, and similar boulder zones found in valley fills, should permit the storage and rapid movement of ground-water. Because of their thick and continuous nature, and their position on the bedrock floor, these zones should be the most capable of providing and storing significant amounts of ground-water.

The spoil material cast by the dragline produces numerous inclined layers of coarse aggregate above the boulder zone (see Fig. 4, feature C). These layers are created by gravity sorting of the spoil material when it is dumped from the dragline bucket: 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 may act as recharge routes from the land surface to

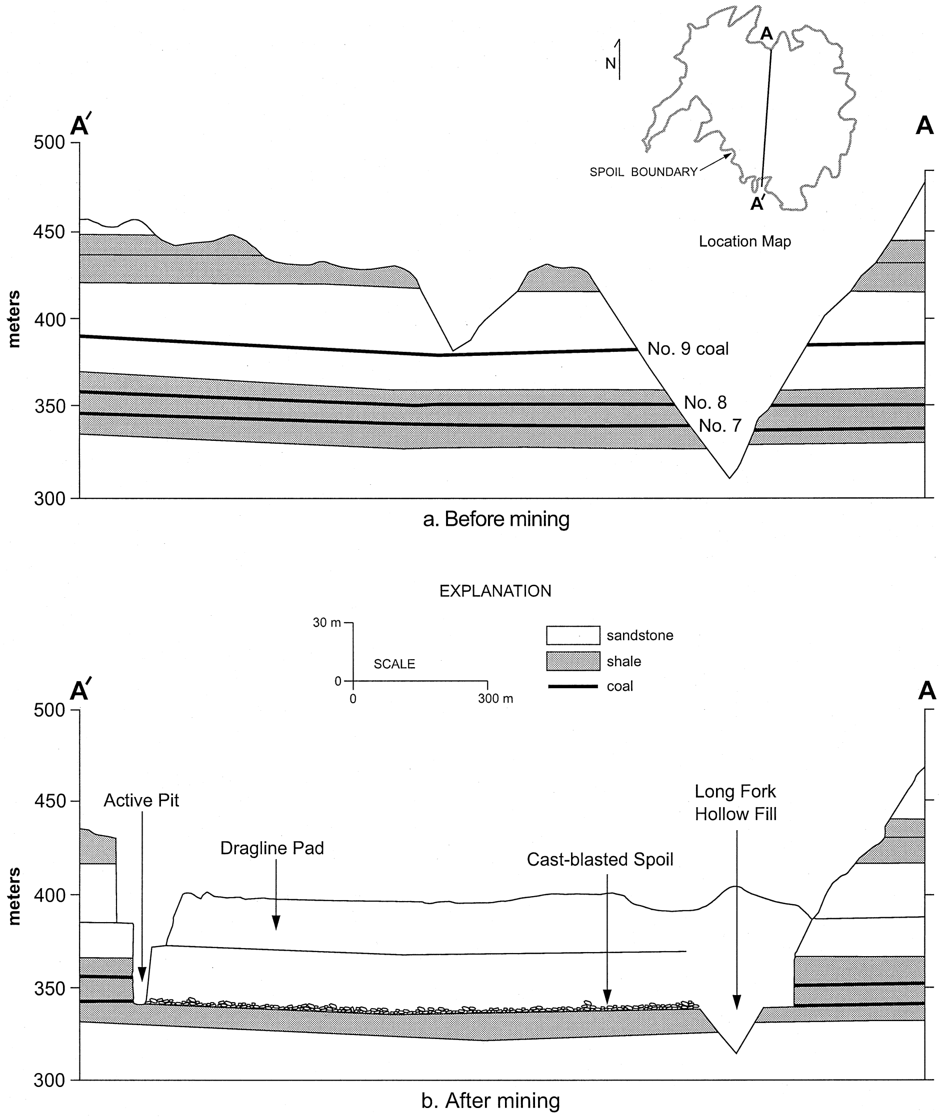

Fig. 3. Before- and after-mining cross sections. Inset shows location of cross sections. Modified from (Kemp, 1990).

the boulder zone at the base of the fill, and the finer material at the base of the spoil cones may behave as an extensive storage reservoir for ground-water as the spoil becomes saturated.

Another sequence of coarse inclined layers is also found in the upper part of the spoil material, where spoil has been dumped by trucks (Fig. 4, feature F). The coarse rock layers are similar to the cast-dragline spoil, but are not as thick or as extensive.

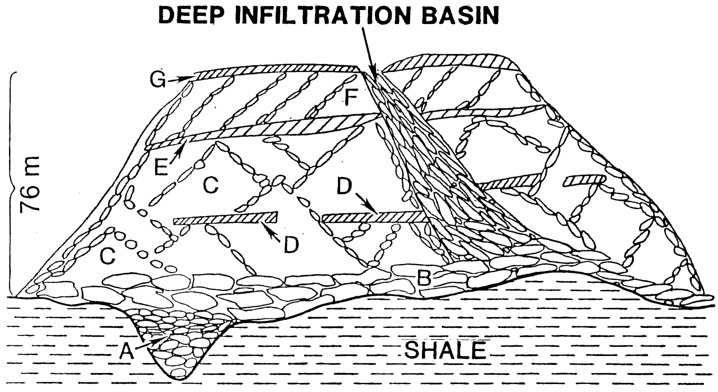

Fig. 4. Schematic cross section showing components of spoil significant to the development of an aquifer framework. A = hollow fill. B = cast-blasted rubble. C = dragline spoil. D = dragline pad. E = temporary haul road. F = truck-dumped spoil. G = final graded land surface.

In contrast to the coarse permeable zones, relatively impermeable compacted zones are also produced by mining within and on top of the spoil (see Fig. 4, features D, E, and G). The final compacted graded land surface (see Fig. 4, feature G) can inhibit surface-water from infiltrating into the spoil material. Therefore, special spoil-handling techniques have been used to capture surface runoff for recharge to the ground-water system within the spoil material. An infiltration basin was constructed that created a direct connection to the rubble zone resting on top of the Hazard No. 7 coal underburden (Fig. 4), and would lead to an understanding of water movement and recharge potential of the spoil after the infiltration basin was operational. An extensive rock drain consisting of sandstone boulders was created to bypass all intermediate compacted zones within the spoil that might tend to perch percolating ground-water (see Fig. 4).

Directing surface runoff into the infiltration basin can have an additional benefit. Typically, surface-water runoff flowing from large spoil areas contains high amounts of suspended solids and sediment, which leads to sedimentation problems in nearby streams. Surface-water directed into the infiltration basin is filtered by the porous media as it percolates down to the saturated zone. Introducing artificial recharge through the infiltration basin may help minimize sedimentation problems in streams surrounding the mine site. Sediment will most likely still have to be periodically removed from the bottom of the infiltration basin, however.

4. Water monitoring methods

Methods used to characterize the hydrogeology of the spoil include precipitation measurements, discharge measurements of streams and springs, ground-water dye-tracing, water-level measurements from monitoring wells, falling-head slug tests, and water-quality analyses. Fig. 5 indicates the locations of features and installations used in this study.

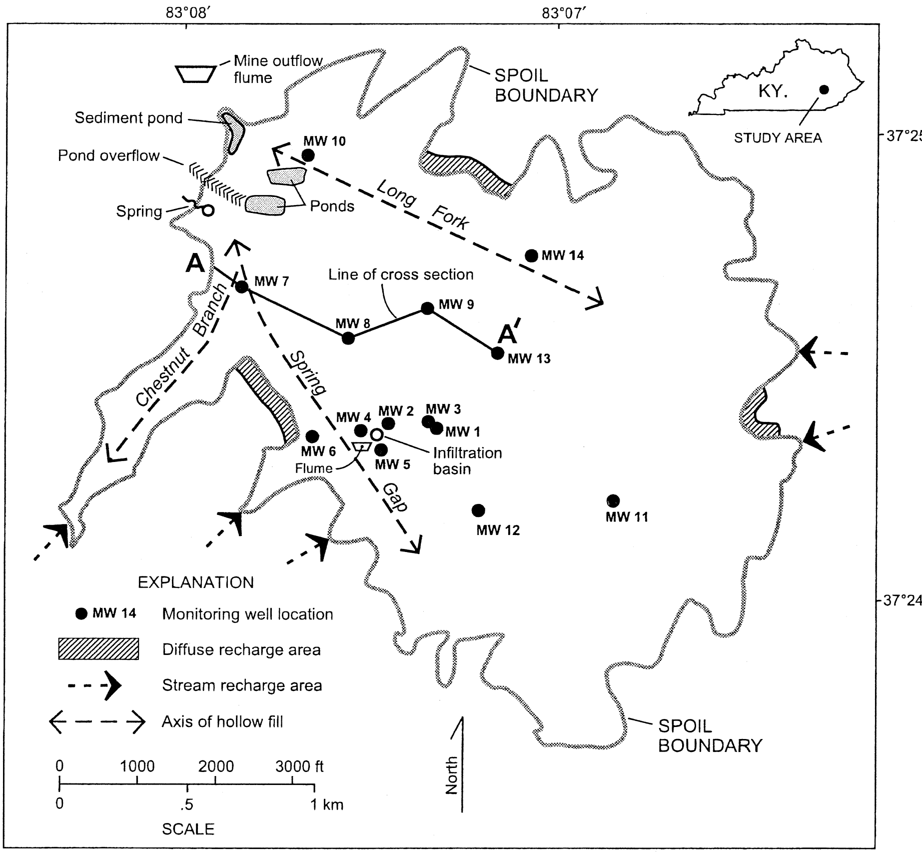

Fig. 5. Significant features at the Star Fire site. The southeast boundary of the mine spoil is approximate because of continued mining.

The infiltration basin was equipped with a stilling well to measure the standing water in the basin after a precipitation event. A stilling well consists of a pressure transducer that measures water stage within a length of PVC well casing that descends to the bottom of the basin. Daily precipitation data have been recorded at the site with a tipping-bucket device equipped with a pulse recorder and data logger. The flume and stilling well measure discharge and stage, respectively, by converting direct head measurements collected by digital data loggers. The digital data loggers record data from pressure transducers.

4.1. Surface-water flow measurements

Surface-water flow was measured at recharge and discharge points at the site. Flow measurements were made using a hand-held meter and summing the flow-velocity readings taken at even increments along a cross section of the stream channel. This method yields a maximum accuracy of within 5% of actual discharge (U.S. Geological Survey, 1980). The total mine outflow was measured at a flume located below the sediment-pond discharge (Fig. 5). The flume was equipped with digital stage recorders, and discharge was determined by establishing a rating curve based on stage levels. Mass-balance was calculated to determine missing components of flow, using surface-water flow data and flume measurements.

4.2. Ground-water measurements

Monitoring wells were installed to study the establishment and fluctuations of a 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. Installation of monitoring wells in deep spoil was hampered by heterogeneity of the spoil, which contains particle sizes ranging from clay to large sandstone boulders; lack of consolidation and spoil instability; and slump and collapse in the saturated zone.

A total of 11 monitoring wells (wells 4 through 14), ranging in depth from 16.7 to 72.7 m, were installed. Various monitoring wells were equipped with continuous data loggers to record changes in the water table for extended periods of time.

4.3. Slug tests

Falling-head slug tests determined the spatial distribution of hydraulic conductivity and the range of variability within the spoil. Nine tests were performed by injecting ground-water derived from the spoil as quickly as possible into the monitoring wells until the water level reached the top of the plastic casing. This technique is based on methods first described by Hvorslev (1951) in the development of 'time-lag' permeability tests. Hvorslev's method assumes that instantaneous changes in water level occur at the initiation of a slug test, which was not always the case in this study. Even under ideal conditions, Hvorslev's method is not precise. However, it is generally considered an appropriate means of estimating the order of magnitude of hydraulic conductivity (Thompson, 1987).

Hydraulic conductivity values were calculated using the computer program TIME-LAG (Thompson, 1987). This program contains several cases that are employed depending on the well-configuration data provided. Unconfined aquifer conditions were assumed.

In some cases, wells took more water than could be injected by the pump (3.2 l/s). In these wells, the hydraulic conductivity calculated represents a minimum value based on a water-injection rate of 3.2 l/s. The static head level used for calculations was the maximum head level (top of casing) for each well, which provided for a minimum hydraulic conductivity value that would sustain the maximum flow rate. Actual hydraulic conductivity values must be higher than these calculated values.

4.4. Water-quality sampling and analysis

Samples were collected to determine the chemical character of the surface and ground-water at the site, provide input data for geochemical models and mass-balance studies, and establish baseline data in order to monitor temporal and spatial variability in water quality. Samples were drawn and analyzed from the largest spoil spring, monitoring wells, the stream in Chestnut Gap Branch (see Fig. 5), and the deep infiltration basin. Some samples were taken from springs and streams to study recharge events. Field parameters determined for most samples were temperature, specific electrical conductance, oxidation-reduction potential (Eh), and pH in accordance with (U.S. Geological Survey, 1980) guidelines for sampling and collecting. The geochemical characteristics of the spoil ground-water are complex, and not within the scope of this paper. Therefore, only total dissolved solids (TDS) data will be used in this paper for general water quality discussions, and for mass-balance calculations.

4.5. Dye-tracing

Ground-water dye traces defined flow paths and travel times through the spoil. Dye-trace data from previous studies (Kemp, 1990) were also used to define ground-water flow paths in the Spring Gap drainage area. The dye used for all tracing was Rhodamine WT, a fluorescent dye. It has been widely used in the study of karstic carbonate aquifers, and to a lesser extent in granular aquifers (Aulenbach et al., 1978). Rhodamine WT exhibits many properties favorable for ground-water tracing, including detectability at very low concentrations (parts per billion), low toxicity, a distinct peak-emission wavelength, chemical stability over a wide range of pH values, photochemical and biological stability, and a low rate of adsorption (Smart and Laidlaw, 1977). The most critical of these factors for this study is its low rate of adsorption, because the dye is assumed to flow through an aquifer matrix rich in clays, organic-rich shales, and ferric hydroxide. Ferric hydroxide was found to adsorb significant quantities of Rhodamine WT in an experiment designed to test fluorescent dyes for use in ground-water tracing in underground coal mines (Aldous and Smart, 1987). Therefore, ample amounts of dye were used to allow for dilution and adsorption.

Dye traces determined the flow path of water entering the spoil through the deep infiltration basin, Chestnut Gap Branch (a stream that flows into the base of the spoil), and MW 1, which is located in the central area of the spoil (Fig. 5). The flow path of ground-water injected with dye at these locations was determined by placing dye detectors, which consisted of permeable textile sacks filled with activated charcoal, at various points of discharge. The elutriant, or solution used to desorb dye from the charcoal detectors, was analyzed with a Turner model 10 filter fluorometer.

5. Results and discussion

5.1. Recharge observations

Field reconnaissance of the study area revealed numerous places where streams and storm runoff recharge the spoil aquifer. Recharge at most of these sites is sporadic and often difficult to quantify.

Several streams flow directly into the spoil at the base. The largest is Chestnut Gap Branch, a first-order stream with a watershed area of 0.5 km^2 (see Fig. 5). Data from

Kemp (1990) show that Chestnut Gap Branch had an average flow rate of 20.7 l/s during a 3-month period in 1989, which equates to a 1788 m^3/d contribution to the total water moving through the spoil.

Recharge from bedrock aquifers occurs where mine highwalls are in contact with the spoil. Although primary permeability is relatively low in the non-coal bedrock forming the highwall (Wunsch, 1992), near-surface and tectonically induced fractures provide highly permeable zones that discharge ground-water into the spoil (Kipp and Dinger, 1991).

In some cases, spoil handling resulted in boulders being randomly exposed at the surface. Small (less than 5 cm in diameter), discrete infiltration points, or 'snakeholes,' were observed where boulders intersect the spoil surface. Storm runoff flows into these discrete holes and rapidly disappears into the spoil. The amount of water that may ultimately reach the saturated zone at the bottom of the spoil by way of these discrete points has not been determined, but is assumed to be minimal compared to the amount of water entering the spoil along the edges of the main spoil body.

On a larger scale, the infiltration basin provides a point source for ground-water recharge. At the present time, the watershed that supplies the basin is limited, and probably contributes relatively insignificant quantities of water in relation to the total amount stored in the spoil. The present watershed surrounding the basin encompasses approximately 7.7 ha, less than 2% of the total spoil area.

Recharge also occurs when precipitation falls directly on ungraded dragline-cast spoil cones or other recently excavated areas. We assumed the infiltration rate in these areas was higher than the rate in the compacted spoil, but have not determined quantitative recharge rates. The size of this spoil cone area varies depending on the amount of grading that has occurred, but is extensive, often 0.2 km^2 or larger (Dinger et al., 1988).

5.2. *Spring discharge*

The most significant area of discharge from the spoil is in the northwest corner, where a group of three springs is located at the toe of the Spring Gap Branch valley fill (Fig. 5). The springs appear at an elevation of approximately 317 m. The discharge point for the largest of the springs (Spring 1) is located at the toe of a 40-m thick truck-dumped sandstone spoil that overrides a 14-m thick truck-dumped shale spoil. The shale spoil is purported to have a lower permeability than the sandstone spoil (Kemp, 1990). During times of extremely high discharge, a number of small springs have been observed along the toe of this lift at an elevation equivalent to or slightly higher than the main spring. Total discharge from the springs ranges from approximately 3780 to 18,900 m^3/d (Kemp, 1990).

Discharge was not observed from the toe of the Long Fork valley fill. Mine personnel observed ground-water discharging directly into the sediment pond at a point below the pond's water level.

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. At times, ground-water has discharged from the spoil into the active pit at a rate high enough to require pumping on a daily basis. On occasion, pumping rates have reached an estimated 1360 m^3/d.

Two ponds have been created to store water for dust control. These ponds, whose locations are shown in Fig. 5, are at the northwest corner of the spoil, above the springs. The bottom of the northern pond is on the underclay below the Hazard No. 7 coal. The bottom of the southern pond has been excavated to a lower elevation and is completed within the shale unit below the Hazard No. 7 coal and the underclay. Both ponds are fed by water from the saturated spoil, as evidenced by the fact that the water level in the northern pond (343.1 m), which has no overflow, is very similar to the water level observed in the nearest monitoring well not located over a valley fill (344.7 m in MW 8). This similarity suggests that the pond is a surface expression of the water table. Also, although these ponds are pumped to fill 37.8 m^3 water trucks, the water is never depleted, and the ponds do not freeze in the winter, which suggests a ground-water source. Finally, the electrical conductance (2100 μS) of the water flowing out of the overflow is similar to that of the spoil-fed springs that discharge below it (average EC 2140 μS, $n = 6$); if the ponds received their water from surface runoff, the conductance values would be much lower because of dilution. Water overflows from the lower pond throughout the year and cascades down the spoil face by way of a riprap-lined drainage channel and contributes to the total mine outflow.

A large-capacity flume below the sediment pond gauges the total water outflow (see Fig. 5 for location). Data have not been continuously collected because of periods of freezing and vandalism, but data were collected on 255 days of the 1992 water year. Table 1 shows the discharge data for several months during the 1992 water year. The monthly mean discharge ranges from 87.2 to 197 l/s. The mean and median discharge are both approximately 113 l/s.

5.3. Mass-balance calculations

Mass-balance was calculated to determine what part of the total mine outflow is provided by the spring that drains the Long Fork valley fill. The spring discharges below water level in the sediment pond at the northwest corner of the spoil, making it

Table 1
Saturated thickness in monitoring wells in June 1991

Wells placed over hollow fills[a]			Spoil-interior wells[b]		
Well ID	Saturated thickness	Water elevation	Well ID	Saturated thickness	Water elevation
4	7.5	344.0	2	6.4	345.1
6	7.2	342.0	3	3.1	345.0
7	8.3	323.0	5	7.0	345.2
10	11.3	319.8	8	3.2	344.8
14	11.6	342.4	9	2.9	344.6
			11	5.4	346.1
			12	5.1	345.5
			13	4.5	345.0

[a] $n = 5$; range = 7.2–11.6; mean = 9.2; median = 8.3.
[b] $n = 8$; range = 2.9–7; mean = 4.7; median = 4.8.
Units are in meters.

impossible to take direct flow measurements or collect water samples (Fig. 6). Flow measurements at all other accessible discharge points were made in June 1994 after a relatively dry spell when streams and springs were considered at base flow. The flow components used in the calculations consisted of the Long Fork flume, spring 1 (SP 1), Chestnut Gap Branch, and the dust-control pond's overflow (see Fig. 5). The cumulative flow for all components was determined by the formula:

$$Q_t = Q_{po} + Q_{cb} + (Q_{sp} - Q_{cb}) + Q_{lf}$$

where Q_t = measured total mine discharge at the Long Fork flume; Q_{po} = measured discharge of the overflow from the dust-control pond; Q_{cb} = measured discharge from Chestnut Gap Branch; Q_{sp} = measured discharge at the Spring Gap spring; Q_{lf} = calculated discharge from the Long Fork spring.

The discharge from Chestnut Gap Branch was subtracted from the discharge from Spring Gap because Kemp (1990) demonstrated by dye-tracing that the total streamflow in Chestnut Gap Branch disappears into the base of the Spring Gap valley fill and re-emerges at spring 1. Thus, it contributes to the flow measured at spring 1. The measured discharge for each site, in l/s, is as follows: $Q_t = 63.1$, $Q_{po} = 23.8$, $Q_{cb} = 5.6$, $Q_{sp} = 17.8$. The flow contribution from the Long Fork drainage (Q_{lf}) is therefore 21.5 l/s.

Mass-balance for the TDS load was calculated to determine if the mass loads were consistent with the discharge data. We could not collect a representative water sample from the submerged Long Fork spring. However, MW 10, located approximately 244 m upgradient from the reported spring discharge site, produces water that is probably representative of the water moving through the Long Fork buried valley, which is the source of the water that discharges from the Long Fork spring. In addition, the coefficient of variation for TDS values from all samples from MW 10 is 14% ($n = 6$), which indicates that the data are consistent. We therefore used the TDS value from MW 10 in the mass-balance calculations.

TDS data for the flow components were determined from samples collected in June 1994, except for the sample from MW 10, which was collected in August 1994. The mass-balance formula used in the calculation was:

$$Q_t C_t = Q_{po} C_{po} + Q_{cb} C_{cb} + Q_{sp} C_{sp} + Q_{lf} C_{lf}$$

where: C_t = TDS determined for water from the Long Fork flume; C_{po} = TDS of the overflow from the dust-control pond; C_{cb} = TDS of the discharge from Chestnut Gap Branch; C_{sp} = TDS of the discharge at the Spring Gap spring; C_lf = TDS of the Long Fork spring.

The discharge value for SP 1 is 12.1 l/s, which is the measured discharge (17.8 l/s) minus the recharge component supplied from Chestnut Gap Branch (5.7 l/s). Solving for C_{lf} yields a TDS value of 2082 mg/l. The TDS of the water sample from MW 10 was 2113, which is in excellent agreement with the calculated value (a difference of less than 1.5%). Moreover, the consistency of the mass-balance calculations suggests that the measurements for discharge sites and the calculated discharge for the submerged spring draining the Long Fork valley fill are reasonable. These calculations show that almost all the total mine outflow can be accounted for by a summation of the ground-water discharge sites located in the northwestern area of the main spoil body.

5.4. Dye-tracing

The dye trace of Kemp (1990) delineated a flow path between where the Chestnut Gap stream disappears into the spoil and spring 1, located at the northwest corner of the spoil (see Fig. 5). Kemp (1990) also determined an apparent velocity ranging from 0.004 to 0.003 m/s based on a straight-line travel distance of 731 m and a travel time between 49 and 73 h. The relatively rapid ground-water travel times indicate that the competent rock drains placed in the valley bottoms prior to infilling the valleys with spoil are effective in allowing surface drainage and ground-water to flow through valleys that are partially filled from mining. Chestnut Gap Branch often contains high levels of suspended sediment after storms, but the consistently clear discharge at spring 1 indicates that sediment in surface-water in Chestnut Gap Branch is filtered by flowing through the spoil. This suggests that directing surface runoff from large spoil bodies through the spoil itself could be an effective technology for treating sediment problems in areas where the mineralogy of the overburden does not create significant acid mine-drainage problems.

A second dye trace by Kemp in 1990 injected dye with a 3784-l slug of water into MW 1 (see Fig. 6). This dye was not recovered in the springs in the northwest corner of the spoil. The dye may have flowed northeast into the Long Fork drainage, but there were no adequate discharge points along this flow route to monitor for dye. Dye was still visible in MW 1 several months after it was introduced, indicating that ground-water movement is sluggish in the vicinity of MW 1. The slow movement of ground-water in the vicinity of MW 1 and the lack of dye emerging from the springs also suggests that a low-permeability barrier may exist; or, ground-water movement may be very slow between the interior spoil area and the lower elevation valley fill areas that encompass the Spring Gap, Chestnut Gap, and Long Fork drainage valleys.

Additional dye-tracing in the spring of 1991 determined the flow path of recharge that enters the spoil through the infiltration basin. Dye detectors were set at several locations that were suspected as possible emergence areas for water entering the infiltration basin. Fig. 6 shows the locations of the dye detectors. Three positive traces were detected west of the infiltration basin. These results are consistent with the direction of flow indicated by hydraulic gradients and basal topography in this area. One positive trace was also found in a pit excavated along the highwall–valley fill contact near MW 6. Additional positive traces were found where water periodically flowed from the spoil slope between the elevation of the infiltration basin and the valley fill near MW 6. This indicates that not all of the water that flows into the infiltration basin penetrates vertically to the base of the spoil; it may be diverted laterally by low-permeability barriers within the spoil. The permeability barrier may be created by the spoil-handling techniques that were discussed previously (see Fig. 4), or from sediment clogging the rock chimney (Fig. 4).

Residual dye in MW 1 from the dye trace of Kemp (1990) may have contributed to the positive 1991 tests; MW 1 is located near the infiltration basin (see Fig. 6). The infiltration basin is situated between MW 1 and where the positive dye traces were found, however, so movement of ground-water is toward MW 6, whether the dye originated from residual dye from the 1990 trace or from the 1991 infiltration-basin test.

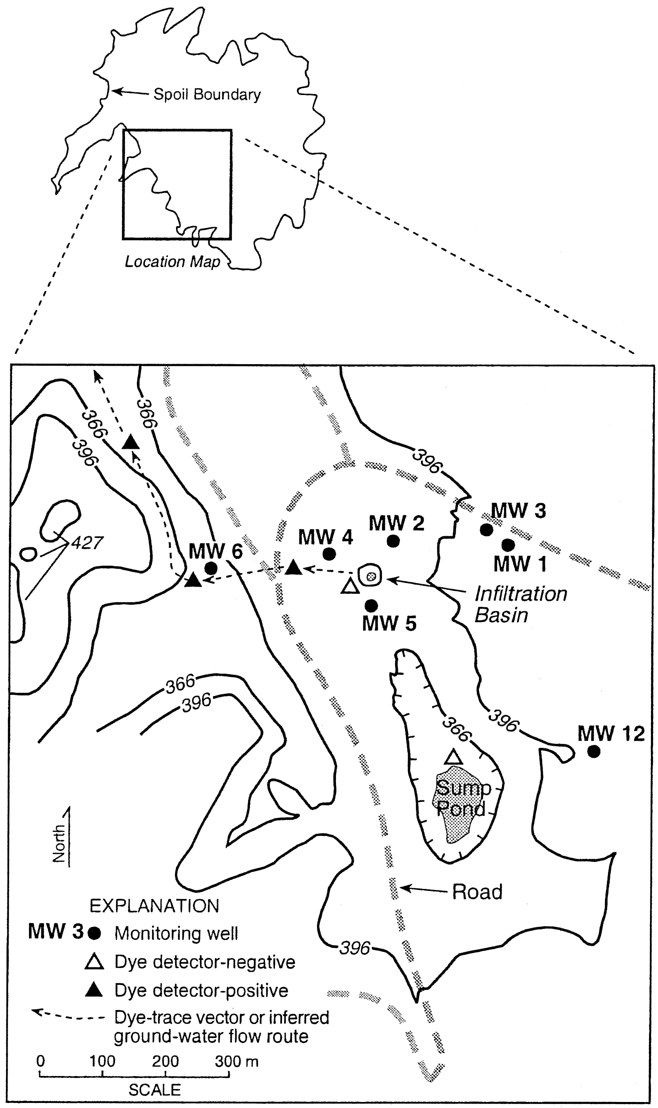

Fig. 6. Dye-trace detector locations around the infiltration basin. Contours represent land-surface elevation in meters above sea level.

5.5. Ground-water occurrence

Fig. 7 shows the outline of the spoil area, along with the contoured surface of the now-buried bedrock topography. This map was created by combining the pre-mining topographic map of the mined area and a structure–contour map on the base of the Hazard No. 7 coal, which is the lowest coal being mined. The bottom surface of the

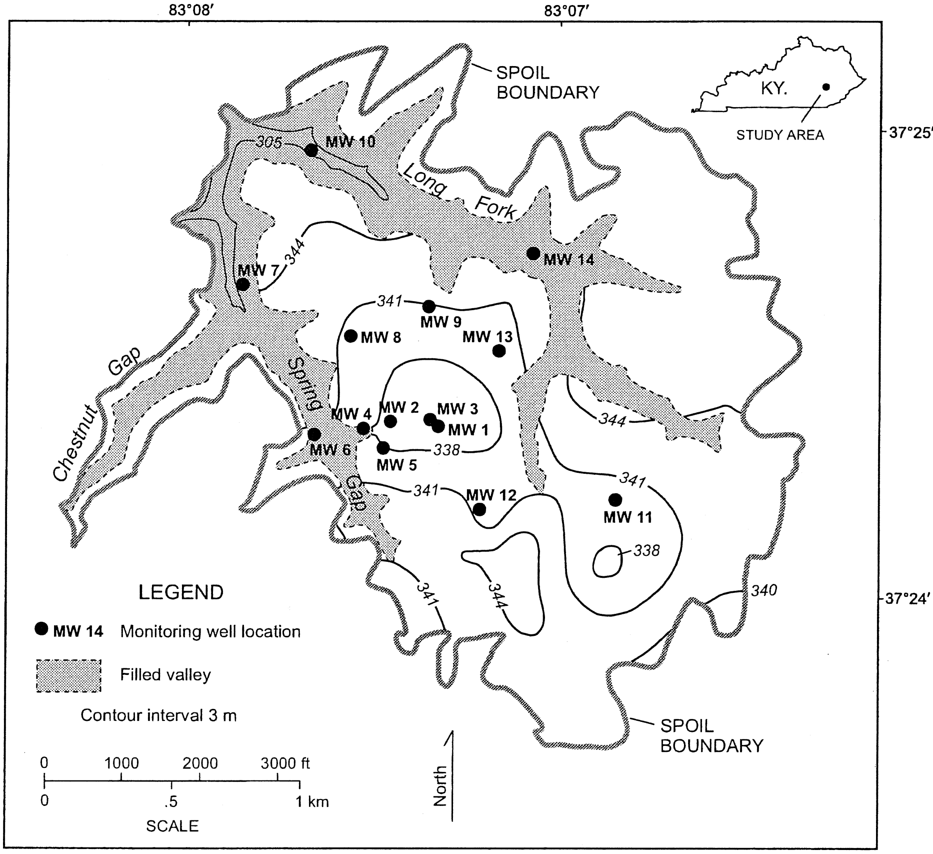

Fig. 7. Outline of the spoil and elevation of basal topography.

spoil's interior is a gently undulating plateau capped by the shale that underlies the Hazard No. 7 coal. This buried plateau is bordered by the pre-existing stream drainage (shaded areas in Fig. 7) formed by Long Fork to the northeast and Spring Gap/Chestnut Gap Branch to the southwest. Elevation drops considerably from the plateau level to the bottom of the old stream drainages. Maximum relief (approximately 40 m) occurs in the northwest corner of the spoil, where the two buried drainage valleys converge around the nose of the plateau.

A contour map of the water table within the spoil (Fig. 8) was created from water-elevation data collected in June 1991 from the 14 monitoring wells on the site, the dust-control pond, and spring 1. There is a slightly mounded water table in the central plateau region, as demonstrated by the closed 344.4 m contour line in the center of Fig. 8. The water mound is probably a reflection of the spoon-like shape of the mine floor, as shown in Fig. 7.

The water table mound shown in Fig. 8 also indicates a low hydraulic gradient in this area. For example, the gradient between MW 9 and MW 13 is 0.0019. The gradient of

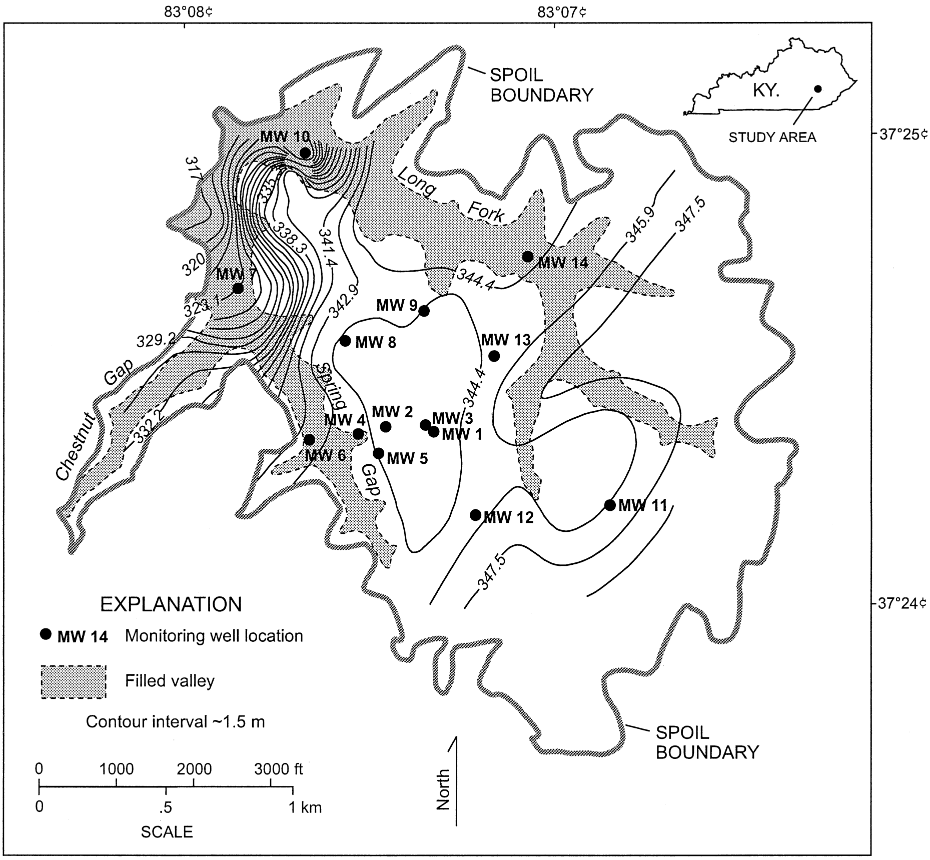

Fig. 8. Contour of the spoil water table.

the water table in the surrounding buried valleys is much higher: the gradient between MW 6 and MW 7 in the Spring Gap valley fill is 0.025, more than 10 times the gradient between the plateau wells.

Steep gradients are also evident between the northwestern area of the plateau and the surrounding buried valleys, which parallel the elevation differences indicated by the buried topography (see Fig. 7). These steep gradients seem unrealistic, and probably represent a boundary between two distinct but connected saturated zones.

The distribution of water within the spoil is illustrated in Fig. 9, which is a cross section of the spoil through monitoring wells 7, 8, 9, and 13 along line A–A′ (location shown in Fig. 5). There are two saturated zones: one relatively shallow zone perched on the buried plateau, and the other in the valley fill of the Chestnut Gap Branch drainage. The difference in elevation between the buried plateau and the valley bottoms decreases toward the southeast, where the elevation of the valley bottoms gradually rises toward the heads of the valleys. The saturated zones are probably directly connected in the heads of the valleys, where the buried valleys intersect the base of the plateau. The

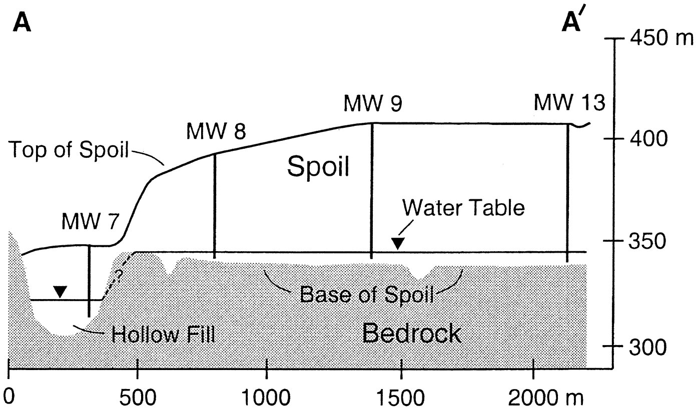

Fig. 9. Cross section through line A–A′, Fig. 5.

spoon-like shape of the interior basal plateau suggests that the bedrock along the edges of the plateau may form barriers that retard ground-water movement into the valley, where the difference in elevation is greater. This interpretation is supported by the dye-tracing data, which show that water movement is restricted in the interior of the spoil. The water levels in wells on the north side of the spoil suggest a similar configuration in the Long Fork valley fill.

The apparent lack of hydraulic continuity and the low hydraulic gradient in the plateau region suggest that the majority of ground-water moving through the spoil flows through the two buried valleys before finally discharging in the northwest corner of the spoil. This conclusion is also supported by the dye-trace data, which show that water moves through the buried valleys at high velocities.

The occurrence of water in each well in the spoil indicates that a significant amount of ground-water has accumulated. Table 1 compares the saturated-thickness data for the five wells located in the valley fills with the eight wells located over the spoil's interior (buried plateau). Based on the June 1991 water levels, the mean saturated thickness for the valley fill wells (9.2 m) is approximately twice the mean value (4.7 m) for the wells located over the spoil's interior. The greater saturated thickness in the valley fills may be the result of low-permeability spoil at the mouths of the valleys retarding drainage from the valley fills and allowing for the accumulation of water (Kemp, 1990). In addition, the lower elevation of the valley bottoms, and constriction of flow because of the V shape of the incised, pre-mining valley, compared to the relatively flat bottom of the Hazard No. 7 coal underlying the plateau region, may also be factors. The increase in recharge along the edge of the spoil in the valley fills, in contrast to the lack of direct recharge over the main spoil body, may also contribute to the difference in saturated thickness.

Based on an average saturated thickness of 6.4 m for all spoil wells, and assuming an estimated porosity of 20%, approximately 5.3×10^6 m^3 of water is stored within the existing 4.1 km^2 of reclaimed spoil. Diodato and Parizek (1994) found that the porosity of mine spoil ranged from 30.1 to 57% in shallow, unsaturated boreholes, but because of the thick spoil, compaction, and saturated conditions at the Star Fire site, the 20% porosity estimate used here seems appropriate.

Hydrographs for the monitoring wells reveal some important facts about the groundwater system. Fig. 10 shows the daily water-level averages for monitoring wells 6, 9, and 11. These data were collected using digital data loggers. Water level gradually increased in each well from May 16, 1991, through June 19, 1991. Wells 9 and 11, which are located in the interior of the spoil, exhibited a steady, gradual rise in water level, while MW 6's water level fluctuated erratically, in a pattern that closely paralleled the precipitation during the observation period. The net rise in water level for MW 6 is similar to the approximately 0.3 m increase exhibited by wells 9 and 11 during this period.

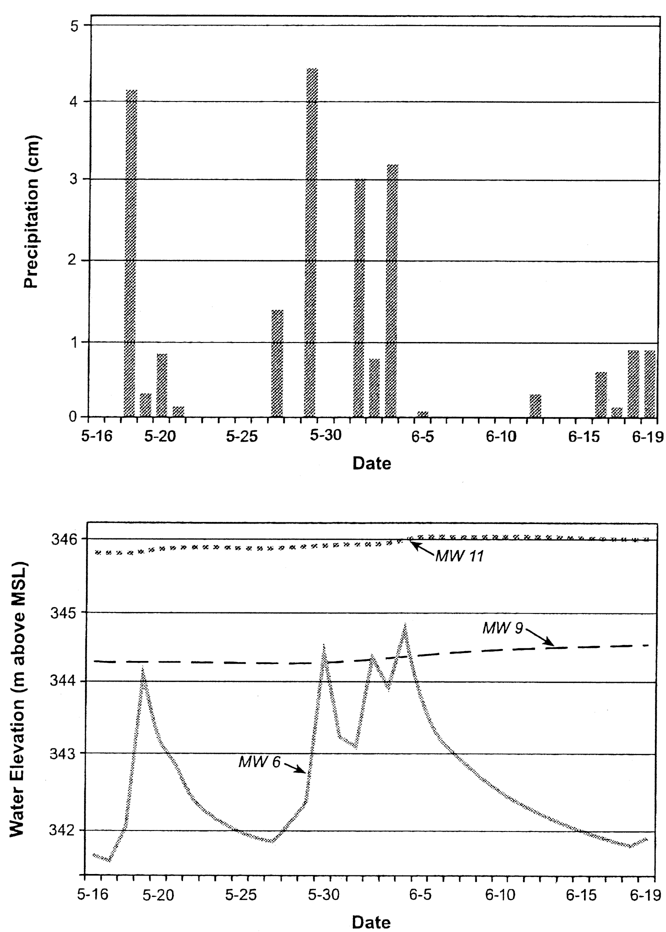

Fig. 10. Precipitation and well hydrographs for monitoring wells 6, 9, and 11 from May 16 through June 19, 1991.

MW 6 is located near a bedrock highwall that resulted from contour-cut mining in this area during the 1950s. The rapid response to precipitation in MW 6 is most likely caused by surface runoff quickly entering the spoil along the contact of the spoil and the bedrock valley wall and by ground-water entering the valley fill from the bedrock in contact with the spoil.

Similar responses to precipitation are also seen in the hydrographs for well 7 (Fig. 11) and wells 9 and 14 (Fig. 12) from December 1993. Each well had a net increase in water level during the period. However, the hydrographs for valley fill wells 7 and 14 indicate that these wells are much more responsive to precipitation than well 9. The increase in water levels following recharge in wells 7 and 14 is probably caused by the same recharge mechanisms described for MW 6.

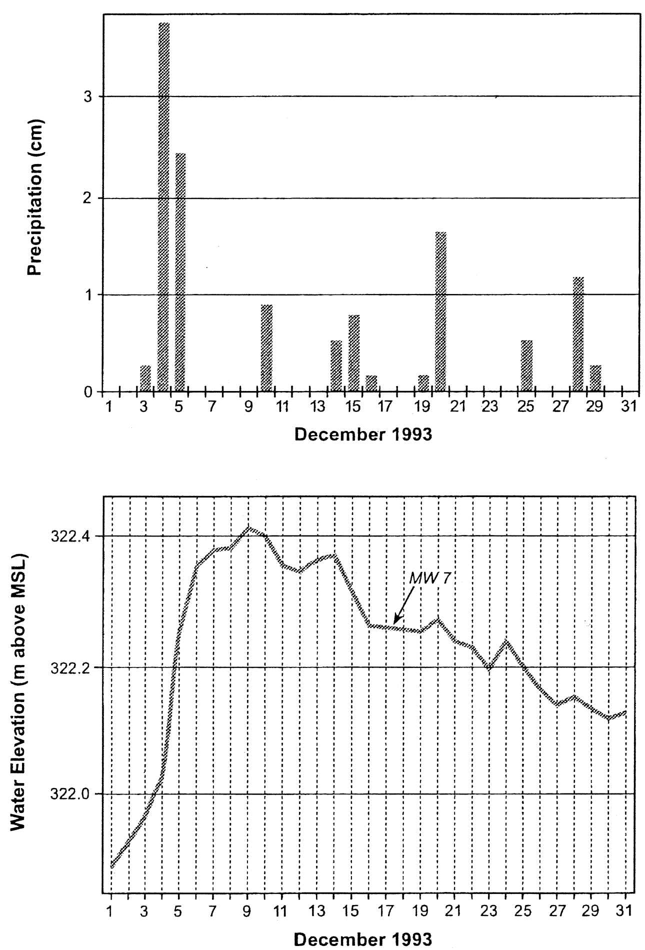

Fig. 11. Precipitation and well hydrographs for monitoring well 7 for December 1993.

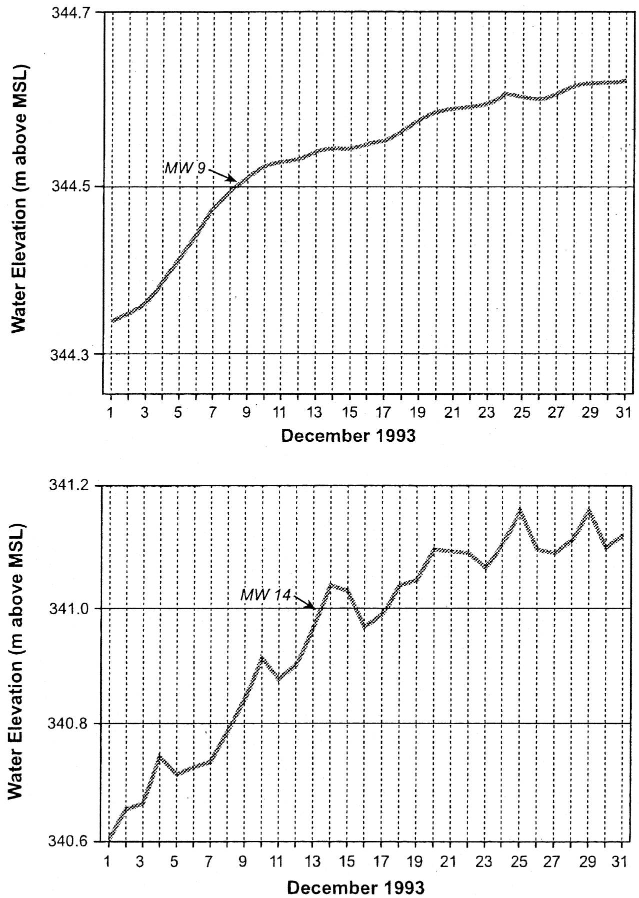

Fig. 12. Hydrographs for monitoring wells 9 and 14 for December 1993.

In summary, the hydrographs for wells 9 and 11 show a relatively smooth response to precipitation, suggesting that the interior of the spoil does not obtain ground-water recharge as readily as the spoil in the valley fills located near the periphery of the spoil (wells 6, 7, and 14). The thickness of the saturated zone in the spoil is a function of the elevation of the bedrock aquitard below the spoil and other barriers to ground-water flow. Generally, the higher the bedrock surface elevation, the thinner the saturated zone. In the valley fill areas the saturated zone is influenced by the pre-existing surface topography of the unmined areas.

5.6. Slug tests

Falling-head slug tests were performed in all monitoring wells, except wells 2, 3, 6, 11 during the fall of 1992. The wells that were tested were chosen to give a representative, spatial coverage of the reclaimed spoil area and subsurface features. For example, four wells (nos. 4, 7, 10, and 14) are over valley fills. Wells 5, 8, 9, 12, and 13 are situated over the mine floor in the spoil's interior. The hydraulic conductivity (K) values ranged from 2.6×10^{-5} to greater than 9.0×10^{-4} cm/s. These values are comparable to K values for silty sand (Freeze and Cherry, 1979), and are also consistent with hydraulic conductivity values determined by other studies of mines that use similar mining methods. For example, Oertel and Hood (1983) found K values from 4.6×10^{-5} to 2.1×10^{-2} cm/s, and Herring and Shanks (1980) found a range from 1.5×10^{-6} to 1.6×10^{-3} cm/s.

Because there is no discernible difference in hydraulic conductivity between the wells in the valley fills and wells in the spoil interior, the sluggish ground-water movement in the spoil interior must be related to the low gradients induced by recharge–discharge relationships. More importantly, the hydraulic conductivities determined in this study, and data collected by others (Harlow and LeCain, 1991; Wunsch, 1992; Minns, 1993), show that the Ks determined for spoil are generally several orders of magnitude greater than those measured in the parent, solid bedrock in Appalachian Coal Field. The relatively uniform distribution of K in spoil, and with the pseudo-karstic nature of flow in the spoil boulder drains (Caruccio and Geidel, 1984; Kemp, 1990) allow for significant lateral movement of ground-water such that a significant saturated thickness will most likely never accumulate except as restricted by buried, topographic barriers.

5.7. Infiltration basin

The deep infiltration basin catches surface-water runoff from a 7.7-ha catchment area. The volume of water flowing into the basin for any recorded precipitation event can be calculated by using the stage–discharge curve for runoff that is recorded by the flume and stage recorder. The water level of the pool that accumulates in the basin is recorded by a pressure transducer and digital data recorder in a stilling well (see Fig. 5).

Response of pool levels to precipitation events from May 16 through June 6, 1991, is shown in Fig. 13. The response of water entering the basin to a storm is nearly instantaneous, indicating very rapid runoff.

Data from a storm on May 29, 1991, are given in Fig. 14. The runoff passing through the flume into the infiltration basin during this event was calculated to be 690 m^3. Three hours passed before all of the water infiltrated into the base of the basin, indicating that the average infiltration rate of the basin was 0.06 m^3/s.

The percentage of rainfall measured as runoff for the May 29, 1991, storm was 22%. Data collected from 42 storms showed the percentage of runoff varied from a low of 0.82% to a high of 34.3%, with an average of 11.9%. Using this average figure, approximately 88% of precipitation either infiltrates directly into the spoil, is transpired by vegetation, or evaporates directly from the spoil's surface.

Typically, the upper few inches of spoil consists of sandstone or siltstone cobbles contained in a sandy or clayey, uncemented matrix. This thin rind of spoil is capable of readily absorbing water. For example, using the May 29 storm data and assuming no evaporation, 78%, or 3.3 of the 4.2 cm resulting from the storm would be available for infiltration into the spoil's surface.

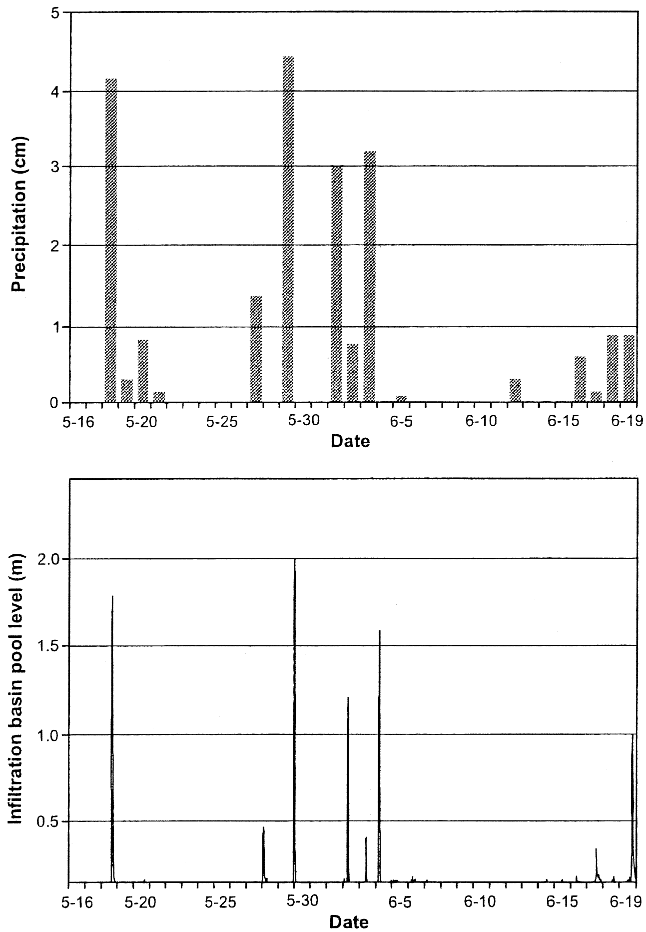

Fig. 13. Response of pool elevation in infiltration basin to precipitation events from May 16 through June 19, 1991.

Using the lower porosity value for shallow spoil of 30.1% determined by Diodato and Parizek (1994), calculations indicate that the upper 10.9 cm of spoil could store all of this water. A thin rind of saturated spoil at the surface would result; this is, in fact, what we observed during excavation immediately after storms (Wunsch et al., 1992).

Three monitoring wells (2, 4, and 5) were placed around the periphery of the basin to monitor the changes in water levels in the spoil as a result of recharge (refer to Fig. 5 for well locations). The water levels for these wells during March, June, and July 1991 are shown in Table 2.

The water level in MW 4 was consistently lower than levels in wells 2 and 5 by nearly 1.2 m. The hydraulic gradient implied by these measurements suggests that the water entering the basin flows in the direction of MW 4 (southwest) toward the Spring Gap valley fill. Monitoring well 4 was placed in or near one of the small drainage

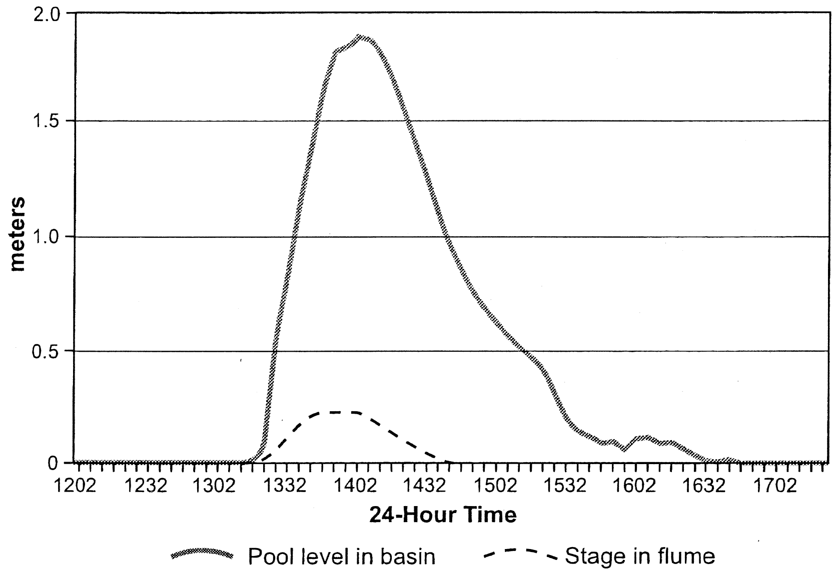

Fig. 14. Relationship between flume stage and pool level during and after the May 29, 1991 storm.

valleys (shaded in gray in Fig. 7) on the upper reaches of the buried Spring Gap stream drainage. The 338 m contour and surrounding intervals indicate a structural low beneath the infiltration basin that opens in the direction of the Spring Gap valley fill. The gradient depicted by the wells surrounding the infiltration basin and also shown by the water-level contours in Fig. 8 is consistent with the dye-trace data, which show that the Spring Gap valley fill is capturing the water infiltrating into the spoil through the infiltration basin.

5.8. Interpretation of spoil water data

Table 2 shows statistical data for the TDS values determine for water samples collected from April 1991 through August 1994. The TDS data are a good indicator of the amount of the degree of dissolved minerals contained in the ground-water, which is a reflection of water–rock interaction, and dilution effects.

Head distribution for wells on the periphery of the infiltration basin indicates that water entering the spoil through the basin moves toward MW 4. This is substantiated by chemical data from water samples taken from wells 2, 4, and 5. The average TDS content of the samples taken from MW 4 is 789 mg/l (see Table 2), which is approximately one-third the TDS values of the other wells surrounding the infiltration basin (MW 2 and MW 5). TDS values for wells 2 and 5 are similar to each other (average TDS values are 2273 and 2216 mg/l, respectively). The lower TDS value in MW 4 is most likely a result of dilution by the less mineralized surface-water entering the spoil through the infiltration basin. A sample of water taken from the intermittent flow that descends into the infiltration basin had a relatively low dissolved solid content

Table 2
TDS data for wells and springs, Star Fire Site, in mg/l

Date	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	Spring 1
4/16/91	2113	2380	773	2064	616	2196	3037	2515	1851	3219	2202	2273	924	1359
7/17/91	2059	2412	841	2109	619	2351	2801	2333	1932	3226	2595	2344	1078	1502
10/23/91	2315	2412	803	2124	675	3073	2703	2205	2157	3160	2740	2287	1163	2182
2/5/92	2605	2650	783	2705	701	2507	2792	2053	1797	2992	2478	2260	1159	1743
6/16/92			729	2077	669	2740	2902	1635	1947	2922	2545	2422	1128	1707
8/10/94									1426					1694
n	4	4	5	5	5	5	5	5	6	5	5	5	5	6
Max.	2605	2650	841	2705	701	3073	3037	2515	2157	3226	2740	2422	1163	2182
Min.	2059	2380	729	2064	616	2196	2703	1635	1426	2922	2202	2260	924	1359
Avg.	2273	2463	789	2216	656	2573	2847	2057	1852	3104	2512	2317	1090	1698
Std.	247	125	47	275	37	344	128	304	242	139	198	67	99	279
CV (%)	11	5	6	12	6	13	4	14.8	13	4	7.9	2.9	9.1	16.4

(177.8 mg/l). We can reasonably 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. Therefore, the low TDS values of water samples from MW 4 probably reflect the mixing of recharge water entering through the infiltration basin and more mineralized ground-water in the saturated zone.

The mean TDS value (see Table 2) for wells in the interior plateau region of the spoil (2, 3, 5, 8, 9, 11, 12, and 13) is 2474 mg/l (S.D. = 349), whereas mean TDS values for the valley fill wells (4, 6, 7, 10, 14) and spring 1 is 1414 mg/l (S.D. = 820). The higher TDS values characteristic of the interior of the spoil are most likely the result of longer contact time between slowly moving ground-water and reactive spoil. The extended contact time allows for greater water–rock interaction and leaching of soluble and reactive rock materials, which results in an increase in the total concentration of the dissolved constituents. Limited data indicate that the TDS concentration of the water entering the spoil at Chestnut Gap Branch is generally lower than that of the water emerging from the springs (data from spring 1 in Table 2) at the discharge zone. Discharging ground-water from spring 1 has a TDS content nearly three times that of the water entering the spoil at Chestnut Gap Branch. This dramatic increase in mineralization probably results from two main processes: (1) the recharging water, although only in contact with the spoil material for a short time (as evidenced by travel times determined by dye-tracing), reacts with minerals in the spoil, and (2) the relatively fresh water from the stream is mixing with the more mineralized water entering the valley fills from the interior of the spoil. Mass-balance calculations demonstrate that the mixing scenario can account for the majority of the dissolved constituent load measured at spring 1. For example, using the TDS data from June 1994 and the surface-water flow data used in previous calculations, the expression for the mass loading at spring 1 is:

$$Q_{sp}C_{sp} = Q_{cb}C_{cb} + Q_{(sp-cb)}C_{spl}$$

where C_{spl} is the TDS load of water in the Spring Gap valley fill, which would mix with water entering the spoil from Chestnut Gap Branch. Solving for C_{spl} yields a TDS concentration of 2378 mg/l. Monitoring well 7 is located approximately 700 ft upgradient from spring 1, and is probably a good indicator of the TDS concentration of water originating from the interior spoil and presently stored in the Spring Gap valley fill. The measured TDS value from MW 7 is 2740 mg/l, and is within 13% of the calculated value. This example suggests that ground-water mixing is occurring, and that mixing is an important determining factor for water quality in the spring. This is a reasonable interpretation, considering that Kemp (1990) demonstrated that travel time for water entering the spoil at Chestnut Gap Branch and discharging at spring 1 is less than 73 h. This rapid rate of water movement would limit the amount of time for chemical reactions that increase TDS concentrations, especially if channelized flow controls the movement of ground-water in the spoil. Channelized, or pseudo-karstic, flow can limit the amount of spoil–water contact that adds dissolved solids to water moving through the spoil (Caruccio and Geidel, 1984).

TDS data indicate that the majority of the water leaving the site is derived from the spoil, and this interpretation is consistent with the ground-water flow data discussed previously. Based on average TDS values, wells 7 and 10, which are closest to the flume monitoring the mine outflow in Long Fork (see Fig. 7 for the location), yield TDS concentrations very similar to the TDS concentration of water discharging the mine site through the Long Fork flume (TDS values are 2573 and 1966 mg/l for wells 7 and 10, respectively, and 1947 mg/l for the flume). These data, along with the mass-balance calculations for the total water budget discussed previously, suggest that the major source of the water discharging from the mine site is ground-water derived from the mine spoil. If surface-water runoff at the site were making a significant contribution to the total mine outflow, the TDS measured at the outflow would be considerably less than that observed for spoil ground-water, because of dilution. Samples of surface-water collected at other areas of the site (e.g., water from the stream at Chestnut Gap Branch and water entering the infiltration basin) have TDS concentrations that are generally less than 600 mg/l (Dinger et al., 1990).

6. Conceptual model for ground-water flow in spoil

Fig. 15 is a digital terrain model showing the post-mining bedrock topography buried beneath the spoil and features such as the buried plateau and the Spring Gap and Long Fork valleys. This map was generated from elevation data derived from several sources, including mine pit and floor elevation data, geologic cores drilled for exploration, and elevation data derived directly from topographic maps at the scale of 1:4800 (1 cm = 48 m). The vantage point is the northwest corner of the spoil. The buried bedrock topography shown here has a pronounced effect on the occurrence and movement of ground-water in the spoil.

Fig. 16 shows several features and ground-water flow directions superimposed on an aerial photograph of the northwestern part of the mine site (top photograph). The vantage point is the same as in Fig. 15. Water contained in the valley fills flows toward the northwest, where it discharges at springs. Water that accumulates in the southeastern part of the spoil's interior flows toward the heads of the buried valleys, which are now

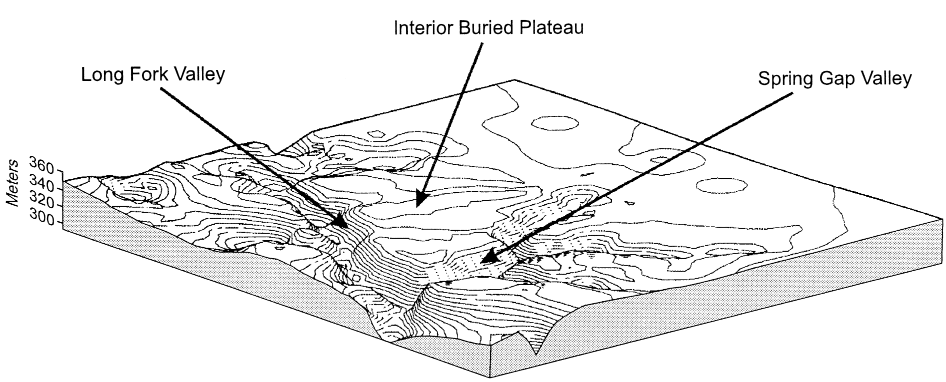

Fig. 15. Digital terrain model showing the bedrock topography buried beneath the spoil. Features such as the buried plateau and the Spring Gap and Long Fork valley fills can be seen in Fig. 16. Vantage point is from the northwestern corner.

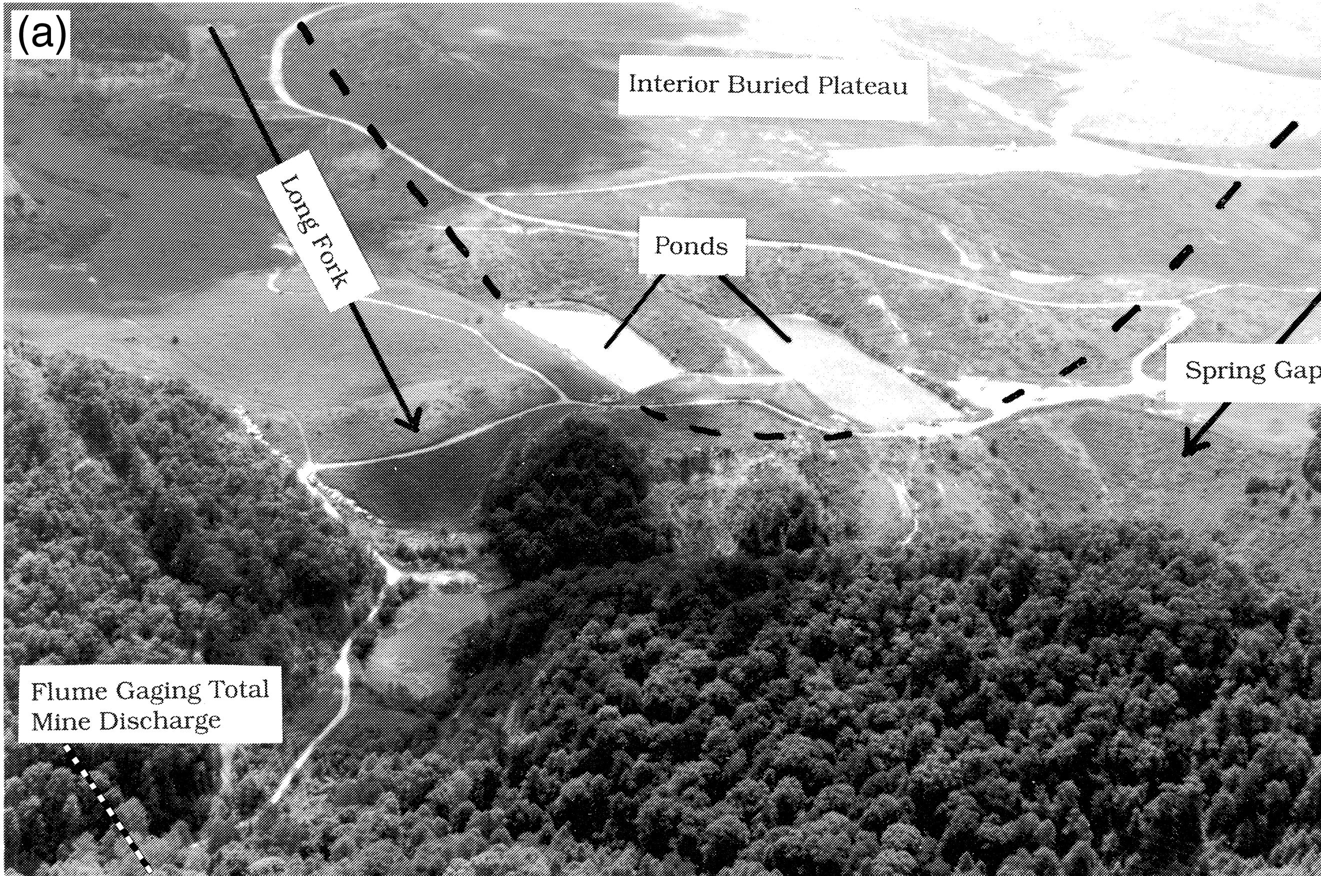

Fig. 16. Aerial photographs of the northwest corner of the reclaimed mine site. The conceptual ground-water flow system is superimposed on the top photograph (a). Ground-water discharge points along the northwest slope of the spoil body are superimposed on the bottom photograph (b).

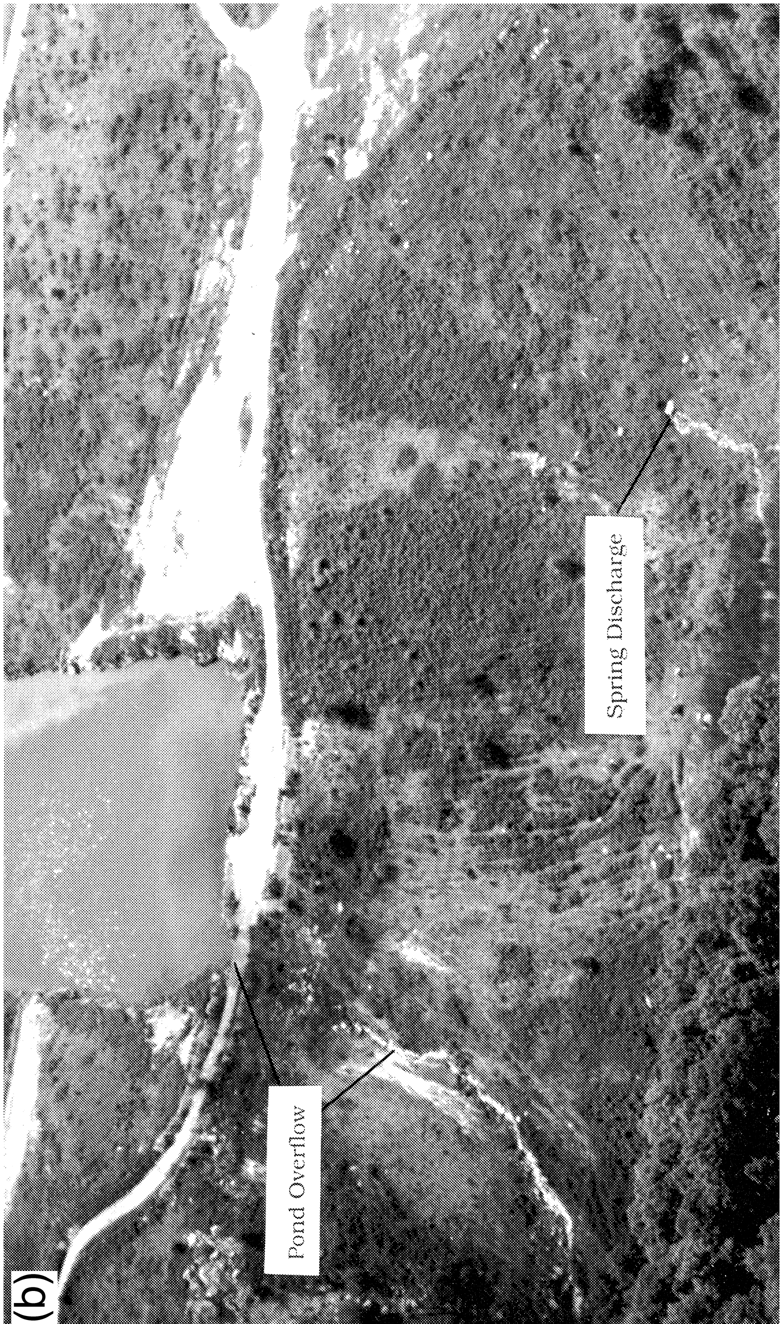

Fig. 16 (continued).

valley fills. This is evidenced by dye-trace data, head data, and the bottom structure of the buried plateau. Some of the water in the spoil's interior discharges to ponds situated above the springs on the northwest face. These points of discharge are illustrated in the bottom photograph of Fig. 16, an aerial photograph with a close-up view of the northwest face of the spoil. Water entering the spoil through the infiltration basin (not within view in either photograph in Fig. 16) probably flows into Spring Gap, as previously indicated by the dye-trace and head data from the wells surrounding the basin. The pond used for dust-control water, in turn, flows down the face of the spoil, where it joins with the spring discharge before entering the lowermost sediment pond, which is located just above the flume (Fig. 16, top photograph).

Mass-balance calculations indicate that the amount of water contributed by the pond overflow to the total mine outflow (24.4 l/s) is less than the amount of water that discharges from the valley fills (39.4 l/s). Water recharging the buried Spring Gap and Long Fork valleys is supplied from (1) ground-water derived from bedrock along the valley fills at the spoil–bedrock contact, (2) surface-water seepage along the spoil–bed-

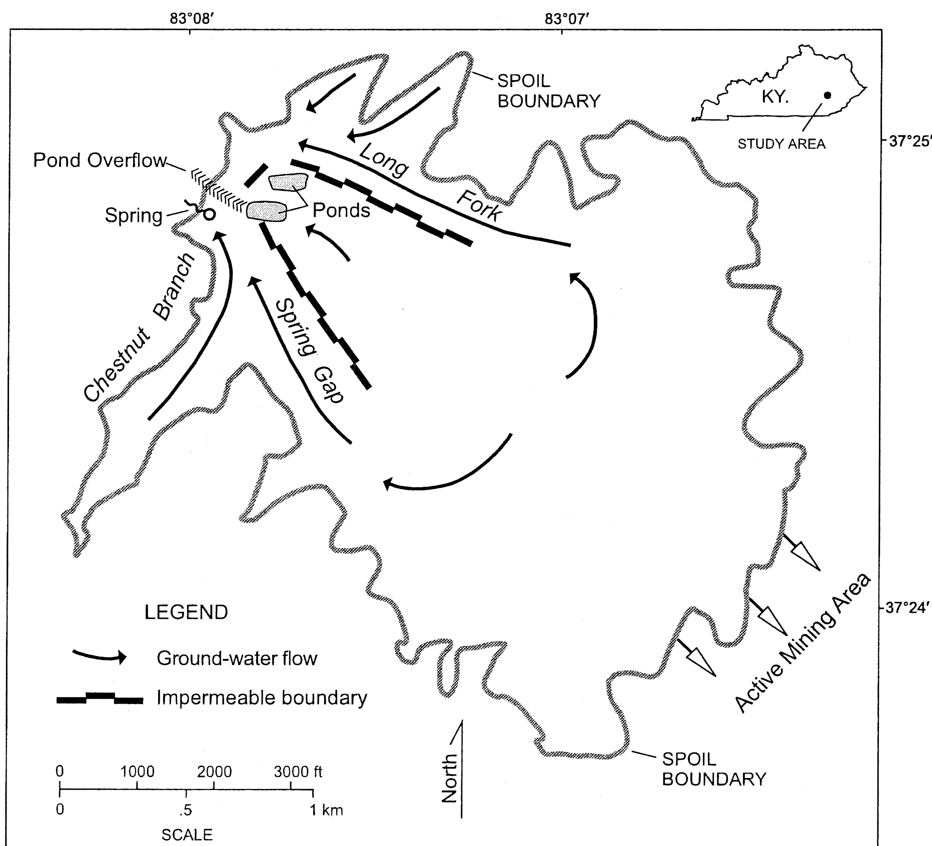

Fig. 17. Conceptual model of ground-water flow in the spoil at the Star Fire site. Direction of flow is uncertain near the active mining area.

rock contact, and (3) the capture of ground-water from the spoil's interior in the southeastern part of the spoil.

Fig. 17 is a map of the spoil body; the arrows indicate the assumed direction of ground-water flow. It represents a conceptual model of ground-water movement through the spoil. In this model the majority of water moves through the valley fills around the main spoil body and discharges at the northwest corner of the spoil. Recharge enters the spoil mainly along the edges of the valley fills, and at discrete points on the reclaimed surface, which includes the infiltration basin.

The three-dimensional representation of the buried, solid rock topography produced for this site shows that the buried bedrock has a pronounced effect on the occurrence and movement of ground-water. Although standard hydrogeological monitoring methods, including dye traces, water level elevation measurements, slug tests, and hydrogeochemistry were used to delineate the hydrogeology of the site, the conceptual model presented here suggests that a reasonable, first approximation for predicting ground-water occurrence can made be made utilizing topographic and mine survey data and aerial photographs. These data are usually already in the possession of the mine engineer, so computer-generated, three-dimensional subsurface representations can be generated quickly and efficiently that can aid controlling mine dewatering problems, and compliment reclamation efforts. Additional data from monitoring wells or ground-water discharges can compliment and validate the hydrologic evaluation of the mine spoil.

7. Future directions

Technological advances in computer graphics and geographic information systems (GIS) now make it possible to quickly process and overlay maps. Image processing shows promise of mapping reclaimed lands where accurate maps and surveying data are not available. High resolution satellite imagery with 1 m pixel resolution will soon be commercially available for much of the developed world, making surface mapping, including the identification of soil and vegetative cover easily attainable. For areas without accurate elevation model data, global positioning system (GPS) technology allows for quick traverses across areas where spatial and elevation data can be compiled at sub-meter accuracy. These data, correlated with digital terrain models of the buried, solid rock surface, will allow for reasonable and timely predictions ground-water accumulation and movement.

8. Summary

Mine spoil at the Star Fire site ranges from approximately 30 to 90 m in thickness. Selected spoil handling techniques, such as cast blasting, dragline casting, and dumping by trucks, is providing a framework for water storage in the 4.1 km^2 that have been mined at the Star Fire site.

Field investigations have identified numerous ground-water recharge and discharge zones at the mine spoil area. Recharge occurs by way of disappearing streams, ground-water infiltration along exposed boulder zones, and at areas where the spoil is in contact with the bedrock highwalls. Minor recharge occurs locally on the spoil's surface through macropores (snakeholes). Discharge of ground-water from the spoil occurs mainly through springs and seeps at the outslope of the spoil body. Ground-water movement within the spoil is controlled by the ground-water gradients within the spoil, which are a function of the buried topography and the interaction of the recharge and discharge zones with zones of low-permeability spoil. The spoil interior, lacking any major direct recharge from the surface, slowly accumulates water, whereas in the valley fills ground-water moves at a rapid rate. Recharge to the valley fills comes from streams, adjacent bedrock aquifers, and from surface-water that seeps in near the bedrock–spoil interface.

Water table elevations measured at monitoring wells, springs, and ponds indicate that a saturated zone in the interior of the spoil slowly discharges to the southeast or northwest, and that two additional saturated zones occur at lower elevations in the two adjoining valley fills (Spring Gap–Chestnut Gap Branch and Long Fork). Most likely, these saturated zones are in hydraulic connection in the upper reaches (southeastern part) of the spoil body, but are separated by the topography of the basal bedrock in the central plateau section of the spoil.

Based on an average saturated thickness of 6.4 m for all spoil wells, and assuming an estimated porosity of 20%, approximately 5.3×10^6 m^3 of water is stored within the existing 4.1 km^2 of reclaimed spoil.

The hydraulic conductivity (K) values ranged from 2.0×10^{-5} to greater than 9.0×10^{-4} cm/s. The upper limit of K for spoil wells could not be determined because of equipment limitations; thus, the upper range could be significantly higher than measured. Because there is no discernible difference in hydraulic conductivity between the wells in the valley fills and wells in the spoil interior, the apparently sluggish ground-water movement in the spoil interior must be related to gradients induced by recharge–discharge relationships. The hydraulic conductivities are generally several orders of magnitude greater than the solid bedrock, and is sufficiently high to allow for the lateral movement of ground-water such that a significant saturated zone (e.g., greater than 10 m) will probably not likely occur.

The head distribution measured in monitoring wells around the infiltration basin indicates that the water entering the basin is flowing toward the Spring Gap valley fill and most likely discharges from the springs in the northwestern part of the spoil.

Chemical analysis of samples from monitoring wells and springs shows that all waters at the site are a calcium–magnesium–sulfate type (Wunsch et al., 1996). The pH of all ground-water samples, except for those from MW 14, fell into a favorable range of approximately 6 to 7. The TDS values for wells located in the spoil interior are higher than the average value for wells located in the valley fills. Higher mineralization of the water samples from the interior spoil area probably reflects the longer contact time of ground-water with reactive spoil material, as inferred from the gentle gradient of the water table and dye-tracing data. Lower TDS values for the valley fill wells probably result from a greater contribution of less mineralized surface-water into the ground-water flow system and a shorter residence time.

A conceptual model of ground-water flow patterns indicates that two separate but connected saturated zones occur in the spoil. Ground-water movement within the spoil is controlled by the gradients that form as a function of the interaction of recharge and discharge zones, by the topography of the relatively impermeable pavement that underlies the lowest coal being mined (Hazard No. 7), and by the drainage patterns that existed before mining began. The major streams that drained the pre-mined area (Chestnut Gap Branch, Spring Gap, and Long Fork) eroded valleys whose bottoms are at elevations well below the level of the Hazard No. 7 coal. These drainage valleys became valley fills as contour-cut mining occurred along the valley walls. The interior of the spoil contains a relatively thin saturated zone from the accumulation of water from discrete infiltration zones within the spoil, the infiltration basin, and the active mining area where uncompacted or reclaimed spoil are present. Water that accumulates in the interior zone most likely flows into the valley fills on either side of the interior plateau in the upper reaches of the buried valleys in the southeastern section of the spoil, or flows to the northwest and discharges into either of the two ponds excavated into the bedrock pavement below the Hazard No. 7 coal.

Water in the valley fills receives contributions of ground-water from the adjacent unmined bedrock highwall and surface-water that accumulates and later percolates along the spoil–bedrock contact. The total mine outflow measured in the northwestern area of the reclaimed spoil produces a base flow of approximately 113 l/s. Variations in water quality observed at the site are related to the flow system described by this model.

Contour lines on maps of the spoil's water table correlate with abrupt changes in topography defined by buried valleys and the pavement bedrock resulting from coal extraction. This implies that the buried topography beneath large spoil areas such as the Star Fire site is important in predicting hydrologic characteristics of the spoil body, and must be considered when evaluating such sites.

The initial water-quality and -quantity data measured at the Star Fire Mine demonstrate that the ongoing mining techniques can provide the physical framework for water storage in the extensive mine spoil. Although the water stored in the spoil is not potable at this time, it likely could serve for various agricultural and industrial uses and may become more useful with time and as water-treatment technology improves. Development of a useful water supply within the spoil will be a key factor in future land use and economic diversity of the site and other similar sites in eastern Kentucky.

References

Aldous, P.J., Smart, P.L., 1987. Tracing ground water movement in abandoned coal mined aquifers using fluorescent dyes. Ground Water 26 (2), 172–178.

Aulenbach, D.B., Bull, J.H., Middlesworth, B.C., 1978. Use of tracers to confirm ground-water flow. Ground Water 16 (3), 149–157.

Caruccio, F.T., Geidel, G., 1984. Induced alkaline recharge zones to mitigate acidic seeps. Proceedings, 1984 Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation. University of Kentucky, College of Engineering, College of Continuing Education and Extension, College of Agriculture—Department of Forestry, Lexington, pp. 43–47.

Chesnut Jr., D.R., 1992. Stratigraphic and structural framework of the Carboniferous rocks of the Central Appalachian Basin in Kentucky. Kentucky Geological Survey, Series 11, Bulletin 3, 42 pp.

Danilchik, W., Waldrop, H.A., 1978. Geologic map of the Vest Quadrangle, eastern Kentucky. U.S. Geological Survey Geologic Quadrangle Map GQ-1141.

Dinger, J.S., Warner, R.C., Kemp, J.E., 1988. Building an aquifer in coal-mine spoil: Concept and initial construction at the Star Fire tract, eastern Kentucky. Proceedings, 1988 Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation. University of Kentucky, College of Engineering, College of Continuing Education and Extension, College of Agriculture—Department of Forestry, Lexington, pp. 85–93.

Dinger, J.S., Wunsch, D.R., Kemp, J.E., 1990. Occurrence of ground water in mine spoil, a renewable resource: Star Fire tract, eastern Kentucky. Proceedings of the 1990 Mining and Reclamation Conference and Exhibition, Morgantown, WV. West Virginia University Services, pp. 171–179.

Diodato, D.M., Parizek, R.R., 1994. Unsaturated hydraulic properties of reclaimed coal strip mines. Ground Water 32 (1), 108–119.

Freeze, R.A., Cherry, J.A., 1979. Ground Water. Prentice-Hall, Englewood Cliffs, NJ, 604 pp.

Harlow, G.E., LeCain, G.D., 1991. Hydraulic characteristics of, and ground-water flow in, coal-bearing rocks of western Virginia. U.S. Geological Survey Open-File Report 91-250.

Herring, W.A., Shanks, T.J., 1980. Hydraulic conductivity of cast overburden. EOS 61 (48), 1193.

Hinrichs, E.N., 1978. Geologic map of the Noble Quadrangle, eastern Kentucky. U.S. Geological Survey Geologic Quadrangle Map GQ-1476.

Hvorslev, M.J., 1951. Time lag and soil permeability in ground-water observations. U.S. Army Corps of Engineers Waterways Experiment Station Bulletin 36.

Kemp, J.E., 1990. Hydrogeologic characterization of surface mine spoil, Star Fire Mine, eastern Kentucky. MS Thesis, University of Kentucky, Lexington, KY, USA.

Kipp, J.A., Dinger, J.S., 1991. Stress-relief fracture control of ground-water movement in the Appalachian Plateau. Kentucky Geological Survey, Ser. 11, Reprint 30, 11 pp.

Minns, S.A., 1993. Conceptual model of local and regional ground-water flow in the eastern Kentucky coal field. PhD dissertation, University of Kentucky, Lexington, KY, USA.

Oertel, A.O., Hood, W.C., 1983. Changes in ground-water quality associated with cast overburden material in southwest Perry County, Illinois. Proceedings, 1983 Symposium on Surface Mining, Hydrology, and Reclamation. University of Kentucky, College of Engineering, College of Continuing Education and Extension, College of Agriculture—Department of Forestry, Lexington, pp. 73–78.

Papp, A.R., 1976. Extractable cations from claystones and shales of the Pennsylvanian Breathitt Formation in eastern Kentucky as related to depositional environments. MS Thesis, Eastern Kentucky University, Richmond, KY, USA.

Smart, P.L., Laidlaw, I.M.S., 1977. An evaluation of some fluorescent dyes for water tracing. Water Resources Research 13, 15–33.

Sobek, A.A., Schuller, A.J., Freeman, J.R., Smith, R.M., 1978. Field and laboratory methods applicable to overburdens and minesoils. U.S. Environmental Protection Agency, EPA-600/2-78-054, 204 pp.

Soil and Material Engineers, 1982. Ground water determination: Star Fire Coals, various pagination.

Spengler, R.W., 1977. Geologic map of the Salyersville South Quadrangle, Magoffin and Breathitt Counties, Kentucky. U.S. Geological Survey Geologic Quadrangle Map GQ-1373.

Thompson, D.B., 1987. A microcomputer program for interpreting time-lag permeability tests. Ground Water 25 (2), 212–218.

U.S. Geological Survey, 1980. National Handbook for Recommended Methods for Water-data Acquisition, Chap. 2—Ground water. U.S. Geological Survey Work Group 2, 147 pp.

Weinheimer, R.L., 1983. Vertical sequence and diagenesis in Breathitt sandstones in eastern Kentucky. MS Thesis, University of Cincinnati, Cincinnati, OH, USA.

Wunsch, D.R., 1992. Ground-water geochemistry and its relationship to the flow system at an unmined site in the Eastern Kentucky Coal Field. PhD Dissertation, University of Kentucky, Lexington, KY, USA.

Wunsch, D.R., Dinger, J.S., Taylor, P.B., 1992. Design, construction, and monitoring of the ground-water resources of a large spoil area: Star Fire tract, eastern Kentucky. Kentucky Geological Survey, Ser. 11, Report of Investigations 6, 16 pp.

Wunsch, D.R., Dinger, J.S., Taylor, P.B., Carey, Daniel, I., Graham, C.D.R., 1996. Hydrogeology, Hydrogeochemistry, and Spoil Settlement at a Large Mine-Spoil Area: Star Fire Tract, Eastern Kentucky. Kentucky Geological Survey, Series 11, Report of Investigations 10, 49 pp.