ISSN 0075-5621

KENTUCKY GEOLOGICAL SURVEY
Donald C. Haney, State Geologist and Director
UNIVERSITY OF KENTUCKY, LEXINGTON

CONCEPTUAL MODEL OF LOCAL AND REGIONAL GROUND-WATER FLOW IN THE EASTERN KENTUCKY COAL FIELD

Shelley A. Minns

Thesis Series 6
Series X1, 1993

DISCLAIMER

ISSN 0075-5621

KENTUCKY GEOLOGICAL SURVEY
UNIVERSITY OF KENTUCKY, LEXINGTON
Donald C. Haney, State Geologist and Director

CONCEPTUAL MODEL OF LOCAL AND REGIONAL GROUND-WATER FLOW IN THE EASTERN KENTUCKY COAL FIELD

Shelley A. Minns

Thesis Series 6
Series XI, 1993

CONTENTS

Page

CONTENTS
(continued)

CONTENTS
(continued)

ILLUSTRATIONS

Figure **Page**

ILLUSTRATIONS
(Continued)

Figure **Page**

TABLES

Table **Page**

CONCEPTUAL MODEL OF LOCAL AND REGIONAL GROUND-WATER FLOW IN THE EASTERN KENTUCKY COAL FIELD

Shelley Ann Minns

ABSTRACT

Ground water in eastern Kentucky is obtained from shallow fractures. Steep topography, fractures, and stratification alter flow paths; consequently, local and regional flow systems are not defined.

A first-order watershed in the Eastern Kentucky Coal Field was instrumented in three nests along a cross section from ridge top to valley bottom. Three core holes, 142 pressure injection test intervals, and water-level and chemical datafrom24 piezometers were used to identify five ground-water zones. Two zones, above and below the Magoffin Member, show water-quality differences. Three zones are differentiated by hydraulic differences. Local ground-water flow discharges to the first-order stream. Flow in the regional system is downward beneath the stream.

Analysis of drill-hole data, water-level data, and pressure-injection and water-quality data for three previous investigations in eastern Kentucky showed the same five ground-water zones.

The above-Magoffin-Member Zones characteristically contains calcium, magnesium, sulfate, and bicarbonate water. The below-and-including-Magoffin-Member zone contains sodium and bicarbonate water. The shallow-fracture zone is a blanket-like, intensively fractured layer that is up to thick, characterized by rapid infiltration of water. The elevation-head zone, located above drainage is characterized by large differences in conductivity between strata, vertical flow in rock and horizontal flow in coal, and head equal to elevation. The pressure-head zone, has a pressure-head comp less variation in conductivity and is located mostly below drainage.

The local flow system is within the shallow4racture zone. Ground-water flow in the region tem is downward toward the fresh-saline interface. The deepest circulation is beneath upland where the fresh-saline interface is deepest. Regional flow discharges to third-order or larger streams.

A monitoring strategy must identify spatial and seasonal water-quality variations. Impacts shallow-fracture zone caused by surface and underground mining may be identified by installing wells in the shallow-fracture zone downslope of the disturbance. Ground-water changes in first-order basins may be detected by monitoring surface streams above and below proposed disturbances.

INTRODUCTION

The Appalachian region exemplifies a stratigraphically layered, hillside setting. Ground-water flow in this system is complex and has not been completely addressed. The coal-field region of eastern Kentucky provides an excellent example of a layered, hillslope, hydrogeologic setting that contains interbedded sandstone, shale, and coal. Ground-water flow is complicated by the presence of coal beds and fractures that are more transmissive than surrounding strata. Surface-fracture zones, located along hillslopes and in valley floors, provide direct conduits for ground-water flow from hillsides to adjacent streams and valley-floor aquifers.

General conceptual models describing this flow system have been developed (Wyrick and Borchers, 1981; Kipp and others, 1983; Kipp and Dinger, 1987; Stoner, 1983; Larson and Powell, 1986; Davis, 1987; Wright, 1987; Harlow and LeCain, 1991; and Wunsch, 1992). Many of these studies seek to characterize water-bearing zones typically developed for domestic water supplies and to investigate potential impacts that land use has on these supplies.

Rural areas in eastern Kentucky rely heavily on ground water for domestic use. Dewatering of wells and streams adjacent to underground mines is alleged to occur where underground mines intercept near-surface and valley-floor fractures. Secondary fracturing from subsidence has allegedly caused water quality and quantity changes. However, in most cases, pre-mining conditions have not been adequately documented. An increased understanding of coal-field flow systems may facilitate remediation or prevention of these problems.

This investigation documents the ground-water flow system of a small watershed in eastern Kentucky. Data from core and rotary holes, pressure-injection tests, piezometers, and rain gage are used to describe the site-specific flow system along a typical basin cross section. Data from three other sites in eastern Kentucky are also evaluated and results used to conceptualize local and regional flow.

A detailed hydrologic investigation requires that straightforward hydrologic concepts be evaluated in the context of complex hydrogeologic settings. Fundamental physical properties and processes governing ground-water flow must be incorporated into a climatic, topographic, and geologic framework to develop a conceptual model of ground-water flow representative of the site. In some instances, the flow system is modified by man-made alterations, such as mining. After the local flow regime is identified, the role of the site-specific system must be defined in a larger, regional context.

ANALYSIS OF PROBLEM

Physical Properties and Processes

Geologic media have hydraulic properties that govern the movement and storage of water within them. Porosity, hydraulic conductivity, transmissivity, and the degree of anisotropy and heterogeneity are among the most important for the study of ground-water movement.

Porosity

Ground water is stored in the open spaces of rocks. The volume of the void space divided by the total volume of rock mass is defined as porosity and is expressed as a percentage of total rock volume. If porosity is the result of arrangement of grains within the rock, it is referred to as primary porosity. Primary porosity varies depending on the arrangement, shape, and degree of sorting of the rock matrix. For example, poorly sorted rocks are less porous than well-sorted rocks. Primary porosity is reduced if the mineral grains are cemented together.

Strata typical of the Appalachian coal-field region generally have low primary porosities. The deltaic depositional environment of Middle Pennsylvanian time in eastern Kentucky was conducive to the formation of poorly sorted sedimentary deposits, i.e. graywacke sandstone, siltstone, and sandy shale. Many of these strata exhibit secondary cementing by quartz, siderite, iron oxide, and calcite (Price, 1956). In the northern Appalachian coal-field region, Booth (1984)noted that coarse-grained rocks, such as sandstone, have greater primary porosity than fine-grained rocks, such as shale. Brown and Parizek (1971) calculated porosities ranging from 0.8 percent to 9.4 percent for various coal-bearing strata in Pennsylvania. Eight samples of sandstone from the Breathitt Formation in eastern Kentucky have porosities ranging from 0.50 percent to 4.41 percent (Price, 1956).

Rocks that are jointed, fractured, or subjected to dissolution exhibit secondary porosity. Secondary fracturing markedly increases the porosity of rocks with low primary porosity by creating additional openings that may store water. For example, fractured crystalline rocks have porosity values that may be twice that of unfractured rocks (Freeze and Cherry, 1979).

Table 1.—Horizontal Hydraulic Conductivity Values for Various Earth Materials.

Material	*Material Type*	*Hydraulic Conductivity (ft./min.)*
gravel	unconsolidated	20 to 2,000
clean sand	unconsolidated	2 to 6E-04
silty sand	unconsolidated	0.2 to 2E-05
sandstone	rock	6E-04 to 2E-08
shale	rock	2E-06 to < 2E-11
unfractured igneous and metamorphic	rock	2E-08 to < 2E-11
fractured igneous and metamorphic	rock	4E-02 to 2E-06

Hydraulic Conductivity

Rocks that are porous, however, do not necessarily allow water to flow through them. Hydraulic conductivity is the rate of flow through a cross section of one square foot under a unit hydraulic gradient (Driscoll, 1986) It is dependent on the degree of interconnectedness of the intergranular pore spaces or fractures. Rocks with high porosity have low hydraulic conductivity if the openings are not connected. Rocks such as shale may have relatively high porosity, but have small-diameter pores that restrict flow. A related term is transmissivity which is the rate that water is transmitted through a unit width of aquifer under a hydraulic gradient equal to one. In other words, transmissivity is the hydraulic conductivity multiplied by the saturated aquifer thickness. Table 1 lists representative horizontal conductivities for various earth materials.

Coal-field strata generally exhibit low primary, hydraulic-conductivity values. Poor sorting and cementation of mineral grains have reduced connectivity of pore spaces within the rocks. Table 2 lists representative field-determined values of horizontal hydraulic conductivity for coal-field strata. Values in Table 2 are representative of unfractured strata and are indicative of primary, horizontal conductivity values. Table 2 shows that primary conductivity values for sandstone and shale are lower (4.0×10^{-7} to 9.0×10^{-5} feet per minute) than well-sorted sands and gravel (Table 1).

Ground-water flow in steep terrain has a strong vertical flow component. Shale and siltstone have vertical conductivity values that are generally less than horizontal conductivities, resulting from platy minerals and the bedded nature of the strata. Laboratory air permeability experiments show that vertical hydraulic conductivity is 10 to 50 times less than horizontal hydraulic conductivity in shale (Schubert, 1980). Freeze and Cherry (1979) states that the horizontal- to vertical-conductivity ratio is approximately 10:1. Brown and Parizek (1971) used a ratio of 4:1 in Pennsylvania. Laboratory studies show that massive sandstones are, on average, three times more conductive in the horizontal than vertical direction (Schubert, 1980). Laboratory values, however, fail to account for fractures that may affect in-situ conductivity.

Hydraulic conductivity in rocks of eastern Kentucky is increased by secondary fracturing. Interconnected fractures create additional openings through which water can be transmitted. The importance of fractures in controlling ground water flow is widely documented, and numerous researchers have conducted field-based tests to quantify the hydraulic properties of fracture zones. Table 3 summarizes representative field conductivities of coal-field strata which display secondary conductivity from fractures.

Table 2.—Horizontal Hydraulic Conductivity Values for Coal-Field Strata.

Reference	*Location*	*Lithology*[1]	*K (ft./min.)*	*Method*[2]
Kipp and Dinger, 1987	eastern Kentucky	sandstone	6.0E-06 to 4E-07	PIT
		shale	1.0E-05 to 3.2E-06	PIT
Wunsch, 1992	eastern Kentucky	sandstone	< 4.2E-06	PIT
		shale	< 4.2E-06	PIT
Wright, 1987	southwest Virginia	sandstone	4.0E-06	PIT
Schubert, 1980	Pennsylvania	> 50% sandstone	9.0E-05 to 6.0E-06	REC
Hasenfus, 1988	West Virginia	sandstone	1.4E-05	PT
		sandstone	9.0E-06	ST
Dixon and Rauch, 1988	West Virginia	composite borehole (100 to 200')	9.6E-04 to "0"	CHIT
Harlow and LeCain, 1991	southwest Virginia	sandstone (100 to 200')	< 7.7E-08 (median)	PIT
		sandstone (200 to 300')	< 7.7E-08 (median)	PIT
		sandstone (> 300')	< 7.7E-08 (median)	PIT
		shale and siltstone (100 to 200')	< 7.7E-08 (median)	PIT
		shale and siltstone (> 300')	< 7.7E-08 (median)	PIT

1 Number in parentheses represents depth from surface

2 PIT–Pressure-injection test; REC–Recovery test; PT–Pump test; ST–Slug test; CHIT–Constant-head injection test.

The effects of fractures and joints on conductivity are apparent in comparing Tables 2 and 3. Fracturing may increase conductivity by several orders of magnitude. An in-depth discussion of fractures and how they affect conductivity in coal-field strata is presented by Schubert (1980).

If hydraulic conductivity is the same everywhere within a rock body and the same in all directions, the rock is homogeneous and isotropic. If the hydraulic conductivity varies spatially throughout the rock, the rock is heterogeneous. A rock is anisotropic if conductivity changes with direction.

Strata of eastern Kentucky are not homogeneous and isotropic. Lateral facies changes and fractures result in conductivities which vary spatially, thus imparting the characteristic of heterogeneity to the strata. Fractures, especially those of tectonic origin, have preferred orientation. As a result, conductivity is commonly aligned with regional joint trends. Coal bed conductivities, in particular, are generally highly directional. This results from development of closely spaced joints, called cleat, which form in response to tectonic stresses. The face cleat is the predominant joint set and is generally parallel to major structural features. A less developed cleat, termed butt cleat, forms perpendicular to the face cleat. Hobba (1991) studied anisotropy of coal and overburden in the Conernaugh Group of West Virginia. The site has one coal seam overlain by 57 feet of interbedded sandstone and shale. Data from constant-head injection tests show that the direction of maximum transmissivity for both coal and overburden is nearly parallel to the face cleat in the coal. Transmissivity along the face cleat is three times greater than along the butt cleat. For overburden, transmissivity in the maximum direction (0.03 to 0.18 feet per minute on average) is seven times greater than transmissivity in the minimum direction ($5.9x10^{-5}$ to $4.9xlO^{-3}$ feet per minute on average).

Potential

The physical mechanism of ground-water flow was described by Hubbert (1940). Hubbert showed that the physical quantity measured in a piezometer is the fluid potential which he defined as "a physical quantity, capable of measurement at every point in a flow system, whose properties are such that the flow always occurs from regions in which the quantity has higher values to those in which it has lower, regardless of the direction in space" (p.794). Fluid potential at a point is equal to the hydraulic head multiplied by the gravitational constant. Because gravity is considered to be equal everywhere, fluid potential and hydraulic head are identical physical quantities. Therefore, water flows from areas of high head to low head. Hydraulic head for ground-water studies is the sum of head due to elevation and fluid pressure. Static water level in a piezometer is the measure of total hydraulic head at a point. Velocity head is considered negligible in porous media.

Validity of Porous Flow in Fractured Rock

Darcy's Law is an empirical equation used to describe flow of fluids through porous media. It states that the rate of ground-water flow through a cross-sectional area of porous media is proportional to the hydraulic gradient times a proportionality constant, called hydraulic conductivity (K) where K is the hydraulic conductivity and not intrinsic permeability. The use of Darcy's Law requires that the micro-scale collection of grains and pores that comprise a rock be defined in terms of a representative continuum for which macroscopic properties, such as hydraulic conductivity, can be defined. A representative elementary volume of rock material can be described, for which at larger sizes, the rock mass behaves as a continuum. For Darcy's Law to be applied in fractured rock, a large enough volume of rock must be considered so that the fractured rocks behave as a continuum. Because fracture spacing is larger than pore spaces in granular media, the representative elementary volume is larger for fractured rock than for granular material. If fractures are sufficiently close over a large area, the system can be assumed to act hydraulically similar to porous flow (Freeze and Cherry, 1979). According to Campbell and Forster (1991), the representative elementary volume for an unconsolidated sand may be on the order of cubic inches; however, the representative elementary volume for fractured rock is on the order of 10 cubic feet or more. Schubert (1980) concludes that near-surface fracture zones can be considered to respond like porous media where fracture or joint spacing is uniform. Merin (1989) used this approach in an investigation of the hydraulic properties of near-surface fractures in flat-lying Devonian-age rocks in the northern Appalachian Plateau. Owili-Eger (1987) cautions, however, that uniform fracture width and spacing are rarely attained in nature.

The alternative to Darcian analysis is discrete fracture-flow analysis where flow in individual fractures is characterized. This method requires much difficult-to-obtain information about fracture orientation and spacing or estimation of fracture properties using geostatistical techniques. For practical reasons, Darcy's Law is applied in most fracture-flow situations where the problem scale is large.

CLIMATIC, TOPOGRAPHIC AND GEOLOGIC FRAMEWORK

Climate

Climate plays an important role in the amount and temporal distribution of recharge and the amount of water lost through evapotranspiration. Eastern Kentucky has a humid temperate climate. The average annual temperature is 57 degrees Fahrenheit. Temperatures range from below zero degrees Fahrenheit in the winter to more than 100 degrees Fahrenheit in the summer. Rainfall amounts range from about 40 inches annually in northeastern Kentucky to 50 inches annually in southeastern Kentucky. Most of the precipitation occurs from January through March, and the least occurs from August through October (Quinones and others, 1981). Intense precipitation events average 4.3 to 4.5 inches in 24 hours for a 10 year occurrence interval (Leist, 1982; Quinones, 1981). Winters are cold and wet; snow is generally negligible except in severe winters. Water tables generally rise during winter and early spring when infiltration exceeds evapotranspiration. Ground-water levels generally decrease in the summer and fall when rainfall decreases and evapotranspiration reaches maximum levels.

Topography

Topography is a major factor which dictates groundwater-flow patterns. For undisturbed systems, the ground-water surface tends to mimic topography. Undulatory water surfaces form, and are subdued replicas of topography. In homogeneous systems, topographic highs are areas of recharge, and topographic lows are discharge zones. The importance of undulatory water surfaces was first presented by Hubbert (1940) while demonstrating hydraulic head in a potential field. The flow net in Figure 1 graphically demonstrates the effect of topography. Toth (1963) furthered the understanding of the effect of water table position on flow systems when he analytically calculated the resulting equipotential field for various water-table slopes in a theoretical, small drainage basin. The analysis is restricted to rectangular basin cross sections where the aquifer is homogeneous and isotropic and the water-table slope is less than 3 degrees. Sine curves of varying amplitude and wavelength are superimposed on water tables of varying slope to simulate a wide range from flat to hilly topography. Toth discovered that relatively flat terrains develop only regional flow systems. Recharge occurs in the upper part of the basin, and discharge occurs near the basin outlet. Where topographic relief is more pronounced, smaller local flow systems develop in response to topography and are superimposed on the regional system (Figure 2). Recharge occurs on topographic highs, and discharge occurs in adjacent valleys. Toth concludes that shallow, local flow systems respond quickly to external inputs, and the ground water has shorter residence times. Deeper, regional systems respond slowly to external factors and water has longer residence times. Intermediate systems also form, depending on basin geometry.

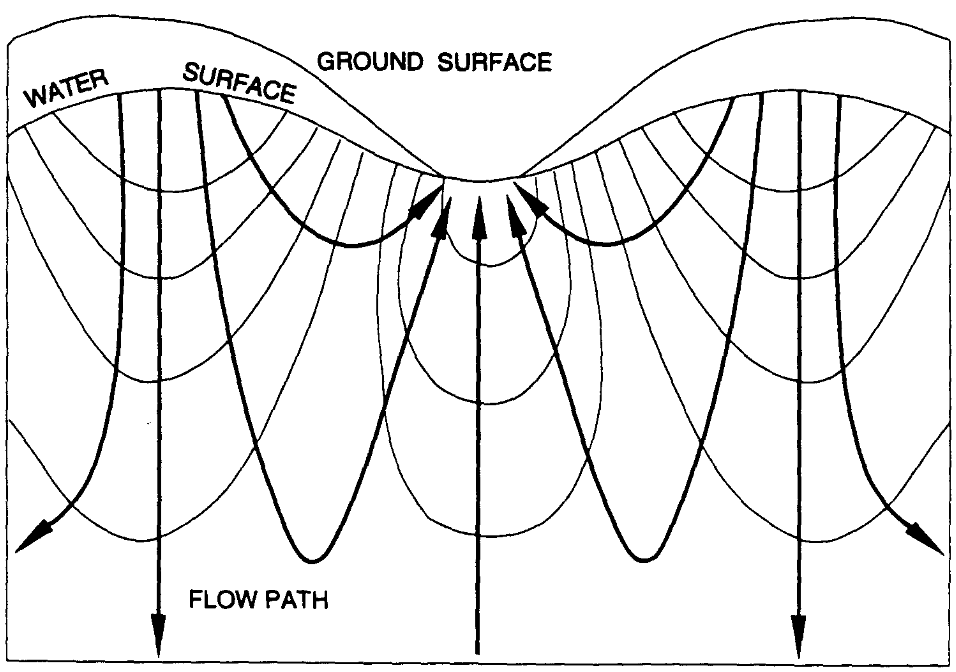


Figure 1. The effects of topography on ground-water flow (*modified from* Hubbert, 1940).

Table 3.—Horizontal Hydraulic Conductivity Values for Fractured Coal-Field Strata.

Reference	*Location*	*Fractured Lithology*[1]	*K (ft./min.)*	*Method*[2]
Wunsch, 1992	eastern Kentucky	sandstone	6.0E-04	PIT
		shale		PIT
Wright, 1987	southwest Virginia	coal	1.8E-03 to 2.0e-04	PIT
		fractures	1.4e-04	PIT
Dixon and Rauch, 1988	West Virginia	fractures (< 100')	6.6E-05	CHIT
		fractures (< 80')	2.8E-05 to 1.2E-04	CHIT
Harlow and LeCain, 1991	southwest Virginia	sandstone (< 100')	9.3E-05 (median)	PIT
		shale and siltstone (100')	2.2E-05 (median)	PIT
		coal (< 100')	1.7E-04 (median)	PIT
		coal (100 to 200')	2.4E-05 (median)	PIT
		coal (200 to 300')	1.5E-05	PIT
		coal (> 300')	6.9E-07	PIT
Hobba, 1991	West Virginia	coal (57')		
		Max. direction	9.9E-03 to 2.2E-02	PT (Theis)
		Min. direction	1.4E-03 to 5.2E-03	PT (Theis)

1 Number in parentheses represents depth from surface

2 PIT–Pressure-injection test; CHIT–Constant-head injection test' PT–Pump test.

Topography is an important element of ground-water flow in the Eastern Kentucky Coal Field. The coal-field region is located in the Appalachian Plateau physiographic province, a hilly to mountainous region. Topographic relief ranges from 300 feet in northern Kentucky to 2,500 feet in extreme southern Kentucky. Ridges are generally narrow and winding. Natural flat land is mainly restricted to flood plains of major rivers. Surface mining has altered natural topography in many places by creating areas of flat to gently sloping land. Low-order streams are generally V-shaped and have no flood plains.

Geology

The properties of the geologic media must be defined to further refine the flow regime. The position of rock units relative to each other and the influence of geologic structures, have a profound impact on the flow system of a particular region. Earl (1986) cites depositional history, lithology, and strata deformation as major geologic controls on ground-water flow.

Depositional History

The environment in which coal-field sediments were deposited influences patterns of ground-water flow. Deposition of thick, laterally continuous strata with little lateral variation favors a system in which the flow paths are reasonably predictable. Abrupt, lateral lithology changes alter flow in complex, unpredictable ways. Freeze and Witherspoon (1967) pioneered study of effects of variations in conductivity on flow patterns using numeric solutions. This approach allowed simulation of complex, more realistic basin configurations than Toth could calculate analytically. Because of lateral facies changes, rocks of differing conductivity are in lateral contact. Laterally flowing ground water will tend to follow the path of higher conductivity and may change flow direction to follow a unit with higher conductivity (Figure 3). Sedimentary layering superposes strata, some of which have different conductivities. Flow may be more nearly vertical through the low-conductivity layer, because equipotential lines concentrate horizontally resulting in large, vertical head drops. Flow in higher conductivity layers is more nearly horizontal. Some individual units are anisotropic because of preferential fracture orientation, or bedding or mineral alignment.

The effects of heterogeneity and stratification in sloping topography are demonstrated numerically by Rulon and others (1985). Their work demonstrates that flow in a hillslope which has uniform, homogenous layers of contrasting conductivities can be simulated by incorporating unsaturated flow into a numerical flow model. Perched water tables develop above layers of low hydraulic conductivity and unsaturated wedges

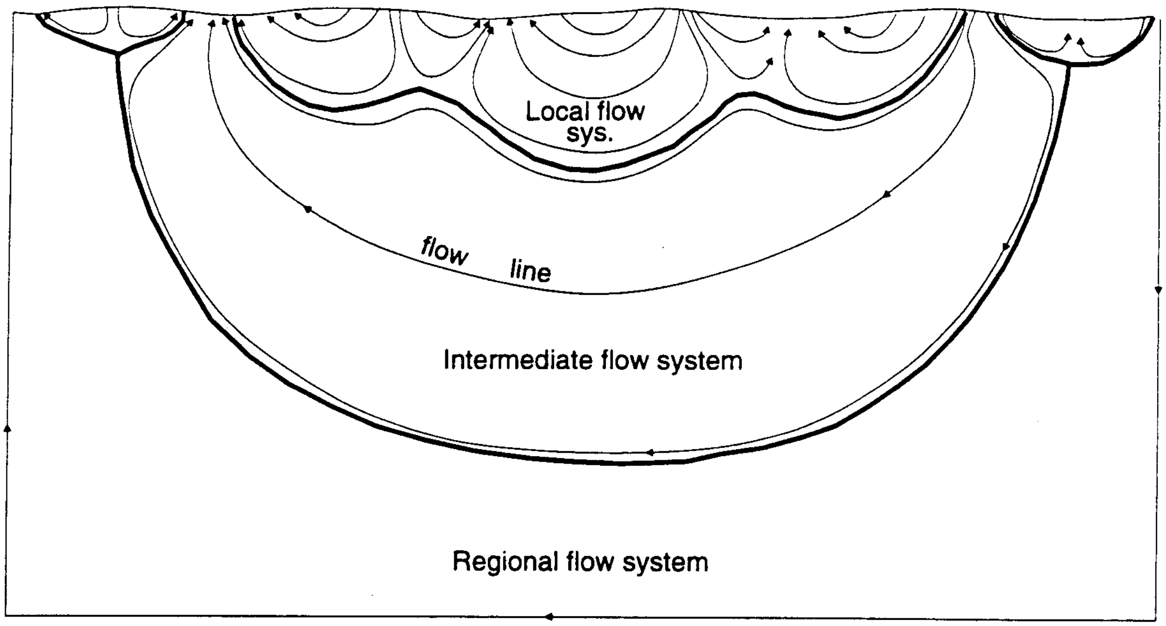


Figure 2. The development of local, intermediate, and regional flow systems in a homogeneous material (*modified from* Toth, 1963).

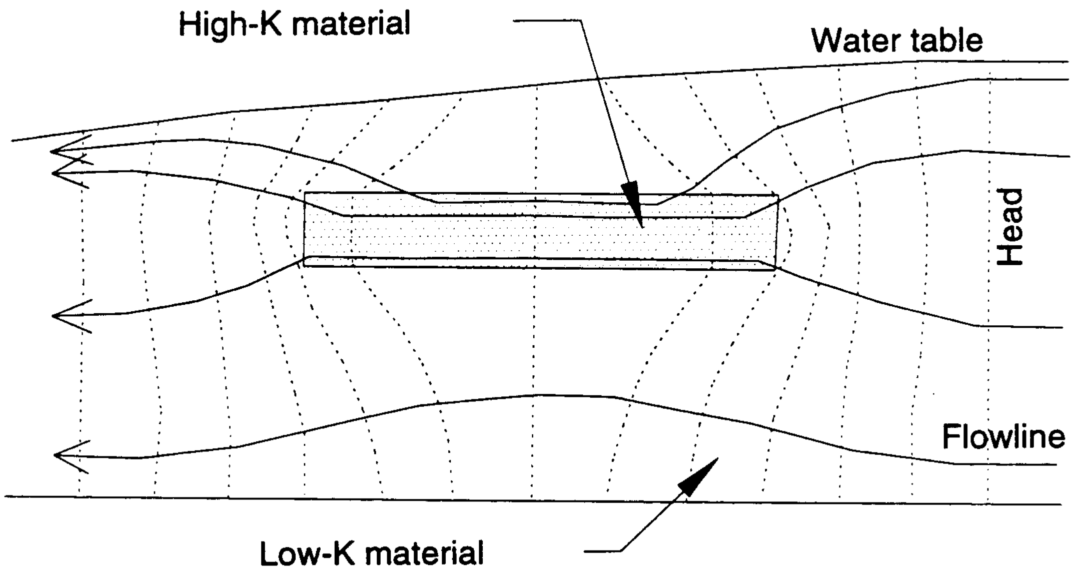


Figure 3. A cross section illustrating the effect of lateral hydraulic conductivity changes on ground-water flow (*modified from* Freeze and Witherspoon, 1967).

develop beneath such layers (Figure 4). Multiple seepage faces develop where several low-conductivity zones are present in a hillside.

Knowledge of the depositional history of the coal-field region of eastern Kentucky will provide insight into the many stratigraphic complexities that are present throughout a particular flow system. Subsidence of the Appalachian basin during the Pennsylvanian Period resulted in widespread deposition of clastic sediments derived from highlands to the east. Ferm (1974) and Rice and others (1980) described a southeastward thickening deltaic sequence of sediments which prograde into the axis of the Appalachian basin. A few widespread marine transgressions occurred during the late Pennsylvanian; however, some coal seams are locally associated with rocks of brackish to marine origin. By the close of the Pennsylvanian, as much as several thousand feet of sediment had been deposited in the eastern Kentucky area.

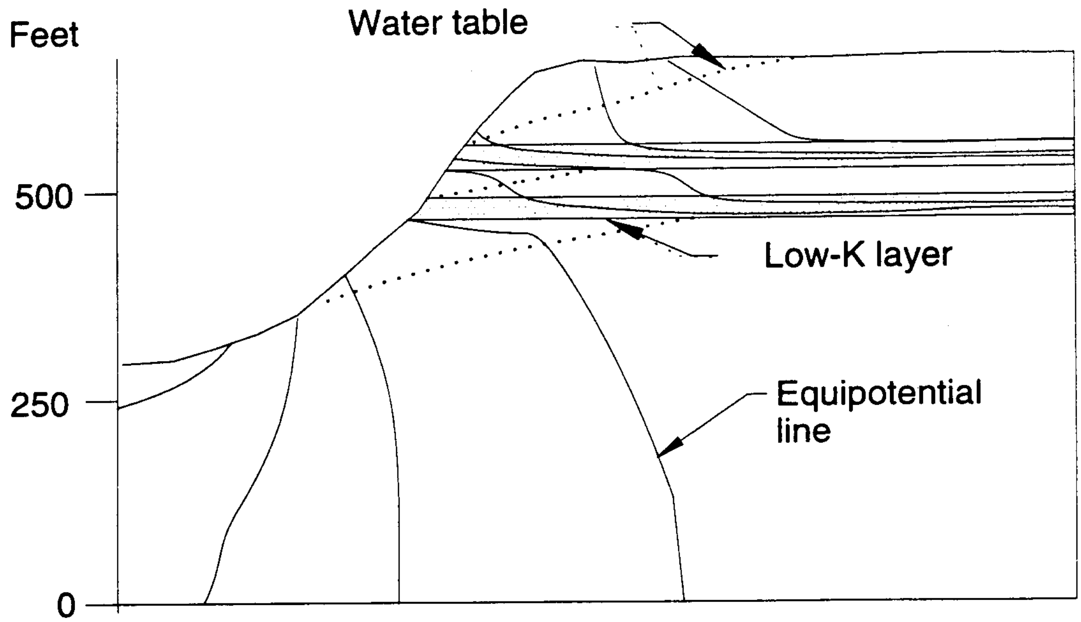


Figure 4. Stratified ground-water flow in a hillslope setting showing development of unsaturated wedges beneath low-conductivity layers (*modified from* Rulon and others, 1985).

Stratigraphy

Most of the rocks exposed at the surface in eastern Kentucky belong to the Lee and Breathitt Formations of Early and Middle Pennsylvanian age. The majority of fresh water in the coal-field region of Kentucky is obtained from these two formations. A general stratigraphic column for the Eastern Kentucky Coal Field is shown in Figure 5.

The Lee Formation crops out along the western margin of the coal field and everywhere underlies the Breathitt Formation. The Lee is approximately 80 percent sandstone (Leist and others, 1982; Rice and others, 1979). The characteristic lithology is a locally conglomeratic, massive orthoquartzite which was deposited as broad, northeast-trending lobes. Successive sandstones thicken to the northwest and in some places cut into the older, underlying sandstone units. The top of the Lee is stratigraphically higher to the northwest. Siltstone, shale, subgraywacke, and coal are present in the upper part of the formation. The Lee Formation which is only 350 feet thick in northern Kentucky, has a maximum thickness of 1,500 feet in southeastern Kentucky. The Lee is a very distinct cliff-former in the southern coal fields but is difficult to distinguish from the overlying Breathitt Formation farther northward where the Lee grades laterally into siltstone and subgraywacke (Rice and others, 1979). In southeastern Kentucky, the top of the Lee Formation is placed at the top of the highest cliff forming orthoquartzite. Farther north, the Lee and Breathitt Formations are lithologically similar and are not differentiated.

The depositional history of the Lee Formation has stirred debate among stratigraphers. Ferm (1974) and Donaldson (1974) proposed that the Lee represents a barrier beach/back barrier depositional environment associated with a northwest-migrating shoreline. Rice and others (1979) note the absence of marine strata which should be associated with a barrier-beach, and propose instead, that the Lee orthoquartzites are large, sand-filled distributary channels in a southwesterly prograding delta.

The Breathitt Formation overlies the Lee Formation and exhibits significant lateral heterogeneity characteristic of a deltaic depositional environment (Rice and others, 1980). The Breathitt consists of alternating subgraywacke, siltstone, shale, coal, underclay, and thin limestone. Siltstone and shale are generally carbonaceous and contain plant fragments and ironstone nodules. Massive sandstones, characteristic of the Lee Formation, are rare as widespread, mappable units in the Breathitt. Sandstones are less resistant than sandstones in the Lee Formation and are primarily subgraywackes, that are fine grained, micaceous, and contain 55 to 75 percent quartz. They probably represent anastomosing channel deposits (Rice and others, 1980). Basal contacts are commonly erosional, containing channel-lag deposits. Many sandstone units grade laterally into siltstones. As a result of lateral heterogeneity, the Breathitt is difficult to divide into mappable units. It contains 30 major coal zones (Rice and others, 19130), making it the primary coal-producing formation in eastern Kentucky.

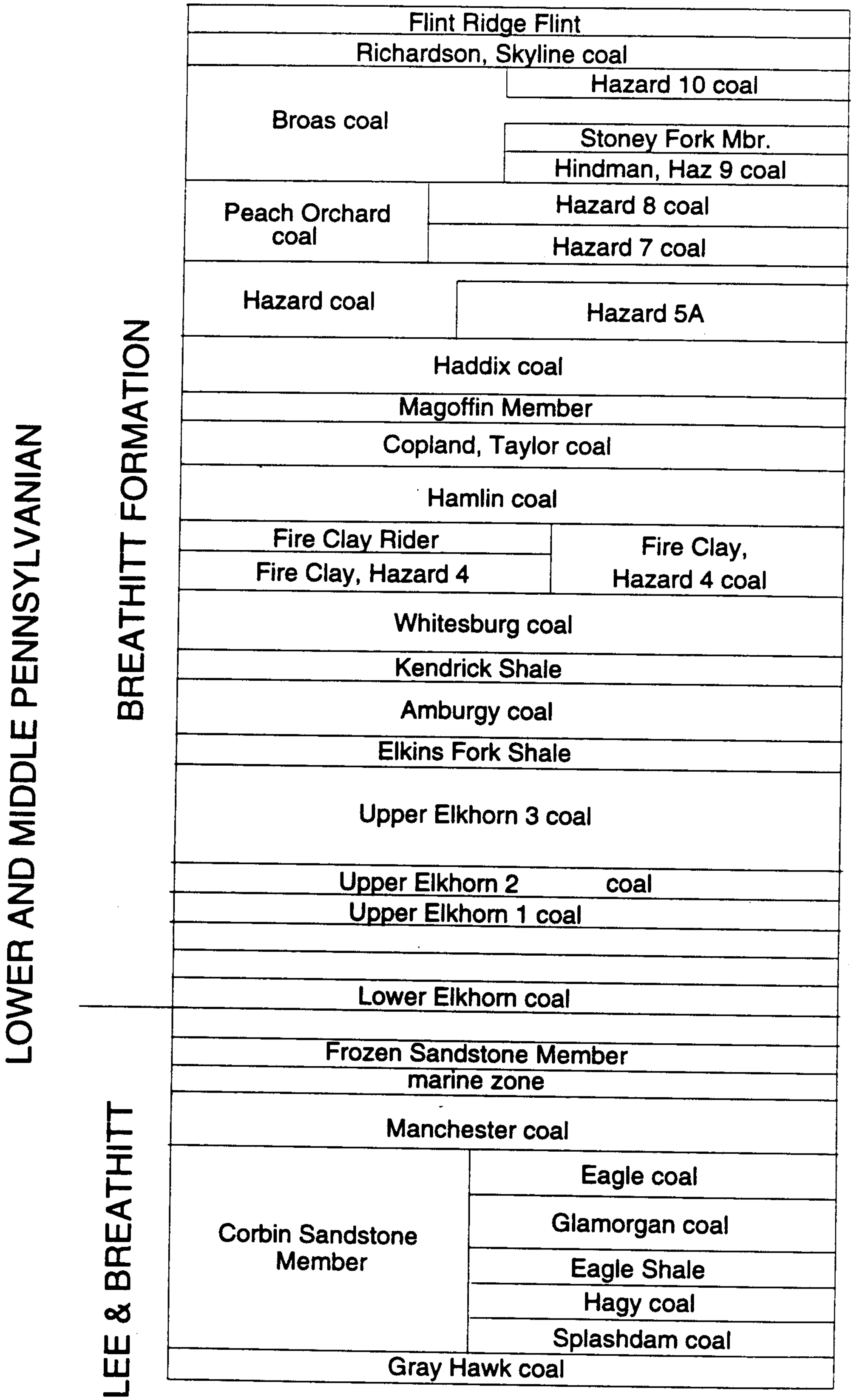


Figure 5. General stratigraphic section of the Eastern Kentucky Coal Field (*modified from* Rice and Smith, 1980).

Subdivision of the Breathitt Formation is based on the identification of key beds. The most useful markers are widespread coal beds and marine zones. The Fire Clay coal (Hazard No. 4) has been used extensively as a marker bed. It contains a characteristic flint-clay parting derived from a volcanic ash fall (Rice and others, 1980). Marine zones, which range from a few inches to more than 100 feet thick, are the primary stratigraphic zones used for widespread correlation. The Lost Creek Limestone of Morse, the Kendrick Shale, and the Magoffin Member are the most widely recognized marine zones in the Breathitt. They are coarsening-upward bayfill sequences of clay, siltstone, and sandy shale (Chesnut, 1981) and represent rapid marine transgressions over extensive flats. The lower section of these deposits is a dark-gray shale which is fossiliferous and commonly contains nodular limestone beds. A coal bed generally is present at the base. The shale grades upward into a siltstone containing siderite lenses. In places, the top of the sequence is overlain by channel sandstones.

The Breathitt also contains sparsely fossiliferous marine zones that are discontinuous and probably represent salinity changes in small, isolated bays or tidal channels (Rice and others, 1980). On the basis of distribution of marine zones, Rice and others (1980) suggest that open water was located south and southwest of Kentucky along the axis of the subsiding Appalachian basin during deposition of the Magoff in and older strata. Open water lay to the north and northwest of the basin during post-Magoffin deposition.

Structure

Structures active prior to and during Pennsylvanian deposition affected the depositional pattern of coal4ield rocks. One of the major structural features is the Appalachian basin (Figure 6a), a foreland basin that subsided periodically in response to the Taconic, Acadian, and Alleghenian orogens (Tankard, 1986). Alleghenian overthrusting during the Middle Pennsylvanian resulted in continued flexural downwarping of the Appalachian basin and deposition of sandstone, shale, and coal beds of the Lee and Breathitt Formations (Tankard, 1986).

The Cincinnati Arch (see Figure 6a), a broad, north-south trending anticline, located west of the Eastern Kentucky Coal Field, forms the west boundary of the Appalachian basin (Tankard, 1986) and was a positive feature during the Early Pennsylvanian. Lower Pennsylvanian strata were deposited on progressively older Mississippian strata toward the axis of the arch, and that onlap is cited as evidence for uplifting during this time (Englund and others, 1981; Sable and Dever, 1990).

The Waverly Arch (see Figure 6b), a north-south trending subsurface anticline (Woodward, 1961) was apparently a positive feature during the Early Pennsylvanian as evidenced by the absence of Lee Formation strata and by the presence of erosional surfaces on Mississippian strata near the arch axis (Ettensohn and Dever, 1979).

The Rome Trough (Figure 6b) is a linear, graben-like structure, formed by Cambrian faulting, that extends from south-central Kentucky into West Virginia (Ammerman and Keller, 1979). It is bounded on the north by the Kentucky River Fault system and on the south by the Rockcastle River-Warfield Fault (Figure 6b). Intermittent post-Cambrian growth-faulting along these bounding faults is responsible for a thicker accumulation of sediments on the downthrown (southern) side. Evidence that growth-faulting occurred in the Pennsylvanian is cited in Haney and others (1975); Horne and Ferm (1978); Sergeant and Haney, (1980); Haney and others, (1985); and Chesnut, (1988). The effect that the Irvine-Paint Creek Fault system, an interior fault system within the Rome Trough, had on Pennsylvanian sedimentation is uncertain (Ettensohn and Dever, 1979).

A unifying model linking development of arch features to orogenic events was proposed by Quinle Beaumont (1984). Loading due to thrusting creates a downwarped (foreland) basin in front of the orogen and a bulge (arch) on the cratonward side of the basin. Cessation of crustal loading and subsequent relaxation of the crust causes uplifting of the bulge (arch formation). This mechanism has been used to explain uplift on the Cincinnati and Waverly Arches (Tankard, 1986) as well as reactivation of faults (Tankard, 1986). The influence of structural activity prior to and concurrent with deposition during Pennsylvanian time is the subject of current research at the Kentucky Geological Survey (G. Dever, 1993, personal communication).

Structural activity following deposition of Pennsylvanian rocks adds to the geological complexity of eastern Kentucky. Crustal stresses of tectonic origin are manifested as fractures which are dependent on rock type. As discussed earlier, fractures increase water flow within a particular rock type and may impart a directional character to individual units, creating preferential flow directions. Structural features may also have more widespread impacts on ground-water flow systems Faults which cut across bedding planes may act as, hydraulic barriers to flow or may function as drains. Barrier influences may cause mounding of water surfaces that are not predictable from stratigraphy and topography alone. Permeable fault zones may depress water surfaces by draining water to regions of lower head.

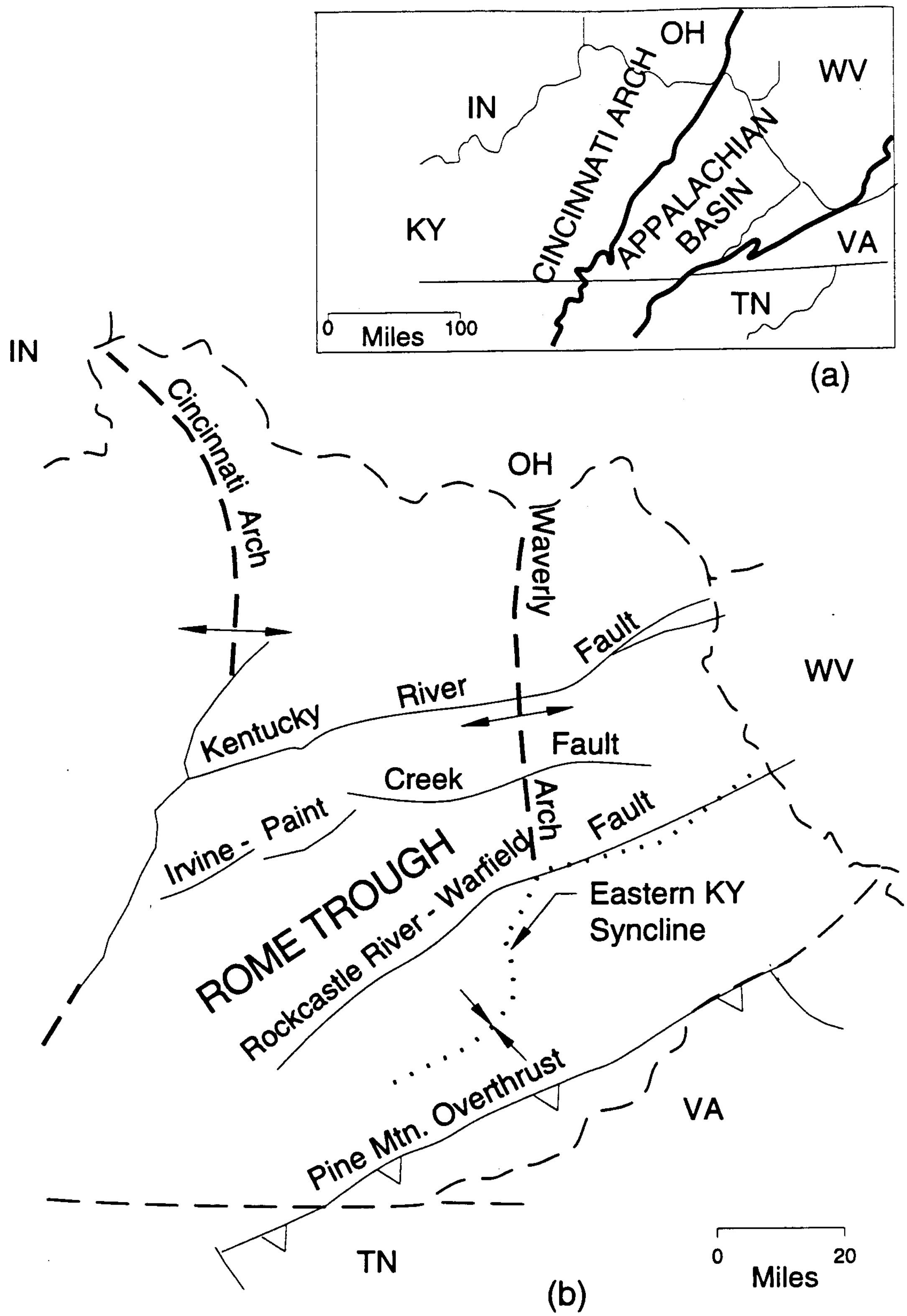


Figure 6. (a) Location of the Appalachian Basin (*modified from* Ettensohn and Dever, 1979); (b) major structural features in eastern Kentucky (*modified from* Rice and others, 1979).

Several structural features displaced Pennsylvanian rocks in eastern Kentucky. The Pine Mountain Thrust Fault, located in extreme southeastern Kentucky, is a northeast-southwest striking structure that is approximately 125 miles long (McFarlan, 1943). This fault marks the boundary between the Cumberland Mountain Overthrust Block and the Eastern Kentucky Syncline (Price and others, 1962). Horizontal displacement is approximately 10 miles on the southwest end and 4 miles on the northeast end (Huddle and others, 1963). It is bounded on the southwest and northeast by near vertical strike-slip faults (Figure 6b). The gently dipping Eastern Kentucky Syncline, described by McFarlan (1943), was apparently formed by upwarping that resulted from 7.5 miles of northwest lateral movement of the Cumberland Overthrust Block (Rice and others, 1979). This syncline is a broad basin located between the Irvine-Paint Creek Fault System and the Cumberland Mountain Overthrust Block (Figure 6b). Deformation is only evident in Pennsylvanian strata (D. Chesnut, 1993; personal communication).

Displacement of Pennsylvanian rocks is also evident in the Irvine-Paint Creek Fault system and in the Kentucky River Fault system. Maximum vertical displacement along these faults is approximately 250 feet (Rice and others, 1980).

Near-Surface Fractures

A three-dimensional network of open joints, extending vertically to depths of more than 500 feet, is universally present in consolidated rock (Trainer, 1983) and comprises the near-surface fracture zone. In sedimentary basins, like eastern Kentucky, fractures influence the depth of fresh-water circulation. The fresh-saline water interface may be determined by the depth of fractures. Saline water represents a region of near-stagnant water where connate water has not been completely flushed by fresh water (Trainer, 1983).

Bedded sedimentary rocks typically have two or more sets of near-vertical joints and some have horizontal bedding joints (Schubert, 1980; Trainer, 1983; Merin, 1989; and Zehner, 1983) in response to residual tectonic stresses. Nickelson and Hough (1967) describe the fundamental unit of jointing in the Appalachians as near vertical systematic and non-systematic joints that intersect at approximately 90 degrees. The systematic joint set is perpendicular to the axis of least compressive stress. The non-systematic set forms later from release of residual tectonic stress.

The spacing of vertical joints in bedded strata is largely controlled by lithology. Nickelson and Hough (1967) state that different rocks show different joint patterns as a result of differing rock strength, variable rates of lithification, and stress differences. Coal beds form joints earlier than do other rocks, and in some places, later joint sets are imprinted in the coal seams. Discontinuities in joint spacing are present at lithologic boundaries. Joint spacing in shale beds is on the order of inches whereas joints in sandstone may be tens of feet apart (Ferguson, 1967; Nickelson and Hough, 1967). Vertical migration of water may terminate at lithologic boundaries, redirecting flow laterally along bedding surfaces to other vertical joints.

Fracture distribution relative to depth has been investigated in non-coal regions of the Appalachians. Merin (1989) studied the distribution of fractures in Devonian siltstone in the northern Appalachian Plateau. He concluded that the frequency of horizontal bedding-plane openings decreased non-linearly with depth but that vertical-joint frequency remained constant with depth. Vertical joints less than 21 feet deep are iron stained. Joints from 21 to 38 feet deep have clean faces. Joints deeper than 38 feet are calcite-filled. Merin identified a stress-relief zone and a transitional zone based on fracture frequency that extends to 22 feet and 55 feet, respectively.

A site investigation for the Maxey Flats radioactive waste-burial site in northeastern Kentucky documents an extensive fracture mesh in Mississippian and Devonian rocks. This mesh consists of blocks bounded by vertical and horizontal fractures that are six inches to one foot square, extending from several feet to several tens of feet in depth (Zehner, 1983).

Ferguson (1967) presented the concept of stress-relief fractures in the Appalachian Plateau after numerous dam-foundation investigations revealed predictable fracture patterns in broad stream valleys. Figure 7 illustrates Ferguson's concept of stress-relief fracturing. Near-vertical stress-relief fractures develop as valleys are eroded in relatively flat-lying strata of differing lithology and competence. The weight of the overlying strata in the hills on either side of the valley places the rocks beneath the valley under compressive stress. Continuing erosion releases the horizontal stresses on the rock units in the valley walls. Less competent rocks stretch until they break. More competent rocks are dragged along until their tensile strength is exceeded. This results in vertical tension fractures within the valley walls. Valley floor strata flex upward as a result of horizontal compression. When the shear strength of the valley floor strata is exceeded, horizontal bedding plane separation results, along with low-angle thrusting. Thus, stress-relief fracturing results in vertical tension fractures in the valley walls and horizontal bedding plane fractures under the valley floors with associated vertical tension cracks from arching of the valley floor.

The term "stress-relief fracture" has been variably used to describe fractures that are present near the surface in the Appalachian region. A distinction should be made between fractures documented beneath wide stream valleys (greater than 500 feet wide) and fractures typically associated with small, V-shaped valleys. Hill (1988) investigated the role of valley shape on rock competence. Finite element analyses of stress distribution showed that V-shaped valleys were under horizontal compressive stress. No tensile stress was observed at the apex of the V-shaped valley that would signify typical stress-relief type failure. Broad valleys, on the other hand, exhibited tensile stresses at depths as great as 100 feet because of valley rebound. Strata below 100 feet in these valleys exhibited horizontal stress. These theoretical results were compared to field investigations in West Virginia. Strata beneath broad valleys showed poor rock quality attributable to fractures, but, V-shaped valleys showed no fracture-related degradation in the rock mass. Evidence from ongoing research by the U. S. Bureau of Mines (Hill, 1988; Moebs, 1989) suggests that mine roof failure under V-shaped valleys, originally attributed to existing fracture sets, may actually be the result of stress relief from mining.

Fracture development in the Eastern Kentucky Coal Field probably results from a combination of regional tectonic joint sets which are enhanced very near the surface by weathering processes and overburden unloading. It is unclear whether or not the stress-relief phenomenon is related to preexisting joints or is more dependent on slope

Drainage patterns in eastern Kentucky are primarily dendritic, a drainage pattern typical of flat-lying sedimentary rocks (Press and Siever, 1974). Alignment of stream segments apparent from satellite imagery (McHaffie, 1982) and from examination of topographic maps, may indicate that some drainage is structurally controlled.

Man-Made Influences on Ground-Water Flow

Man-made factors after natural flow systems. In eastern Kentucky, alterations to topography and hydraulic properties of underlying strata from mining are the rule, rather than the exception. Ground-water investigators must be aware of these potential influences on the ground-water system.

Surface mining commonly reshapes areas of the land surface, altering flow systems. Surface-mine contour benches may become discharge zones where the former land surface may have been a recharge region. Contour-mining excavations generally impact fractures near the surface that transmit much of the local groundwater flow. Bench floors are commonly underclay that inhibit re-infiltration of water seeping through fractures in the highwall. Benches may be sloped so that water drains to another watershed. Backfilled areas are commonly more permeable than in-situ rock, and may function as storage zones for ground water. Water tables in backfilled areas may have different configurations than

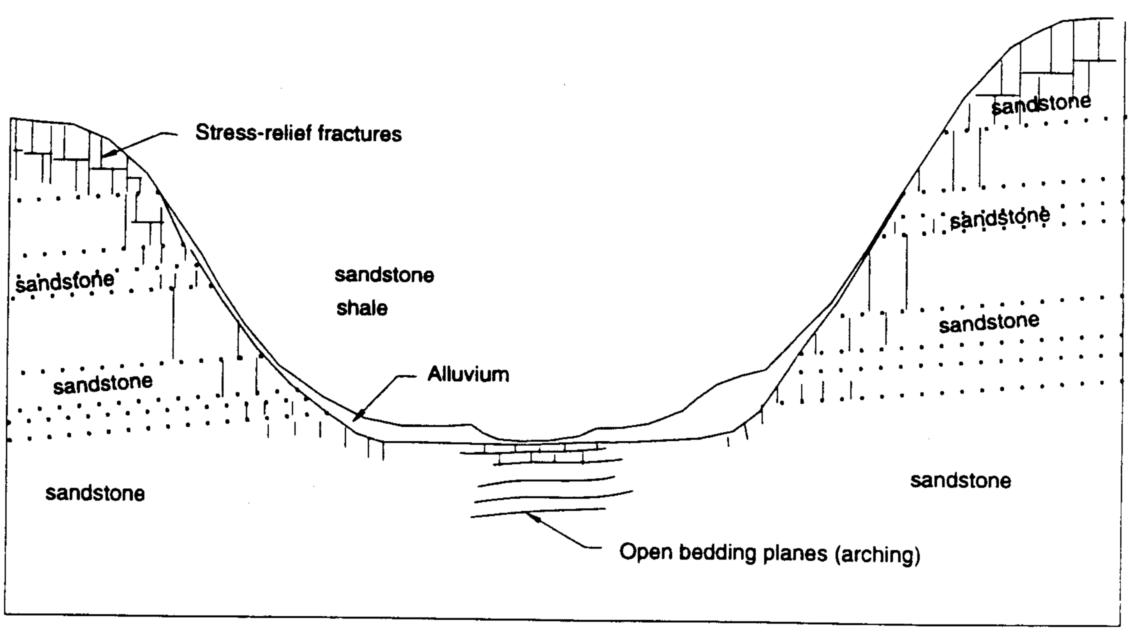


Figure 7. Stress-relief fracture development (*modified from* Ferguson, 1974).

in in-situ rocks. The net result of mining disturbance may be either an increase or decrease in areal recharge.

Underground mining effects are less visibly apparent, but can cause profound changes in a ground-water system. Booth and Saric (1987) identified two separate effects of underground mining. Open mine voids may become ground-water sinks and drain water away from surrounding strata. In addition, mining-related fractures alter hydraulic characteristics of overlying strata by changing conductivity, storage, and hydraulic gradients in the vicinity of the mine.

Conceptual Models of Coal-Field Ground-Water Flow

Numerous advances in the understanding of coal field hydrogeology and flow have been made by investigators throughout the Appalachians. Early workers, like Price and others (1962), and Musser (1963) in Kentucky, recognized the importance of joints and fractures as pathways for ground-water flow. Ground-water investigations such as Wyrick and Borchers (1981) in West Virginia, Kipp and others (1983); Kipp and Dinger (1987); Davis (1987); and Wunsch (1992) in Kentucky, Larson and Powell (1986); Wright (1987); Harlow and LeCain (1991) in Virginia, and Stoner (1983) in Pennsylvania, developed conceptual ground-water flow models incorporating near-surface fractures.

Wyrick and Borchers (1981) presented the earliest conceptual model of stress-relief-controlled, ground-water flow for the Appalachian coal field (Figure 8). Their primary focus was how fracture systems affect the storage and movement of ground water in typical Appalachian valleys. The chosen study site was a third-order, undisturbed valley in Twin Falls State Park in West Virginia. The valley is typically 400 to 600 feet wide. Such a valley should exhibit stress-relief fractures as described by Ferguson (1967). All wells are installed in the valley bottom to determine how aquifer characteristics are related to fracture systems. Drill data showed that stress-relief fractures extend to a maximum depth of 200 feet below the valley. The surface-fractured zones are the most transmissive zones and form an interconnected shallow aquifer system linking vertically fractured valley walls and horizontal bedding-plane fractures in the valley bottoms. "Impermeable boundaries" are presumed where highly transmissive fracture zones merge into unfractured strata at depth. This "impermeable zone" is thought to separate the shallow, surface flow system from adjacent valleys. Wet-weather springs emerge on hillslopes if the ability of the fractures to vertically transmit water is exceeded. This study was limited to the valley-bottom setting and no attempt was made to characterize, in detail, the flow system in the ridge interior.

Kipp and others (1983) and Kipp and Dinger (1987) presented a conceptual model of ground-water in the Wolfpen Branch basin, Knott County, Kentucky (Figure 9). The primary goal of this project was to develop a conceptual model of ground-water flow in a first-order basin.

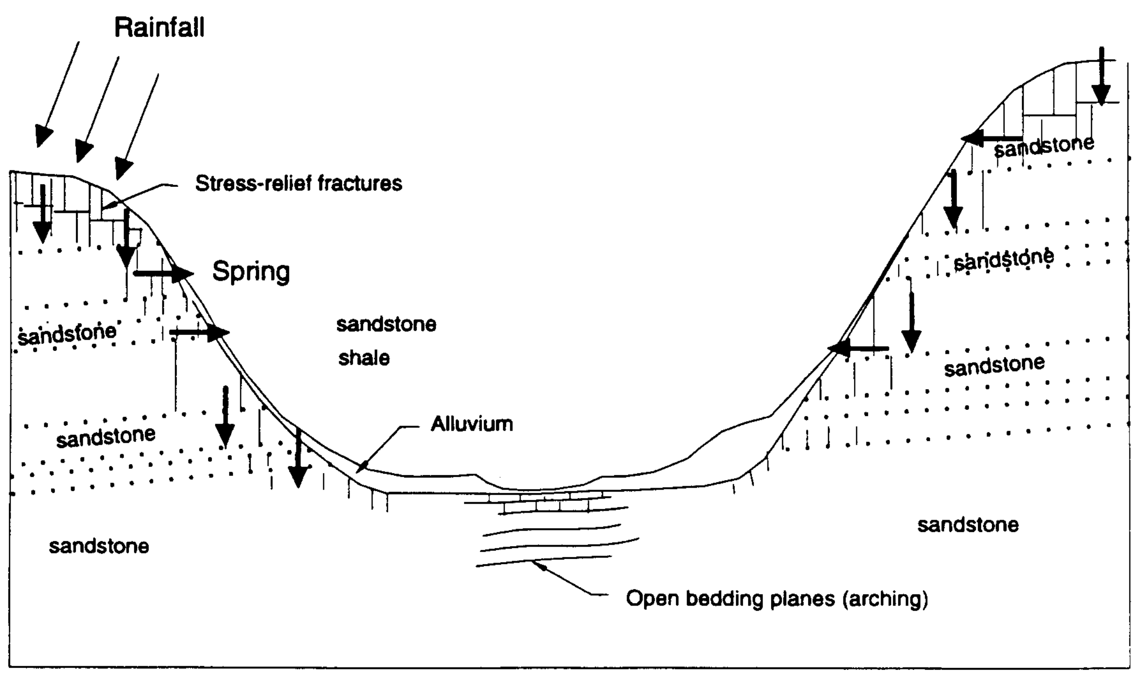


Figure 8. Conceptual model of ground-water flow (*modified from* Wyrick and Borchers, 1981).

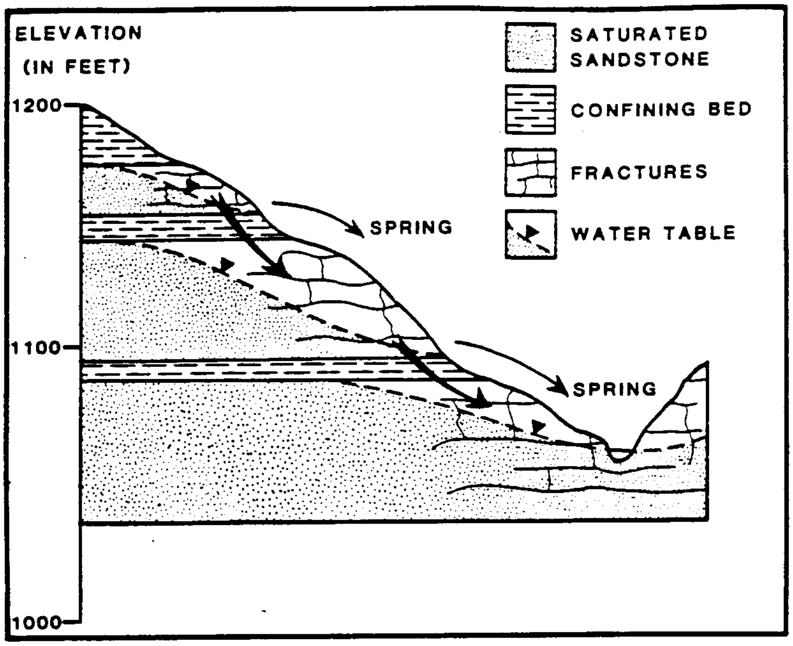


Figure 9. Conceptual model for ground-water flow in a small watershed (Kipp and others, 1983).

Thirteen wells were installed to monitor stratigraphic zones from different topographic positions. Results show that ground water flows primarily in hydrostratigraphic units composed of sandstone. Water-bearing zones are separated by low-permeability claystone or shale beds. Highly conductive, near-surface fracture zones in valley bottoms and valley walls respond directly to precipitation and evapotranspiration, indicating a direct connection to the surface. Discontinuous, perched water conditions exist near the valley walls, depending on rainfall conditions. Wells in the ridge interior do not respond directly to rainfall but strata are saturated. Water is probably released from storage in the ridge interior only during extended dry periods. Wells near valley walls that breach confining layers permit water to cascade from upper water-bearing zones to lower ones. Near-surface fractures allow infiltration of water downward to relatively impermeable beds. Water may flow horizontally along low-conductivity layers to fractures that allow vertical movement. If horizontal flow is uninterrupted, water is directed to the surface as wet weather springs. The resulting flow pattern is described as a stair-stepped pattern of ground-water flow from the hillsides to the valley bottom.

To quantify flow in the near-surface zone at the Wolfpen Branch site, Songer and Ewers (1987) conducted fluorescent dye traces utilizing the monitoring wells. Seepage velocities measured in the near-surface fracture zone were 4.6×10^{-4} and 9.5×10^{-4} feet per minute.

Wells at this site are installed with large intervals open to hydrostratigraphic zones between major coals. This type of construction does not allow detailed determination of vertical head distribution throughout the basin or a detailed investigation of flow mechanisms such as behavior in the coal seams and the response of individual units to precipitation.

Stoner (1983) conceptualized the flow system in the coal-bearing rocks of southwestern Pennsylvania (Figure 10). This is an area of relatively low relief (240 feet) and gentle slopes of less than 5 degrees. Three bedrock wells, one in each of three topographic positions (valley, hillslope and ridgetop) are used to describe ground water occurrence. The ridgetop and hillslope wells are constructed with intervals open to surface fractures. The ridgetop well exhibits the greatest water level fluctuations as a result of direct infiltration from precipitation. The hillslope well is located in a steeper, forested area and appears to receive less direct recharge. A deeper well is completed in a confined aquifer in the valley bottom. This well does not respond directly to precipitation. Stoner conceptualizes that most ground water circulates within 150 feet of the surface in the fractured bedrock. At shallow depths, ground water can perch above low-conductivity layers such as shale and claystone, then move laterally to form seeps and springs. At depth, hydraulic head is usually sufficient to force flow through the low-conductivity layers into the underlying confined aquifer. Stoner's work is limited to studying shallow fracture zones in areas of gentle relief. His conceptual model is schematic and does not attempt to define head distribution or site-specific flow within the system.

Larson and Powell (1986) conducted a hydrologic study of the Russell Fork basin of southwestern Virginia. The objective of this study was to evaluate the ground water and surface water of a river basin containing mined and unmined sub-basins. A sub-basin of approximately second order was chosen to evaluate different hydrogeologic environments. This basin is typical of mountainous regions, having topographic relief in the immediate study area of about 600 feet. Five wells are installed in a ridgetop nest and three wells are located in the valley bottom. Three ridgetop wells are open to a coal zone together with the overlying strata, up to, but not including, the next coal seam. Open intervals range from 100 to 180 feet. The remaining two wells are open to the shallow fracture zone. One valley bottom well encompasses a shallow coal seam and one is completed as a 50 foot open interval below the shallow coal seam. An alluvial well point is also located in the valley bottom.

Water-level fluctuations related to rainfall and evapotranspiration are greatest in the shallow wells, both on the ridge and in the valley. Larson and Powell conceptualize that ground-water flow occurs primarily within colluvium, alluvium, weathered bedrock, and coal seams (Figure 11). The principal flow direction in the ridgetop and hillslope is downward. Small amounts of water flow downward through unweathered bedrock to coal seams. Springs associated with coal seams result from lateral flow within the coals. Hillslope flow discharges to the stream valley.

A study of coal-field flow adjacent to Fishtrap Lake in Pike County, Kentucky, was presented by Davis (1987). Topographic relief in the study region is approximately 1000 feet with steep slopes. The purposes of this investigation were to determine hydraulic connection between vertical, near-surface fractures and stratigraphically lower, permeable zones and whether or not land use activities are isolated from lower aquifers. Sixteen monitoring points consisting of piezometers and open holes are located in various topographic settings. Packer-injection tests indicate that surface fractures, coal seams, and isolated fractures at depth are permeable zones. A dye trace from a near-surface ridgetop well is used to indicate interconnectivity of various zones. Dye traces indicate that dye was present in all wells within one month after dye was injected into the system. Davis's conceptual model describes ground water as moving from high head to low head in a stair-step fashion through sub-vertical fractures and laterally through permeable rocks, in this example, coal seams. He concludes that land-use effects on ridges could affect lower

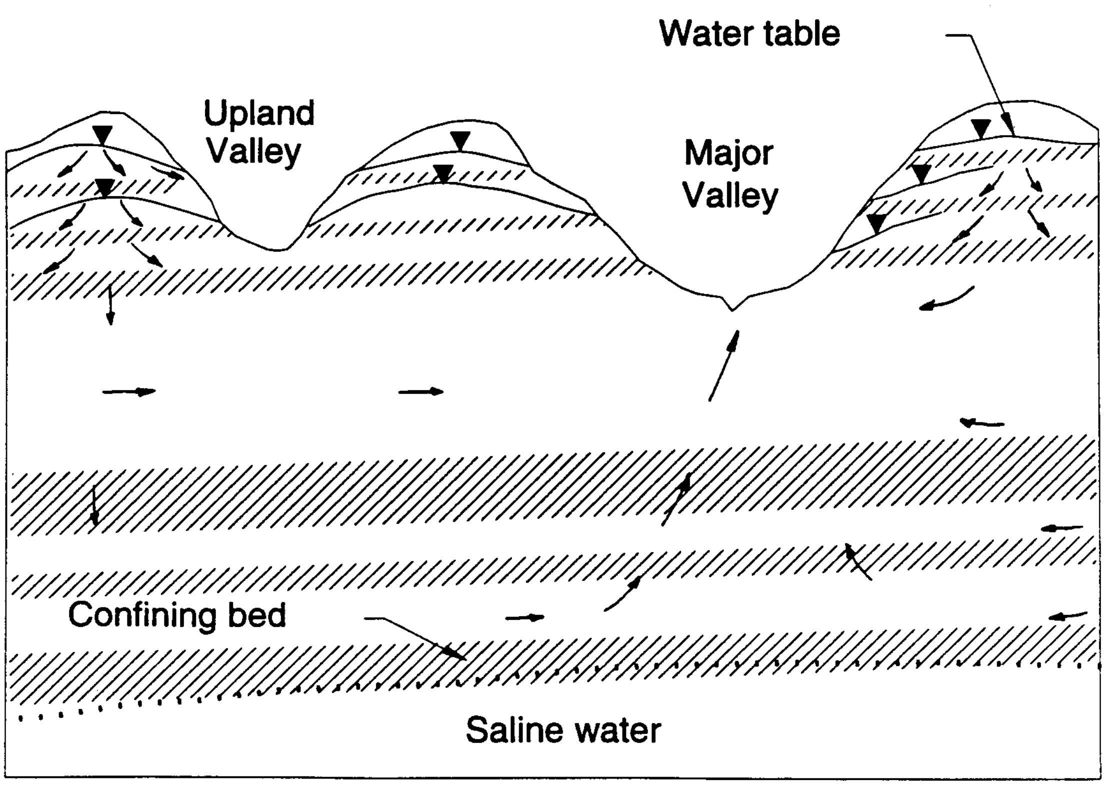


Figure 10. Conceptual coal-field flow model (*modified from* Stoner, 1980).

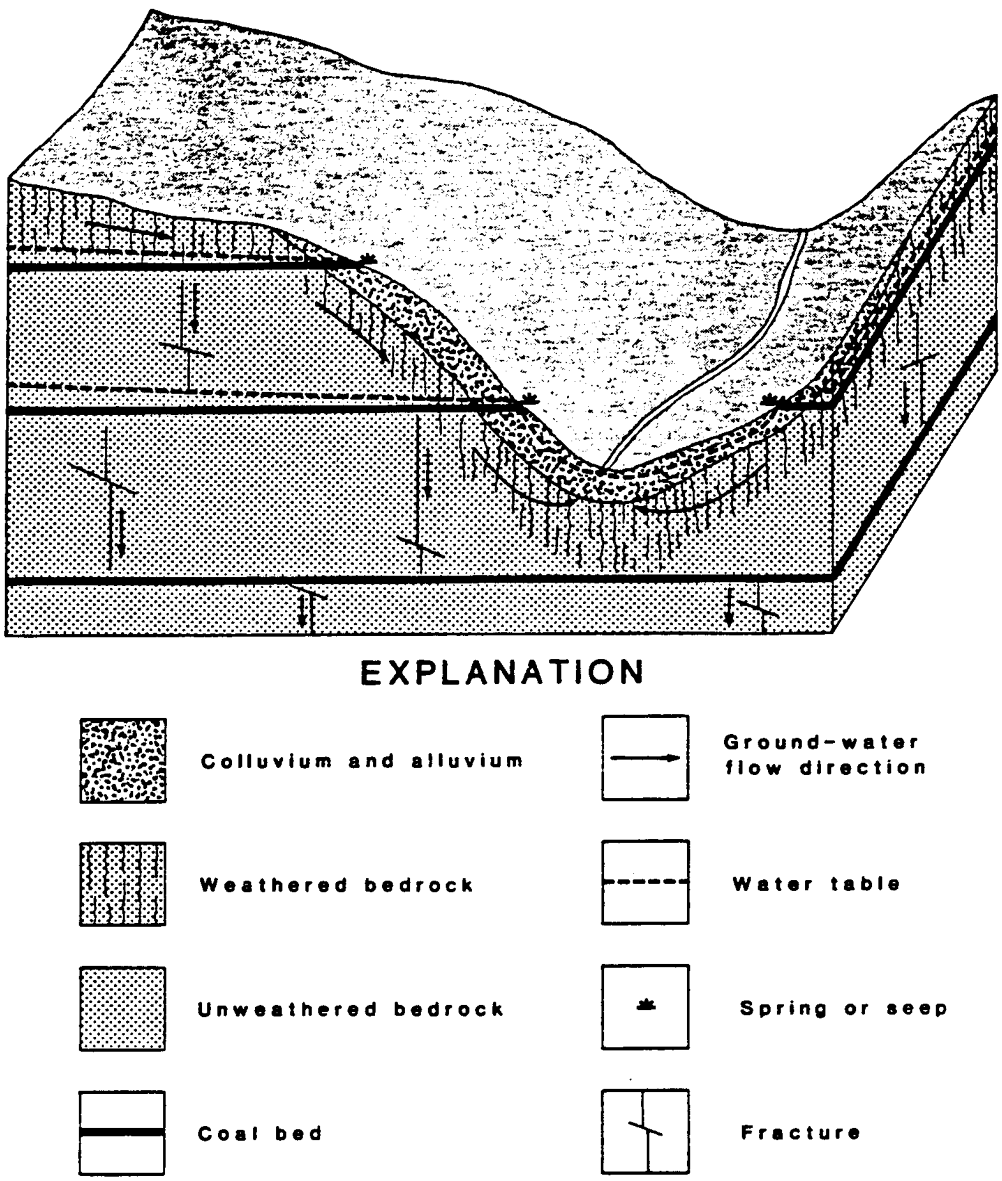


Figure 11. The conceptual model of coal-field ground-water flow of Larson and Powell (1986).

aquifers, even though separated by sequences of low permeability rocks. Results presented to date have not included a discussion of the site-specific flow system where head relations within the area are interpreted.

Wright (1987) generally described local ground-water flow associated with ridgetops, hillsides, and valleys throughout the coal-field region of southwestern Virginia. This was accomplished by compiling available data from drill logs, water-well logs' - packer-injection tests, and lineament analyses. He concluded that ground-water flow in valleys is most affected by lineament-related fractures. In hillsides and ridgetops, ground-water flow is most affected by stress-relief fractures, colluvium, and chemical weathering. Wright's conceptual model proposes that recharge along ridges and slopes moves toward the valleys through fractures, weathered and unweathered rock, colluvium, and coal seams. Water moving through weathered rock is intercepted by underclays and diverted to the surface. A typical ridgetop potential field is constructed from head data measured in five packer-injection test intervals and is shown in Figure 12. This study is designed as general overview throughout typical coal-bearing rocks of southwest Virginia. There is no attempt to define detailed flow patterns.

Harlow and LeCain (1991) present the results of 349 packer-injection tests from 43 drill holes throughout eight counties in southwest Virginia. The main objectives of this investigation were to describe the hydraulic characteristics of water-bearing zones in the coal-field region and develop a conceptual ground-water flow model. Results show that all rock types are permeable to a depth of about 100 feet; but that only coal seams have significant permeability at depths below 200 feet. Deeper coals are less conductive than shallower coal beds because of high overburden pressure. As a result of overburden pressure and subsequent reduced fracture occurrence, most flow takes place within 300 feet of the surface where rocks are fractured and coals are most permeable.

A conceptual model developed from packer-test data is presented in Figure 13. Precipitation percolates through colluvium and weathered rock in ridges and flows downward and laterally through shallow fractures. If vertical flow is inhibited, flow proceeds laterally along fractures or coal seams. Where vertical conductivity is present, water follows a stair-step pattern through colluvium, fractured bedding planes and coals. Flow discharges to adjacent streams or recharges coal seams at depth. The conceptual model implies flow within fractures below drainage as random. If the valley bottom is indeed a discharge zone, flow in these fractures would be toward the stream; not random and downward as shown in the enlarged detail.

The study by Harlow and LeCain (1991) recognizes the importance that coals play in the coal-field flow system; and, that topographic relief results in large vertical head differences within the flow system. On the basis of head data, they conclude that coal seams may only be partly saturated and may have water perched above them.

The conceptual models described above do not provide details of the potential field in a typical small watershed in eastern Kentucky or describe the local and regional flow system. The emphasis for most of these investigations is to assess the water-bearing capability of different topographic settings. Wells with intervals open to several water-bearing zones used by many of the investigators are typical of domestic water well construction in eastern Kentucky. Wells of this type do not allow definition of the potential field, especially if there is a vertical flow component. Water levels are a

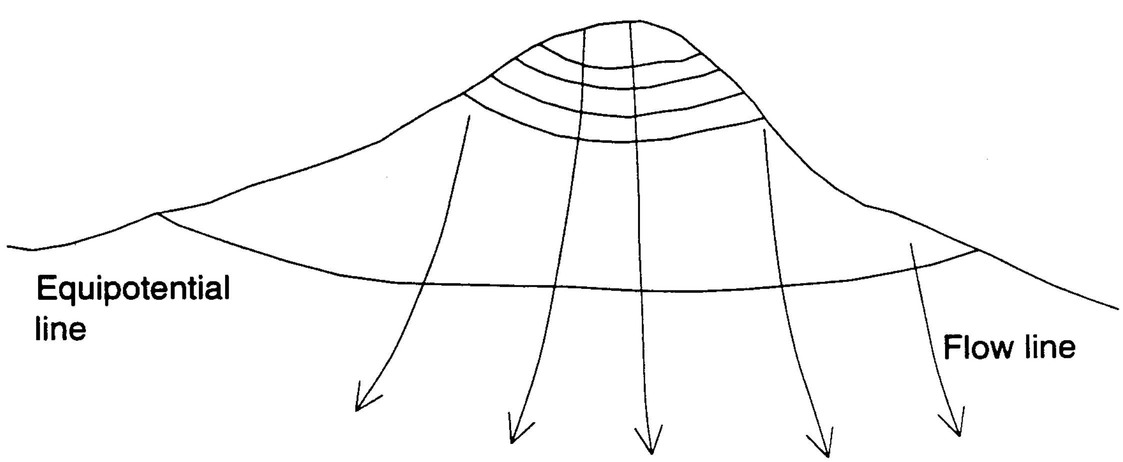


Figure 12. Potential distribution in a ridge setting (Wright, 1987).

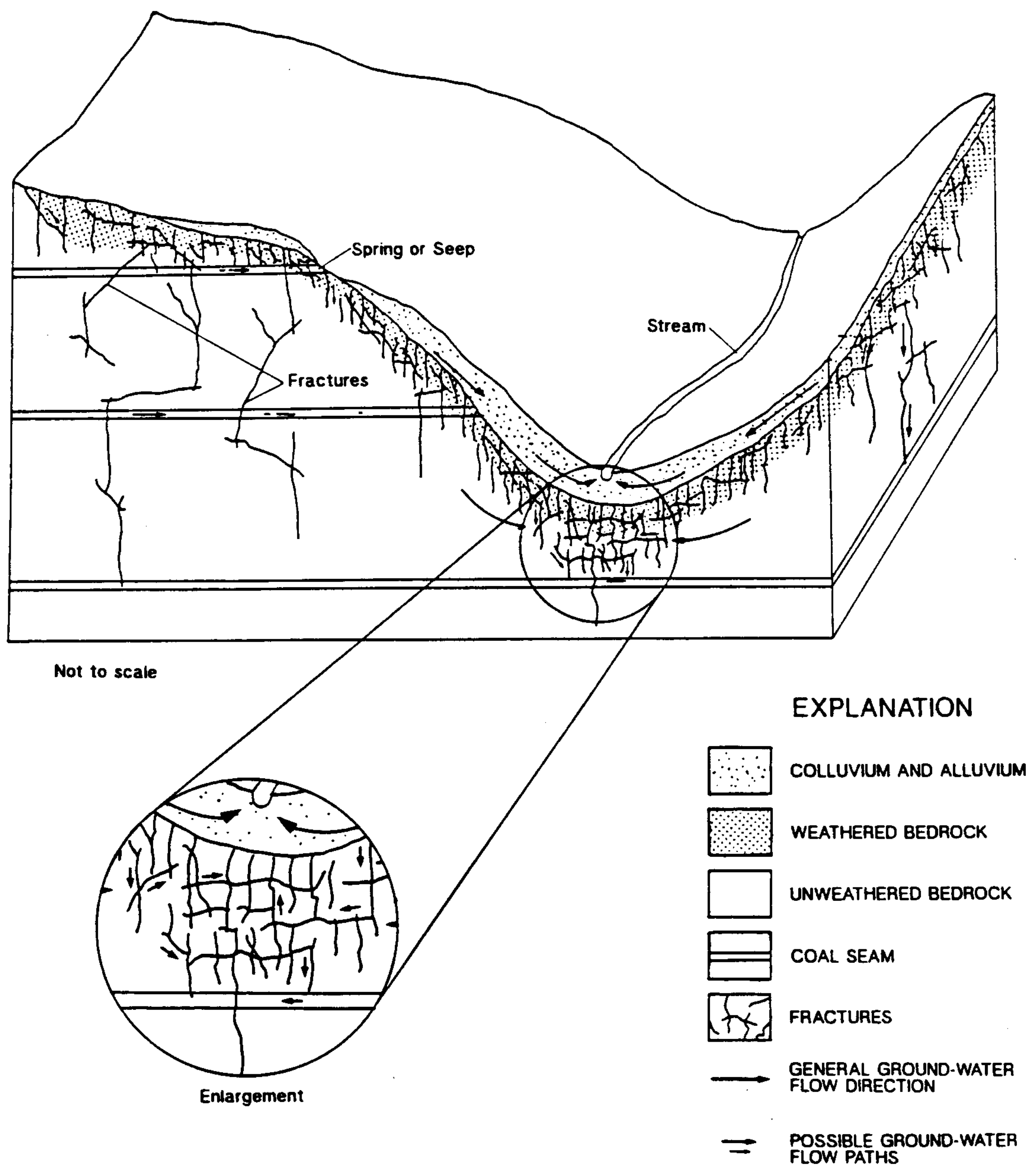


Figure 13. Conceptual coal-field ground-water flow model of Harlow and LeCain (1991).

function of the head differential in the interval, conductivities, and rate of recharge (Saines, 1981). This limits interpretation of water level data especially when trying to determine if unsaturated zones exist.

Larson and Powell (1991) used wells with large open intervals for their investigation. As a result, interpretation of data must be generalized. Larson and Powell (1991), however, reference unsaturated zones between coal beds. This conclusion appears based on water-level data from large open intervals where beds with different hydraulic heads are interconnected. One should use caution in interpreting water level position for such wells. Water levels could be controlled by fractures or coal seams which may function as drains. Data presented are insufficient to conclude that strata between coals are unsaturated.

To effectively obtain potentiometric head data from specific intervals, piezometers with relatively short open intervals must be used. Piezometers limit the effects of differential in head and changes in conductivity. In eastern Kentucky, however, discrete fracture intervals are encountered, and water levels within the piezometers may be controlled by fractures.

The most comprehensive investigation of coal-field hydrogeology to date is presented by Wunsch (1992). Wunsch's study area is an unmined, third-order watershed located in Perry County, Kentucky. The objective of his investigation was to describe the relationship between ground-water geochemistry and the flow system at the site. Head data and geochemical samples were collected from sixteen piezometers located in various stratigraphic positions. A profile of dry-season piezometric heads at the site are shown in Figure 14. Wunsch concluded from piezometers in the upper part of the ridge that head is approximately equal to the elevation head; and suggested that unconfined or semiconfined conditions exist in this region. Dry piezometers in the ridgetop suggest that this zone is at least partially unsaturated. Wunsch (1992) also observed that coal beds in the upper part of the ridge probably act as drains which dewater overlying strata. Head data from the ridge interior show that rocks are saturated.

Regional Ground-Water Flow

Site-specific conceptual flow models must be integrated into the regional flow system to provide a more complete understanding of ground-water flow in eastern

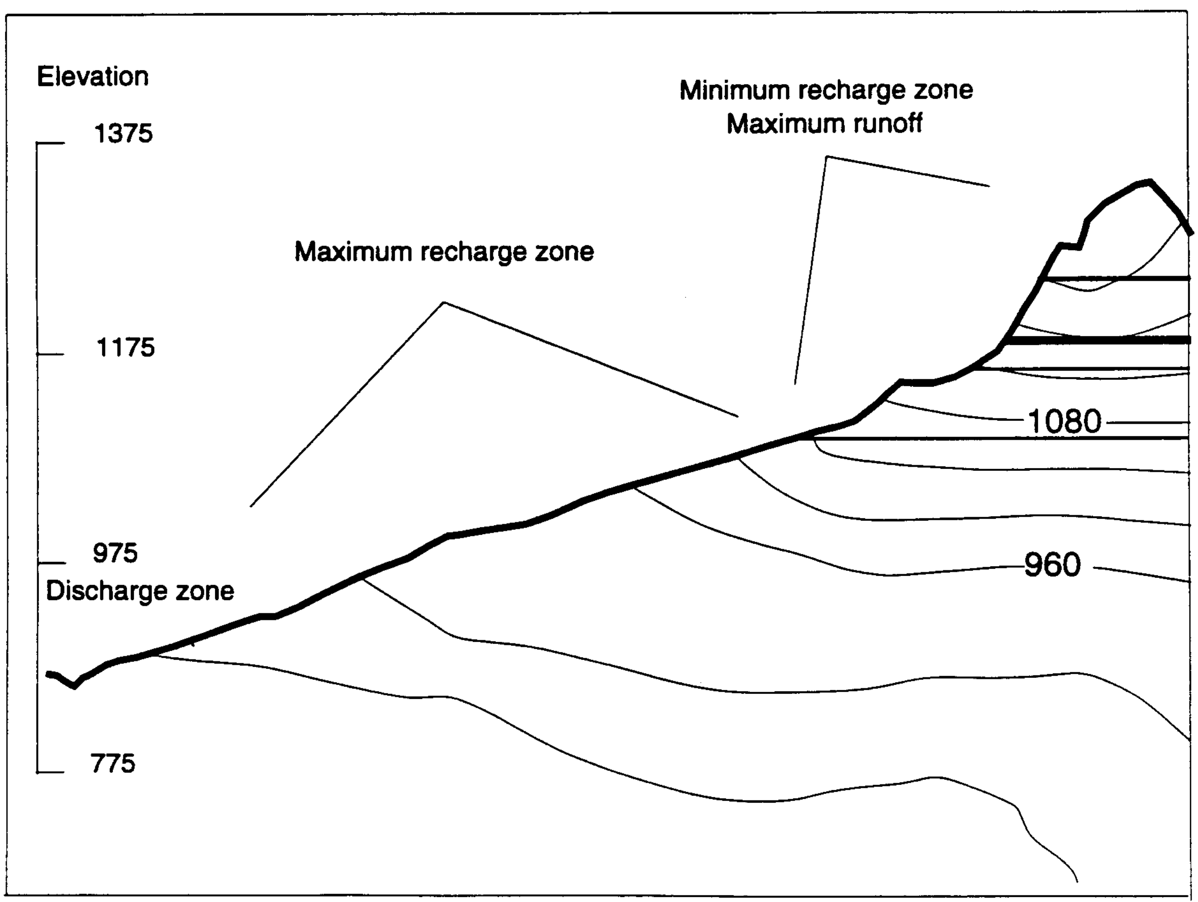


Figure 14. The distribution of piezometric head in a hillside (*modified from* Wunsch, 1992).

Kentucky. Several authors recognize that the aquifer systems in low-order watersheds are local in that they discharge to adjacent streams. Hollyday and McKenzie (1973) describe these local, discontinuous flow systems as "hydrologic islands" overlying a more regional system. The presence of regional systems has also been discussed by Brown and Parizek (1971), Helgeson (1982), Razem (1980), Stoner (1983), and Wunsch (1992).

Brown and Parizek (1971) identified a regional flow system in Pennsylvania while graphically analyzing two flow systems which had been previously undermined. Three vertically separate flow systems are identified. The upper two systems discharge to the adjacent stream. A regional system discharging to a major valley several miles away is also identified.

Carswell and Bennett (1963) described the groundwater flow system in a hilly, glaciated region in northwestern Pennsylvania. Ground water, infiltrating through Mississippian and Pennsylvania rocks, partially discharges laterally through sandstone to upland streams. The remaining water flows downward into a regional system, the base of which is static, connate brine.

In Kentucky, the base of the fresh-water zone is the fresh-saline-water interface, where saline water is defined as having a total dissolved solids concentration of between 1,000 and 3,000 mg/L (Hopkins, 1966). Salty water is generally encountered approximately 100 feet below major drainage (Price and others, 1962). An inventory of wells in the Prestonsburg quadrangle showed that wells, in the Breathitt Formation that were approximately 100 feet deep and located along major streams, contained greater than 250 mg/L chloride (Price, 1956).

Little work has been done in eastern Kentucky relating local flow systems to regional systems. Wunsch (1992) identified brine at a depth of 120 feet below a third-order stream in Perry County, Kentucky. The same stratigraphic level in the ridge interior yielded water with very low chloride concentrations. Wunsch hypothesizes that the fresh-water boundary in a third-order or higher watershed may undulate inversely with topography, meaning the interface is depressed beneath the ridges where pressure is high, but that it migrates upward in low-pressure valley regions. Data are not available from the study by Wunsch (1992) study to document the position of the interface beneath the ridge interior.

Aquifer Delineation

Large-scale, regional, fresh-water aquifers do not generally exist in mountainous, coal-bearing regions such as eastern Kentucky. Alluvial valleys of larger rivers are relatively continuous and produce water in large enough quantities to supply small communities. However, most wells in eastern Kentucky are domestic, bedrock wells, capable of supplying only a few gallons per minute or less. Water-bearing strata are dissected by local drainage, thus they have limited areal extent. Several investigators have worked to delineate water-producing zones in the coal-field regions.

Dyer (1983), from his work in eastern Kentucky, groups ground water into three modes of occurrence. The first group contains valley alluvium and shallow subsoil overlying bedrock. These zones generally maintain flow except during extended dry periods. The second water-bearing group is the upper bedrock zone, which Dyer describes as the fresh, circulating water zone. The lower boundary of this zone is the saline-fresh-water interface. The third group is the relatively stagnant saline zone.

Kipp and others (1983) and Kipp and Dinger (1987) conclude that in Knott County, Kentucky, aquifers equate to hydrostratigraphic units composed primarily of sandstone. Hydrostratigraphic units are separated by claystone beds of low hydraulic conductivity.

Aquifers in eastern Kentucky are classified by Bienkowski (1990) as a group of isolated aquifers with similar lithologic properties rather than a continuous aquifer with large areal extent. Water-bearing zones are dissected by valleys, creating local flow systems that discharge to adjacent stream valleys. Bienkowski grouped the strata of eastern Kentucky into hydrostratigraphic units based on geology and water quality (Figure 15).

In Pennsylvania, Booth (1988) delineates aquifers by hydrostratigraphic divisions where sandstone-dominated members are classified as aquifers. Shale- and clay-dominated members are classified as aquitards. Geology favors multiple, but separate, sandstone aquifers which have predominantly lateral flow. Recharge occurs up-dip and discharge occurs at down-dip outcrops. Vertical leakage is slight with sudden head drops between aquifers.

Status of Knowledge on Ground-Water Flow

Investigations in the Appalachian coal fields have documented various aspects of ground-water flow on a case-by-case basis. All studies conclude that fractures are the major avenues of ground-water flow; useable ground water is obtained primarily from fractures less than 200 feet deep. Rocks deeper than 200 feet generally do not yield much water to wells. Relatively direct connection of fractures to the ground surface provides recharge, as well as increasing susceptibility to surface

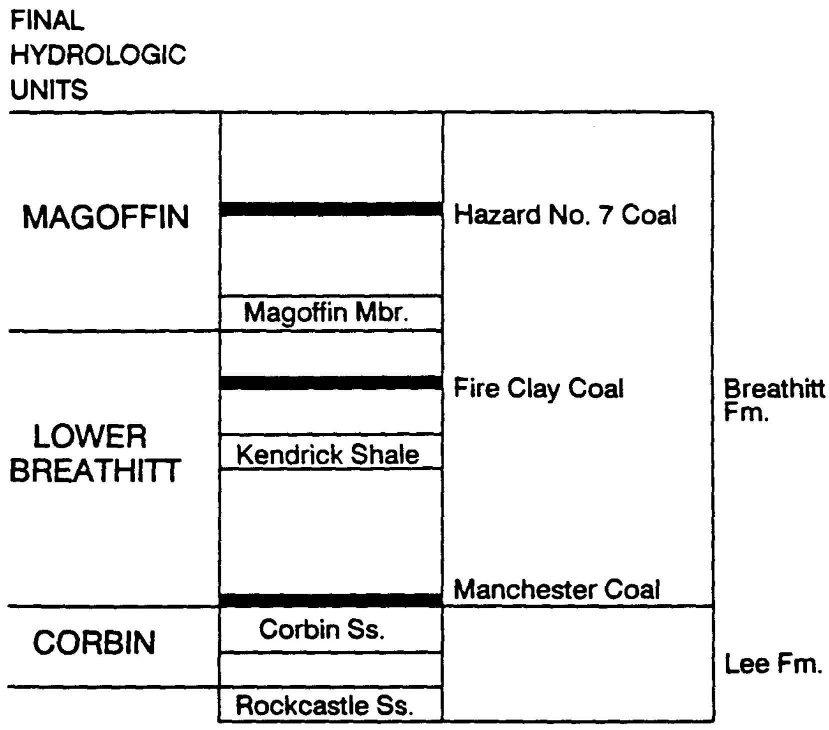


Figure 15. Hydrologic units of the Eastern Kentucky Coal Field (*modified from* Bienkowski, 1990).

disturbances or contaminants. Fracture-dominated ground-water flow is described as "stair-stepped" (Kipp and Dinger, 1987) because water migrates vertically through fractures and laterally along lithologic boundaries or within conductive coal beds.

Vertical head loss with increasing depth is documented in ridges using wells and piezometers. The general lack of discrete piezometric data precluded detailed descriptions of flow within individual lithologic units in the ridges, however. The study by Wunsch (1992) in eastern Kentucky provided the first interpretation of coal-field hydrogeology and geochemistry using discrete intervals. The results of this study were applied to watersheds of similar order.

Despite the previous work done throughout the Appalachians regarding coal hydrology, there has been no attempt to integrate available information into a regional-scale, conceptual framework by identifying common components in these studies. Data are available, especially from work in eastern Kentucky, to consider these studies collectively, in an attempt to identify similarities and differences among sites, as well as identify aspects of ground-water flow that require additional investigation.

OBJECTIVES

This research will utilize data from a new study site and data from previous investigations in eastern Kentucky to refine the existing conceptual flow models for the Eastern Kentucky Coal Field. Distinct ground-water zones will be defined and a conceptual model for local and regional flow will be developed. Monitoring strategies consistent with the conceptual model will be proposed. Specific objectives are described below.

Objective 1

The first objective is to install an extensive piezometer network along a cross section from ridge top to valley bottom and collect water level and water quality data. Ground-water zones will be defined for this site and the ground-water flow system will be described. Edd Fork, the watershed selected for this study, is located in Leslie County, Kentucky.

Objective 2

The second objective is to summarize ground-water data from three previous investigations. Ground-water zones will be identified. Data from the following investigations will be used:

Objective 2

1. Ground Water Geochemistry and its Relationship to the Flow System at an Unmined Site in the Eastern Kentucky Coal Field (Wunsch, 1992),

2. A Conceptual Model of Ground-Water Flow in the Eastern Kentucky Coal Field (Kipp and others, 1983) and Stress-relief Fracture Control of Ground-Water Movement in the Appalachian Plateau (Kipp and Dinger, 1987),

3. Data from Test Drilling to Trace Movement of Ground Water in Coal-Bearing Rocks near Fishtrap Lake, Pike County, Kentucky (Davis, 1986) and Movement of Ground Water in Coal-Bearing Rocks near Fishtrap Lake in Pike County, Kentucky (Davis, 1987).

These studies will be referred to as Star Fire, Wolfpen Branch, and Fishtrap Lake, respectively.

Objective 3

Ground-water zones identified in all study areas will be described in general and integrated into a conceptual model describing local and regional flow. Findings from this study will be related to the aquifer delineation and characterization study by Bienkowski (1990) for the

Five ground-water zones are proposed and are applicable throughout a large region of Kentucky. These are:

1. Above-Magoffin Member zone
2. Below-and-including-Magoffin Member zone
3. Shallow-fracture zone
4. Elevation-head zone
5. Pressure-head zone

Zones 1 and 2 are differentiated on the basis of water quality differences. Topics addressed include extent of zones and water-quality characteristics. Zones 3,4, and 5 are differentiated on the basis of hydraulic and flow characteristics. Specific topics addressed relative to these three zones are extent of zones, fracture occurrence, hydraulic conductivity characteristics, water-level responses, and flow characteristics.

Objective 4

The fourth objective is to propose a ground-water monitoring strategy that will detect adverse quality and quantity changes to ground-water resources.

EDD FORK STUDY SITE

Objective

The first objective was to install a piezometer network in a small basin and collect head and chemical data from these piezometers. Data are used to describe specific ground-water zones and to describe the ground-water flow system.

Study Area

The study area selected for this investigation encompasses a 173 acre watershed located in southern Leslie County, Kentucky, on the Helton 7.5 minute quadrangle (Figures 16 and 17). It is drained by Edd Fork, a first-order tributary of Trace Branch. Trace Branch flows into Beech Fork, a major tributary of the Middle Fork of the Kentucky River. Edd Fork basin is located approximately midway between Beech Fork and Middle Fork of the Kentucky River. These are third and fourth order streams, respectively, and represent local base level. Elevations of these streams are approximately 1,160 feet in Beech Fork and 1,240 feet in Middle Fork of the Kentucky River.

Elevations in the Edd Fork watershed range from about 2,160 feet on the ridgetops to about 1,550 feet at the mouth of Edd Fork. The Hindman Coal seam, at an elevation of 2,000 feet, was extensively mountaintop-mined in the 1980's. Ridges higher than 2,000 feet consist primarily of replaced overburden. Survey data indicate that post-mining elevations are similar to pre-mining elevations shown on topographic maps. A contour surface-mine cut in the Hazard Number 8 Coal seam is located along the western slope of Edd Fork. This disturbance has been partially reclaimed but a prominent highwall exists. Other mine-related features include a small hollow fill, breached sediment-pond embankments, and down-slope overburden material (Figure 18). Although this watershed has been disturbed by previous surface mining, this type of disturbance is fairly typical of small watersheds in eastern Kentucky. Edd Fork has not been mined by underground methods.

Terrain in the watershed is steep; slopes average 26 degrees. Most of the site is forested except in areas that were mined. Vegetation in mined areas is mostly lespedeza and locust. Rainfall in Leslie County averages 48 to 50 inches per year (Kentucky Water Resources Study Commission, (1959). There are no inhabitants in the Edd Fork basin.

GEOLOGY

Strata in the study area belong to the Breathitt Formation of Middle Pennsylvanian age. Above-

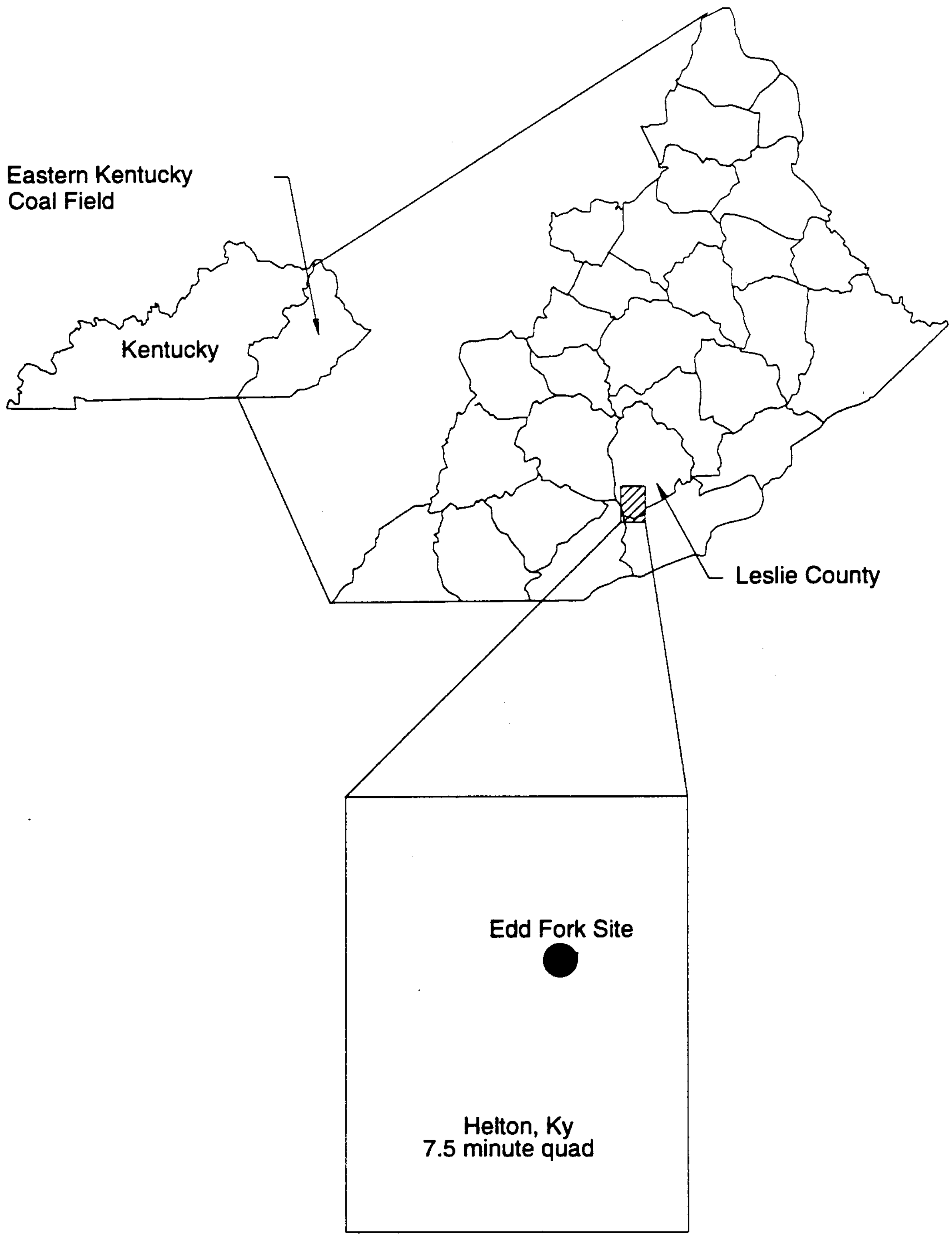


Figure 16. Location of Edd Fork watershed.

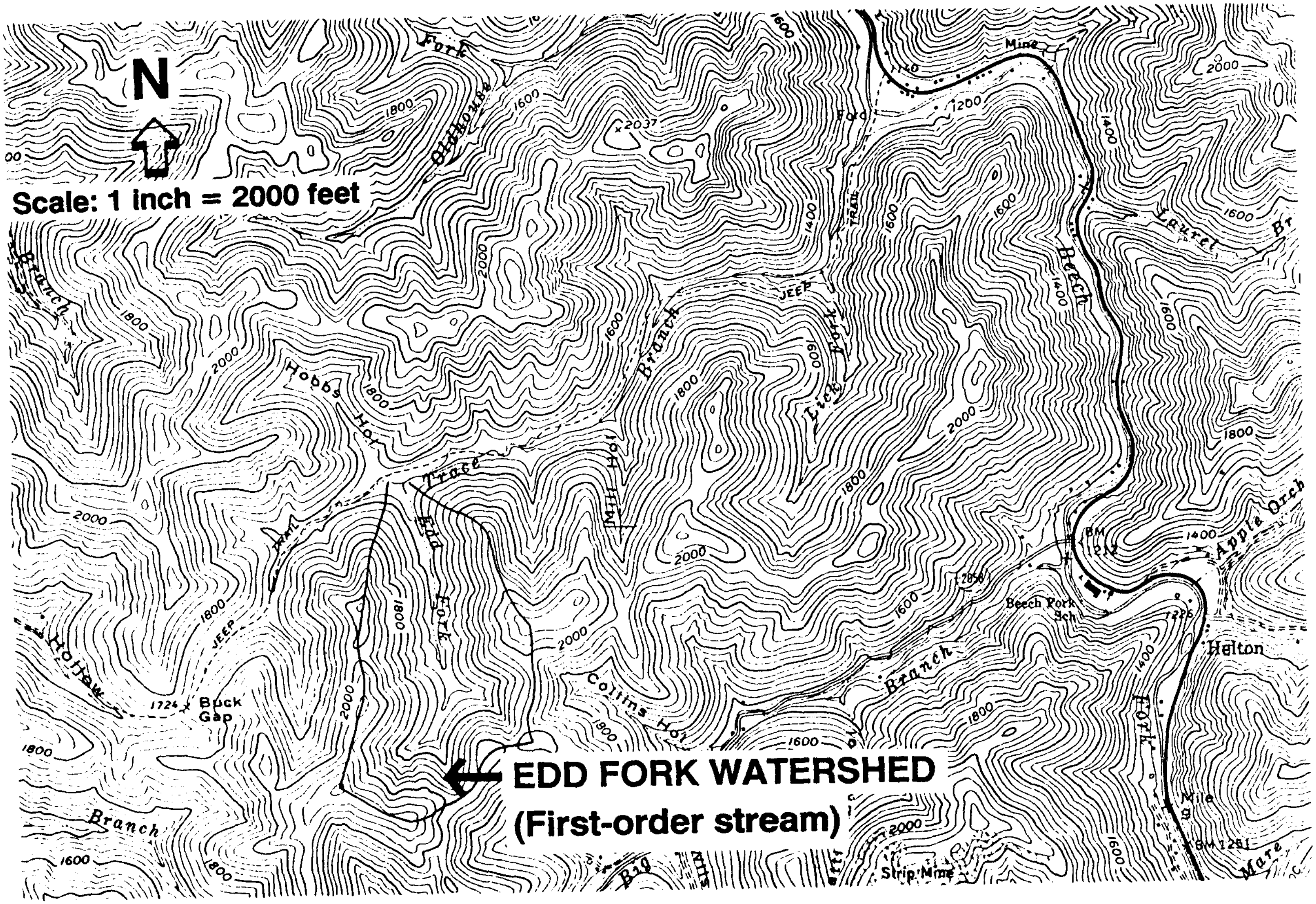


Figure 17. Topographic map of Edd Fork and vicinity.

Figure 18. Edd Fork watershed showing surface disturbances.

drainage strata in the watershed range from the Hindman Coal bed down to just below the Haddix Coal bed. Stratigraphy in the vicinity of the site is illustrated in the stratigraphic section in Figure 19.

The Helton, Kentucky, Geologic Map (Rice, 1975) indicates that surface rocks are slightly undulatory in the vicinity of Edd Fork. In general, the rocks dip gently toward the northeast. The Pine Mountain Overthrust is located approximately 5.5 miles southeast of the Edd Fork watershed.

METHODS

Site Characterization

Site Selection

The study site was selected to fulfill requirements outlined in a research proposal by Sendlein and Dinger (1990) to investigate effects of longwall mining on hydrology of eastern Kentucky. The chosen site is situated such that monitoring of hydrogeologic effects in ridgetop, valley-side, and valley-bottom settings along a cross section can be effectively accomplished.

Mapping

Base maps for this study were created from the Helton, Kentucky, 7.5 minute topographic map, 1974 edition. A detailed watershed map was constructed by digitizing topographic contours using AUTOCAD then overlaying roads and mining disturbances, and relocated drainways digitized from an enlarged 1:24,000 scale aerial photograph of the watershed. Additional disturbances not clearly shown on the aerial photograph were field mapped and digitally incorporated into the base map.

Core Drilling

One NX (3 inch) core hole was drilled at each of three topographic settings to provide stratigraphic control on the site. Core hole depths are 763.4 feet, 500.5 feet, and 344.0 feet for the ridgetop, valley-side, and valley-bottom settings respectively. Coring began in November, 1991, and was completed in early January, 1992. Core holes were grouted after drilling.

All core was examined in the field immediately upon removal from the core barrel. Core descriptions are consistent with the classification developed by Ferm and Melton (1977). Additional features such as fractures and weathered zones are described. All core was boxed and placed in storage at the Kentucky Geological Survey, Lexington, Kentucky.

Characterization of Hydraulic Properties

Pressure-Injection Testing

Pressure-injection tests are used to estimate the hydraulic conductivity at selected intervals within a borehole. A fluid, usually water, is injected into a borehole interval isolated between two inflatable packers until injection pressure and injection rate stabilize. Hydraulic conductivity for each discrete interval can be estimated.

Pressure-injection tests were performed on the three core holes immediately after completion of drilling. The packer assembly used for testing was a ten-foot-long section of perforated steel pipe connected to sliding-end inflatable packers from Tigre Tierra (Model 34B). The packer assembly was lowered to the bottom of the borehole on BX drill rods. Packers were inflated through 1/4 inch high-pressure tubing using bottled nitrogen. A schematic of the testing apparatus is shown in Figure 20. Water was injected into the test interval using a diesel water pump capable of pumping 50 gallons per minute. Water pressure was measured with a damped gage calibrated in two psi increments. Water flow to the test interval was measured using a Sensus water meter calibrated in 0. 1 gallon increments. Flow rates less than 0. 1 gallon per minute were estimated to hundredths of a gallon. The injection rate for intervals that did not take water was recorded as 0.01 gallon per minute. Flow to the test interval was controlled by valves that permitted excess water to bypass the packer system. Upon completion of testing in an interval, the packer assembly was raised to the next test interval by removing a ten-foot-long drill rod. Methodology for calculation of hydraulic conductivity from packer-injection data is included in Appendix B.

Precipitation Monitoring

A tipping-bucket rain gage (WEATHERtronics, Model 6011 A) is located on a reclaimed, surface-mined area midway between the ridgetop and valley-bottom piezometer nests. The rain gage is bolted to a twelve inch-square concrete slab and is leveled using shims under the bolts. The growth of weeds in the immediate vicinity of the rain gage is controlled by anchoring plastic and geofabric to the ground surface. A pulse recorder (Telog, Model 2107) automatically counts the number of bucket tips which occur each 10 minute interval. Each bucket tip registers 0.01 inch of rainfall. Precipitation data are downloaded to a laptop computer monthly.

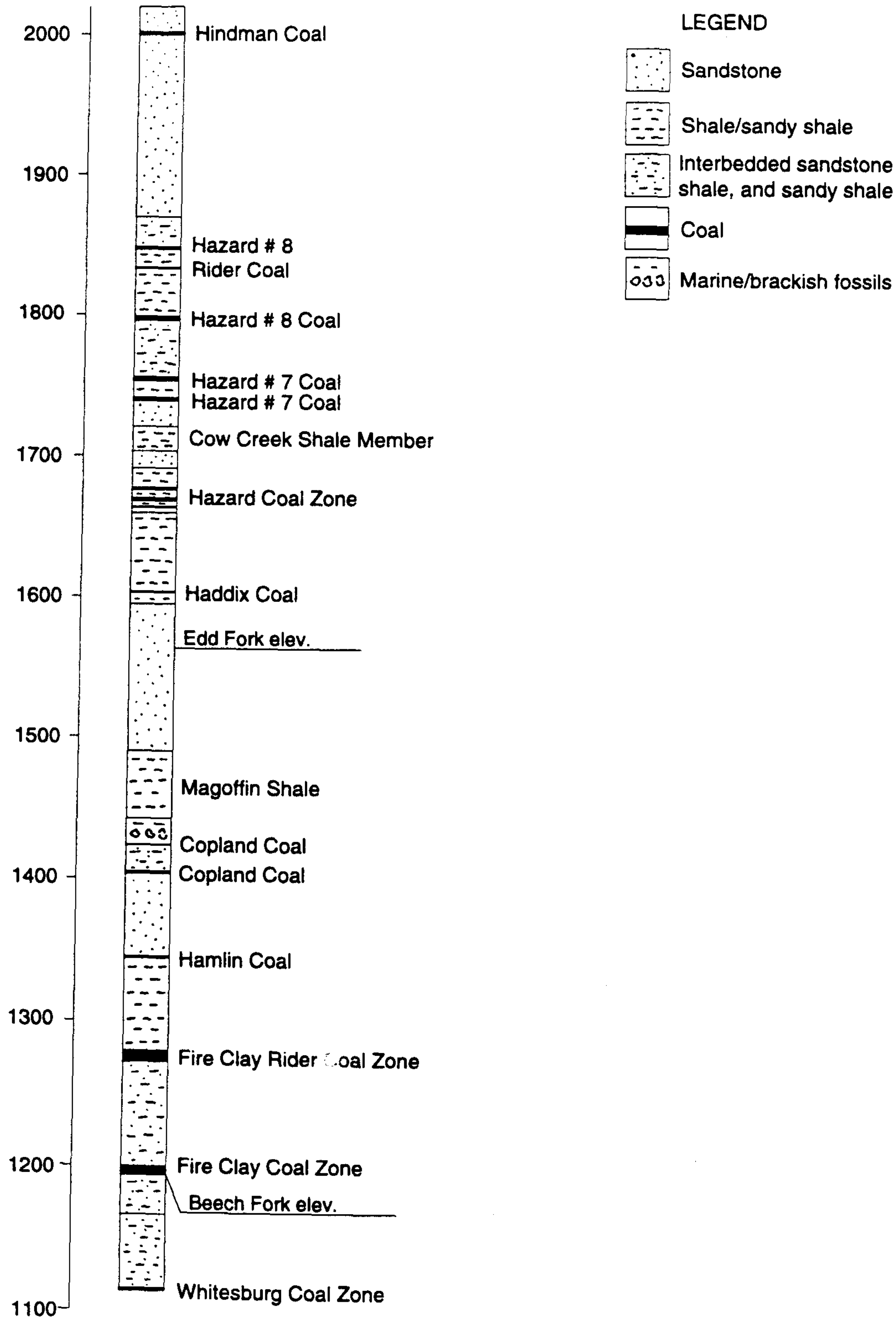


Figure 19. Stratigraphic section of the Edd Fork site.

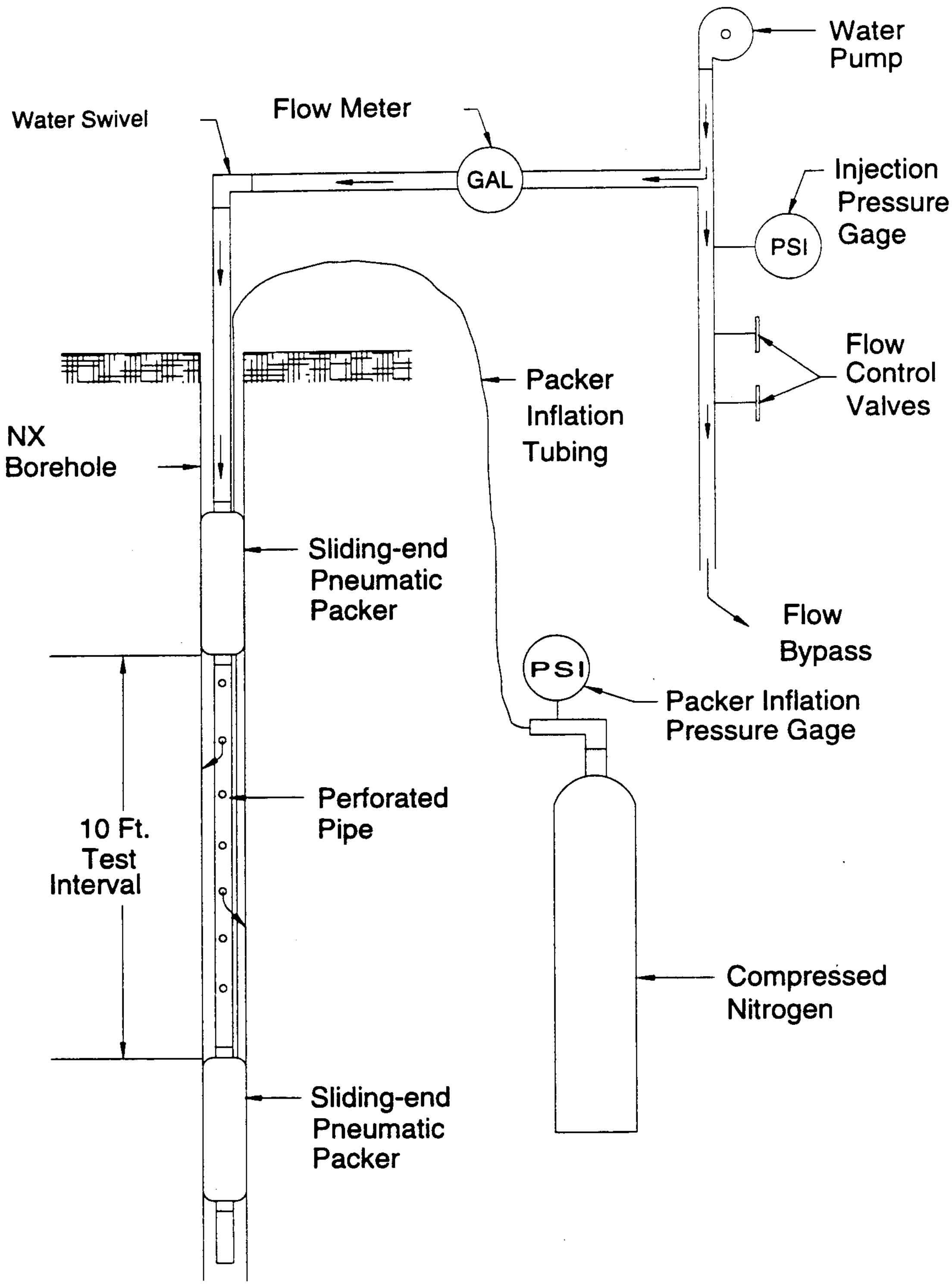


Figure 20. Pressure-injection test apparatus.

Ground-Water Monitoring

Piezometer Installation

Twenty-four piezometers are located in three nests along a cross section from the ridgetop to the valley bottom. These locations:

1. provide monitoring points in three different topographic positions; ridgetop, valley-side, and valley bottom,
2. allow monitoring of stratigraphic zones in different topographic positions,
3. facilitate construction of a cross section and,
4. allow completion of above and below drainage piezometers.

Specific stratigraphic intervals for monitoring were selected where head and quality data would most contribute needed information, either about one specific zone or about interrelationships among different zones. Exact screened intervals are based on the results of coring, geophysical logs, and pressure-injection tests. Piezometers are installed as close as practical to the core hole at each site. The maximum distance of any piezometer from a core hole is approximately 75 feet. Individual boreholes were drilled approximately 15 feet apart to minimize interference among piezometers at any one site during drilling and construction.

Piezometer installation began in early May, 1992, and was completed at the end of July, 1992. Boreholes for piezometers were drilled using air-rotary methods, utilizing air as the circulation medium where possible. Water was added to assist cuttings removal when mudcakes formed around the bit or when air was no longer sufficient to lift cuttings from the hole. Twelve of 14 boreholes are eight-inch holes with eight-inch I.D. steel surface casing. Surface casing in these hole is set in a ten inch hole drilled with a tri-cone bit. Two boreholes are six-inch holes with six-inch I.D. steel surface casing. Surface casing is set in an eight-inch hole drilled with a tri-cone bit. After surface casing was installed, holes were completed to the desired depths with a 7-7/8 inch diameter air-percussion hammer. The two six-inch holes were completed with a 6 inch hammer. Two drill rigs were utilized where possible in order to speed completion of boreholes. Drills used were a Driltech Model D40K, mounted on a crane carrier, and a Schramm T-64HP, mounted on a five ton M821 all wheel-drive military truck. The required air volume for drilling deep eight-inch holes was obtained by connecting the compressors on the two drills in-series.

All monitoring pipe is 2-inch O.D. flush-joint, PVC. The two deepest piezometers are constructed with schedule 80 riser and screen. Schedule 40 riser and schedule 80 screen are used for piezometers at depths exceeding 300 feet. The remaining piezometers are constructed using schedule 40 pipe and screens. Piezometers installation follows accepted methodology as described in "Handbook of Suggested Practices for the Design and Construction of Monitoring Wells" (Aller and others, 1989). Construction details are illustrated in Appendix D.

All piezometer locations are surveyed to the nearest 0.01 foot by a licensed surveyor. Elevations are rounded to the nearest 0.1 foot to be consistent with the level of accuracy of water-level measurements. The top of the protective casing is used as datum.

Piezometers were either pumped using a Grunfos Redi-flo two-inch submersible pump or purged of standing water using a two-inch stainless-steel bailer. A pump-hoist truck equipped with nylon-coated stainless steel cable was used to raise and lower the bailer.

Water Levels

Water levels are measured using a Slope Indicator, Inc. Model 51453 water-level indicator. Measurements are recorded to the nearest 0.1 foot. The measuring point (MP) for water levels is the top of the protective steel casing.

Water-Quality Sampling

One set of water-quality samples was collected. A combination of pumping and bailing was used to purge piezometers and collect samples, depending on the depth and water-producing capabilities of each piezometer. Several piezometers produced little water and had to be purged, then sampled the following day. At least three well volumes were purged from 9 of the 19piezometers sampled. Less than three well volumes were removed from the remaining piezometers.

Specific conductance, temperature, and pH, were measured in the field during pumping and sampling using a YSI 3500 flow-through meter. Probes from the YSI meter were used for field measurements on bailed samples, but the air-tight chamber was not used. The pH probes were calibrated at least daily using pH 7.0 and 10.0 standards. Specific conductance was measured with a Cole-Parmer 1481-55 temperature-compensating conductivity meter. The specific conductance meter was standardized at least once per day using 75 3m siemen and 2,000 3m siemen standards. Field measurements were corrected using linear regression techniques.

Water for non-metals analyses was placed in certified clean polyethylene cubitainers. Samples for dissolved metals were field-filtered through a 0.45 micron cellulose-acetate filter, placed in certified clean 250 ml bottles and preserved with 1 ml of 1:1 double-distilled water to nitric acid solution. All samples were stored in an ice chest after collection. Sampling equipment was thoroughly rinsed with deionized water between piezometers.

Laboratory analyses were performed by the Laboratory Services Section of the Kentucky Geological Survey. Metals were analyzed using a thermal-Jarrell Ash Inductively Coupled Plasma Emission Spectrometer (ICAP).

One surface water sample was collected from Edd Fork. Sampling procedure is the same as for piezometers.

RESULTS

Site Selection

Three sites representing ridgetop, valley-side, and valley-bottom were selected for intensive ground-water monitoring. These sites are designated as Site A (valley-side), site B (ridgetop), and site C (valley-bottom) as shown in Figure 21. Each site contains one core hole and a closely spaced piezometer nest.

Site A is located below a contour strip bench at a surface elevation of about 1,756 feet. This site was selected because it represents the valley-side position and is located on undisturbed ground. Site B, at an elevation of 2,020 feet, is located on a ridge that has been surface mined. Site C, located in an undisturbed area about 65 feet from Edd Fork, has an elevation of 1,593 feet. There is no mining disturbance associated with this site.

Core Drilling

One core hole was drilled at each site to define stratigraphy along a cross section, delineate the extent of fractures, and to guide the installation of piezometers. A generalized geologic cross section A-A '(Figure 22) is constructed from core holes A, B, and C. Core descriptions are provided in Appendix A.

Pressure-Injection Tests

Pressure-injection tests were conducted in core holes A, B, and C to determine an approximate conductivity profile for each core hole. A 10-foot-long packer-test interval was used for all tests. The results of the injection tests are shown in Figures 23, 24, and 25. A discussion of pressure-injection test calculations and data for these tests are presented in Appendix B.

Results of these tests were used as an aid to design the piezometer network. Highly conductive zones correlate with fracture zones and coal seams identified in core logs. Conductivity differences of an order of magnitude or greater between test intervals are not uncommon. It is evident that highly conductive zones include discrete fractures, fracture zones, or coal beds. Intervals with no evidence of fracturing have very low conductivities. These results are consistent with results reported by Wunsch (1992) and Kipp and Dinger (1987) for the Eastern Kentucky Coal Field.

Precipitation Monitoring

Precipitation data were collected from June 12,1992, through February 2,1993. The location of the rain gage is shown in Figure 21. Monthly precipitation totals for the study period are shown in Figure 26. Daily precipitation data are presented in Appendix C.

Ground-Water Monitoring

Piezometer Installation

Twenty-four piezometers, distributed among three sites, were installed in the Edd Fork watershed. Each piezometer has a three-character alphanumeric identifier which designates site location, hole number, and piezometer identification. The deepest piezometer in each hole is designated as "A" and the shallowest piezometer is designated as "B". Cross section A-A:, shown in Figure 27, illustrates the location of screened intervals for all piezometers. Table 4 summarizes piezometer depths, screened intervals, and monitored zones. Twelve piezometers, located in the site B ridgetop nest, are completed to depths ranging from 67 feet to 684 feet. Six piezometers are located in the valleyside nest at site A and have completion depths from 35 feet to 417 feet. Six piezometers are located in the nest at site C adjacent to Edd Fork. Completion depths range from 18 feet to 262 feet. Appendix D contains detailed construction information for each piezometer.

Water Levels

Water levels in each piezometer were measured on irregular intervals. Measurements were taken to characterize both wet and dry periods. Twenty of the 24 piezometers had measurable water levels throughout the monitoring period. Three shallow piezometers remained consistently dry and one shallow piezometer contained water after rainfall events. Water-level data from August 13, 1992, through February 2, 1993 were

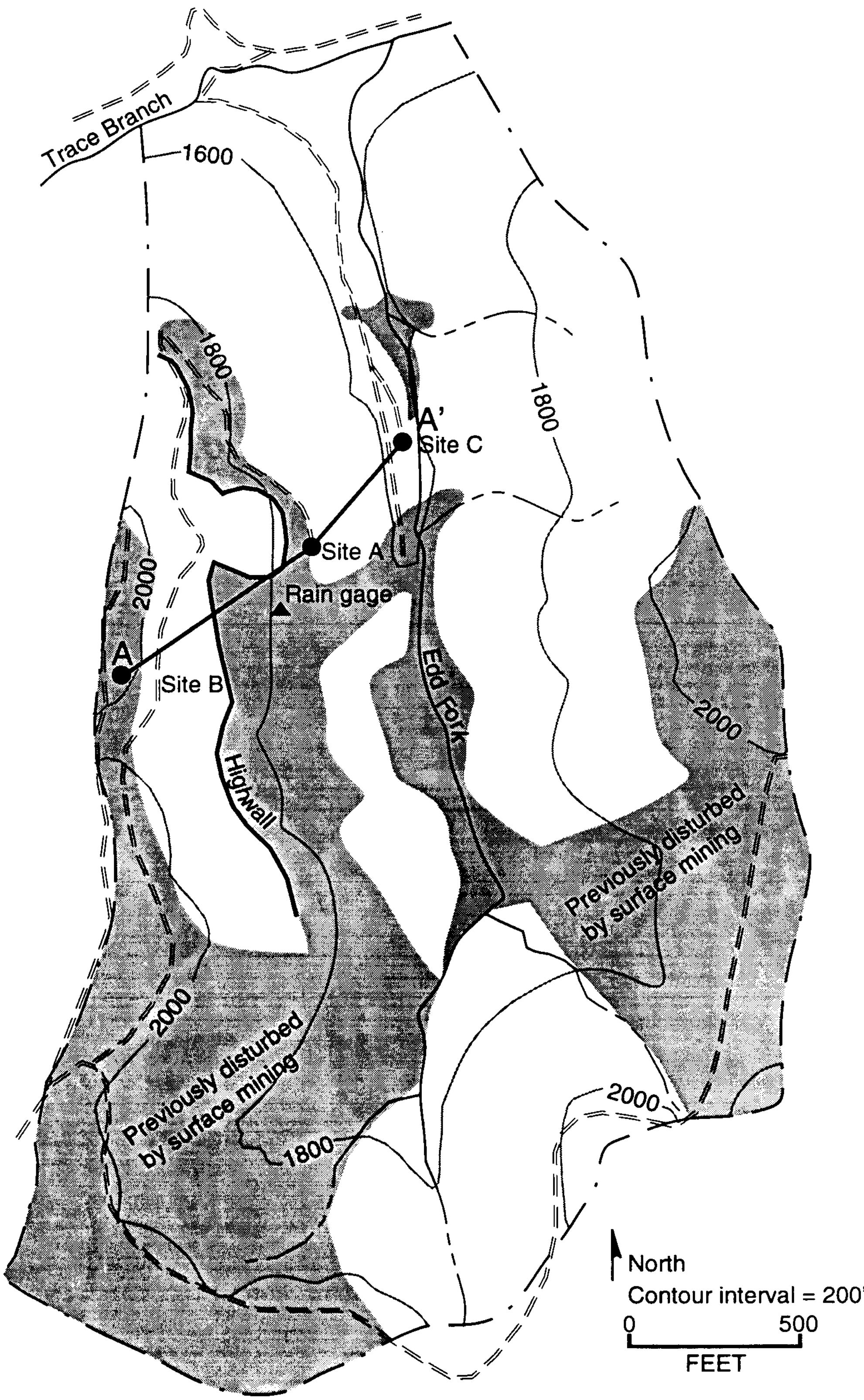


Figure 21. Monitoring point locations in Edd Fork.

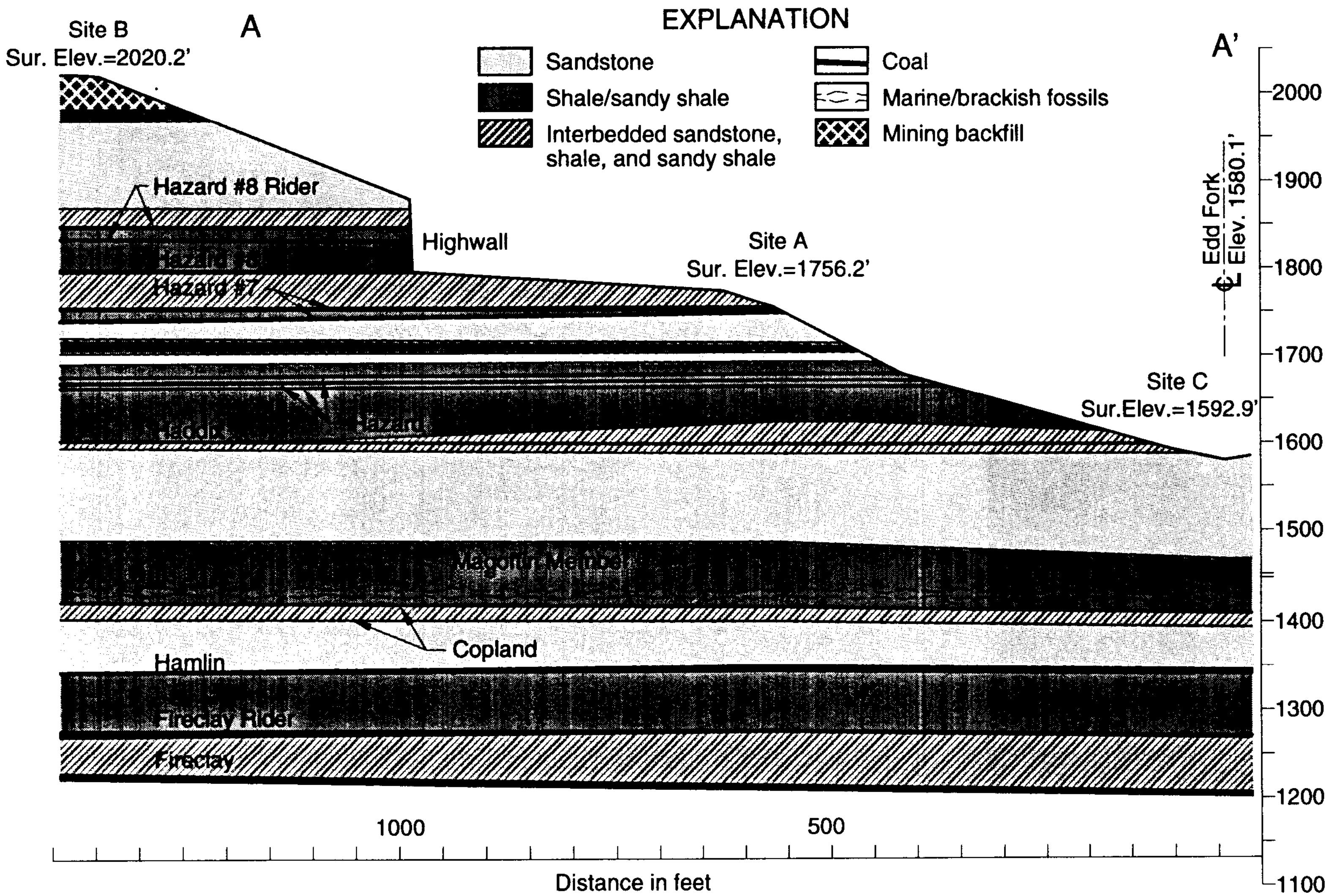


Figure 22. Geologic cross section A–A' (see Figure 21 for location).

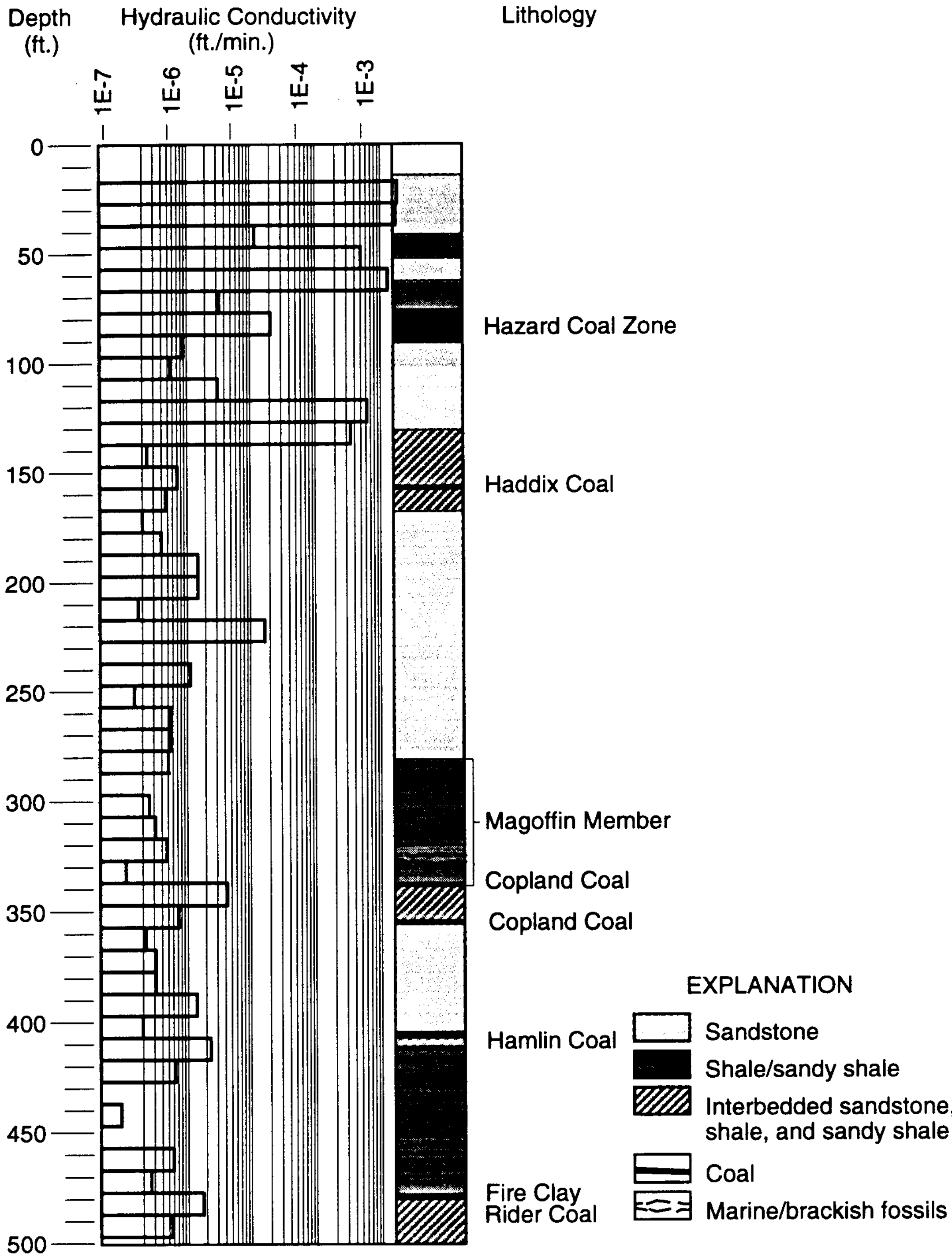


Figure 23. Geologic column for core hole A showing calculated hydraulic conductivity values.

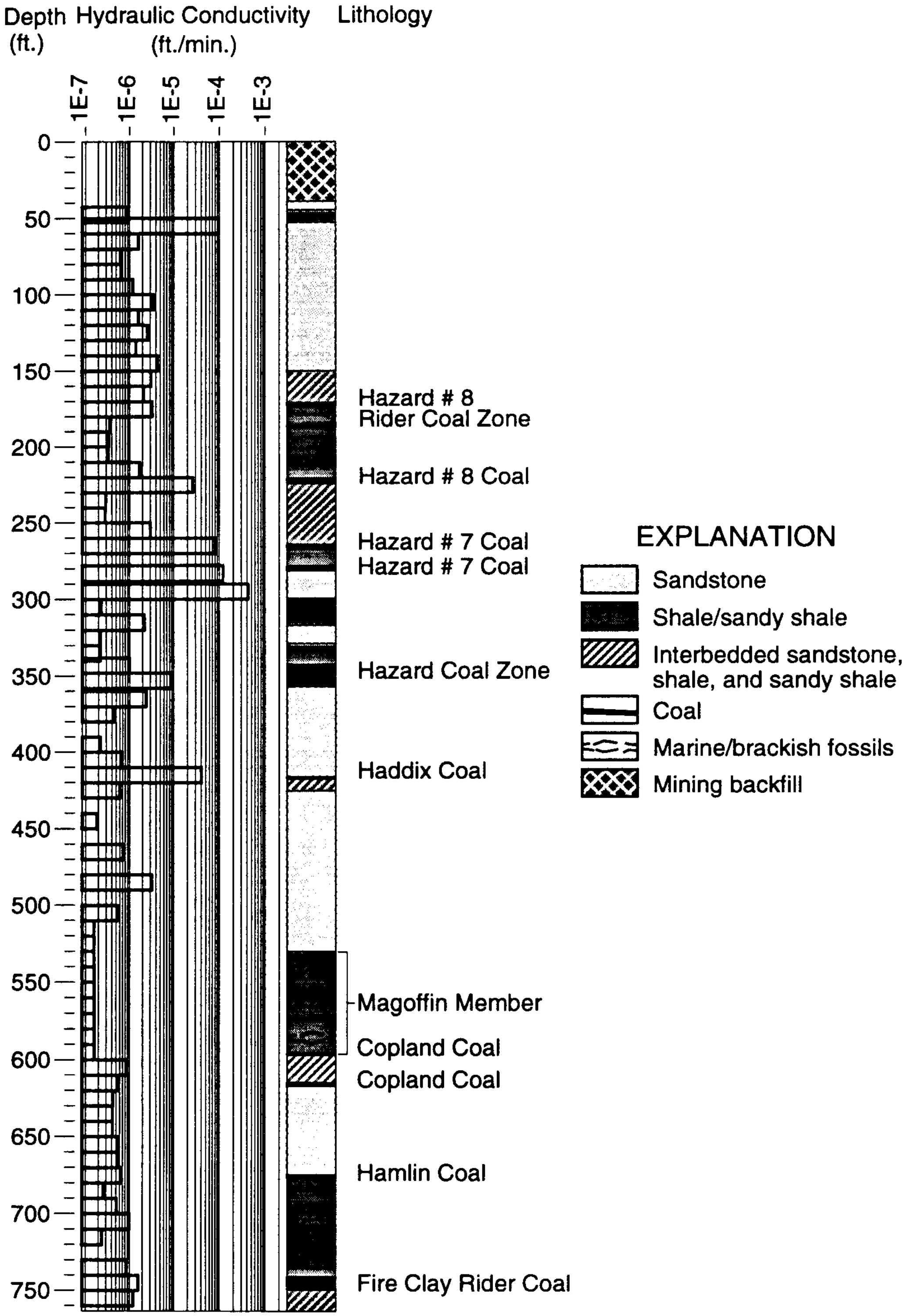


Figure 24. Geologic column for core hole B showing calculated hydraulic conductivity values.

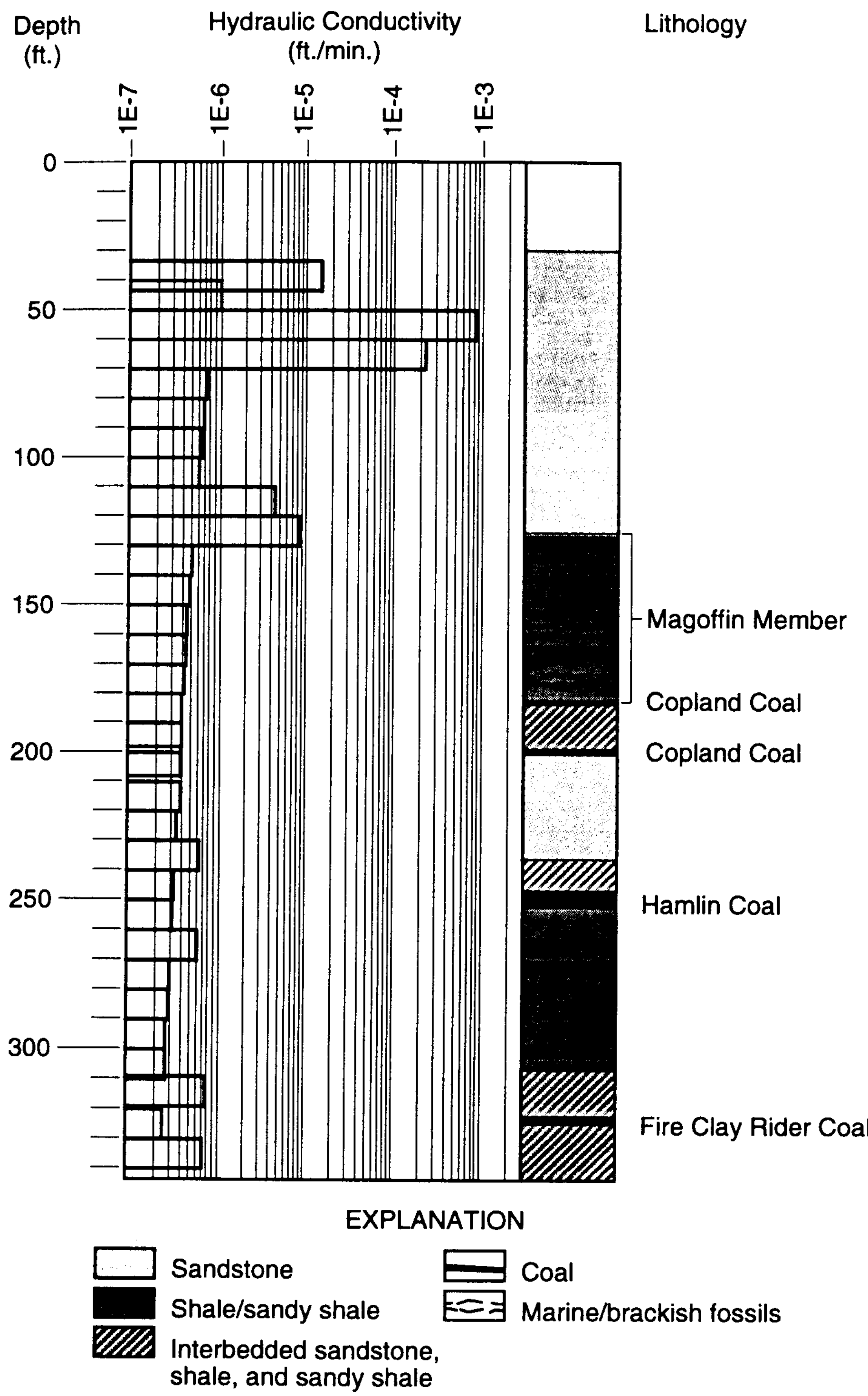


Figure 25. Geologic column for core hole C showing calculated hydraulic conductivity values.

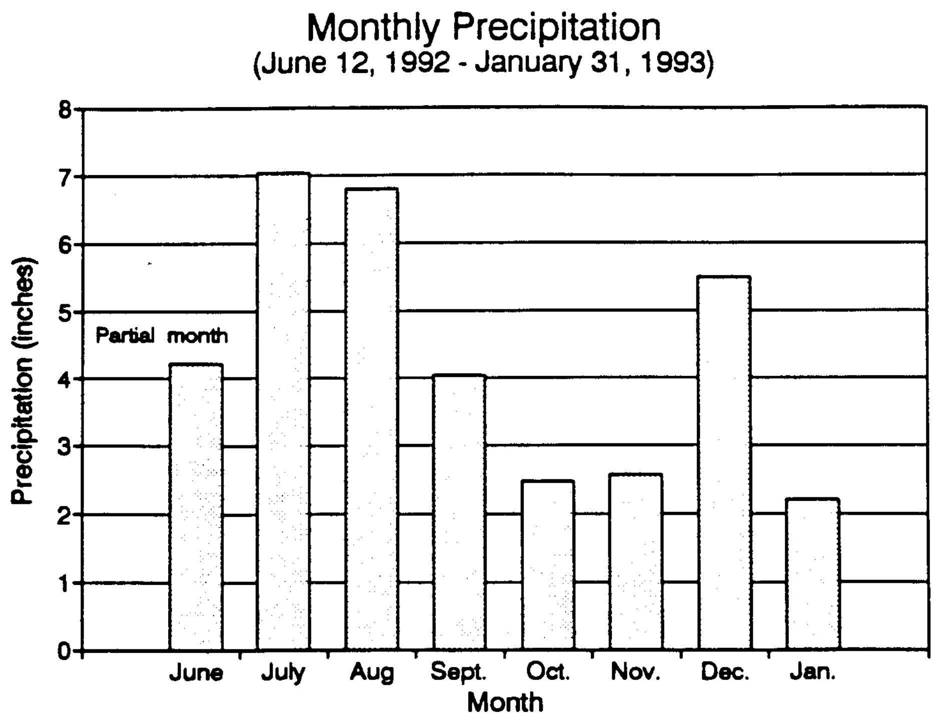


Figure 26. Monthly precipitation totals for Edd Fork.

considered in this analysis. A summary of water-level elevations is presented in Tables 5, 6, and 7. Piezometers were partially purged in September and again in November. Complete water level data for each piezometer is presented in Appendix E.

Water-Quality Sampling

One set of water-quality analyses was collected from 19 of the 24 piezometers on the site. Data from 14 of these piezometers were determined to be representative of water quality in the formation and are included in this study. The remaining piezometers have not been sufficiently developed for data to be representative of the formation water. Three criteria were used to determine if water quality was representative of the formation: (1) piezometers produced at least three well volumes when purged, (2) water exhibited quality characteristics of a sodium-rich "deep" water, and (3) little residual bentonite was present in the sample. Major constituent percentages for water samples are presented in Table 8. One surface-water sample, SWC, was collected from Edd Fork adjacent to piezometer nest C. Major-ion percentages for this sample are also presented in Table B. Complete water quality analyses are presented in Appendix F.

DISCUSSION

Hydraulic Conductivity

Pressure-injection tests conducted on three core holes provide an equivalent-porous-media estimate of horizontal hydraulic conductivity in the vicinity of the hole. It is important to remember that conductivity estimates from pressure-injection data are calculated assuming that water is injected into the formation over the entire area of the test interval. In layered and fractured strata, the interval accepting water may be a discrete fracture or a particular lithology, such as a coal seam, that is thinner than the entire test interval. If a particular zone within the interval is accepting the majority of the water, the hydraulic conductivity for that zone is higher than the value reported for that interval. One must also consider that calculated values represent horizontal conductivity and that conductivity in the vertical direction may be larger or smaller, and be dependent on lithology. This method, however, provides approximate values for conductivity that can be compared, allowing examination of conductivity variations with depth, lithology, and topography.

Figures 28, 29, and 30 show the variation in hydraulic conductivity with depth for core holes A, B, and C. The distribution of points indicates that hydraulic conductivity typically varies three or four orders of magnitude over

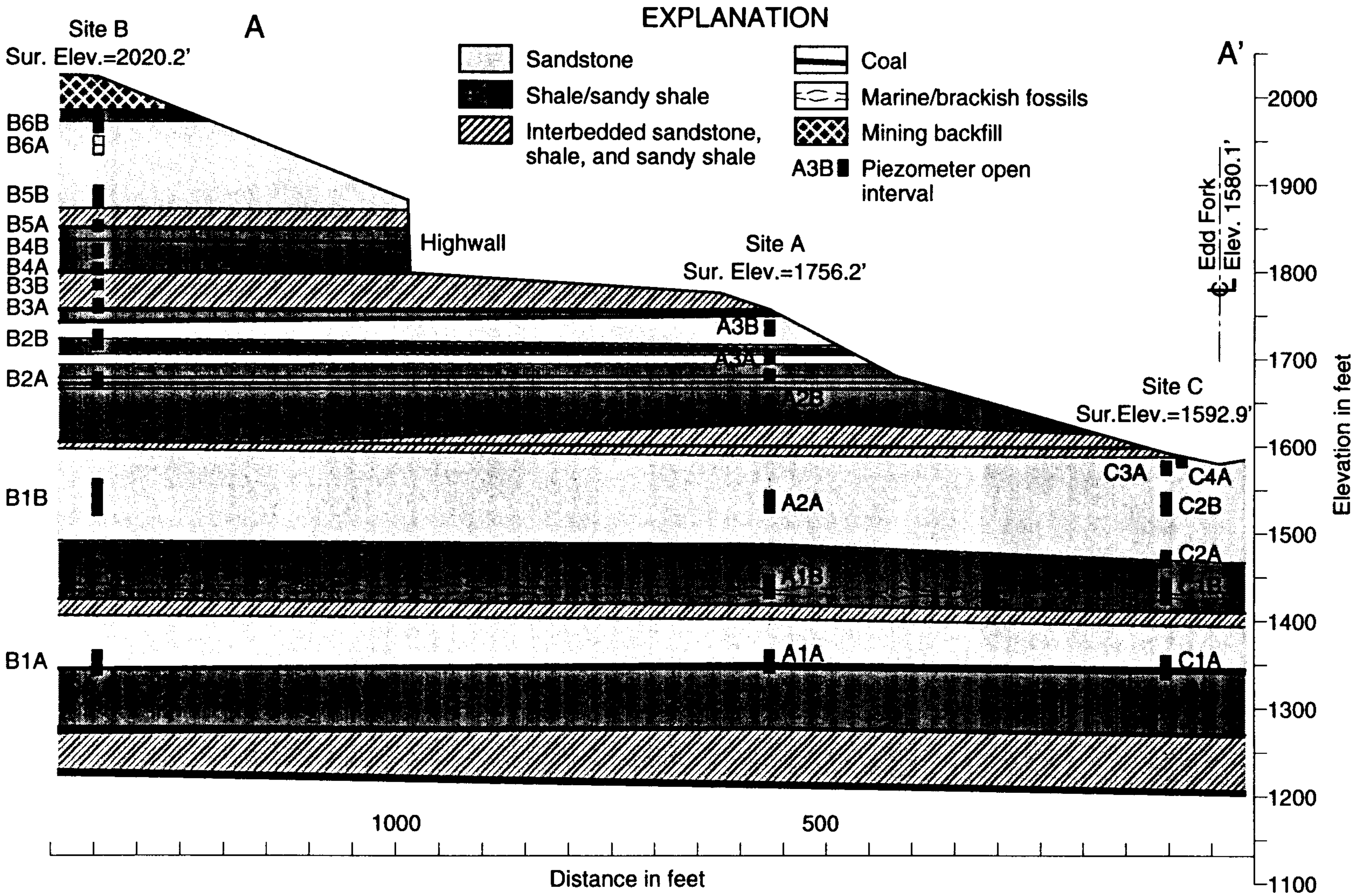


Figure 27. Piezometer locations along cross section A–A' (see Figure 21 for location).

the depth of a hole. Values range from $1X10^{-7}$ to $1X10^{-3}$ feet per minute. In general, the most conductive strata are near the ground surface where open fractures are common. Strata deep within the ridge are the least conductive.

Conductivity values plotted in Figures 28, 29, and 30 are differentiated according to major lithology. Major lithologic groups are sandstone, shale/sandy shale, interbedded sandstone and shale, and coal. Intervals that include major lithologic contacts are generally considered as interbedded strata. Fractured zones are not differentiated by lithology. Coal beds and fractures stand out as highly conductive zones; however, below-drainage coal beds have conductivities that are smaller than those above drainage. Unfractured sandstone, shale/sandy shale, and interbedded strata do not exhibit values that are markedly different from each other.

Table 9 summarizes conductivity relationships among different strata from core holes A, B, and C. A total of 140 intervals in three holes is included. Fracture zones are the most conductive and have a median conductivity of $9x10^{-4}$ feet per minute. Intervals containing above-drainage coals are the second most conductive group, having a median conductivity of $9x10^{-6}$ feet per minute. Unfractured, non-coal strata have median conductivities between $4xl0^{-7}$ and $1x10^{-6}$ feet per minute. Coal-bearing intervals below drainage have a median conductivity of $6x10^{-7}$, a value that is more on the order of unfractured sandstone and shale than above-drainage coal.

Table 4.—Summary of Screened Intervals for Piezometers in Edd Fork.

Site	*Hole Number*	*Piezometer*	*Total Depth (ft.)*	*Elevation at top of screened interval (ft.)*	*Elevation at bottom of screened interval (ft.)*	*Zone*
A	1	A	415.0	1367.0	1340.5	Interbedded
A	1	B	328.0	1453.0	1425.5	Shale (Magoffin Member)
A	2	A	233.5	1549.0	1523.0	Sandstone (> 50%)
A	2	B	85.5	1687.0	1671.0	Hazard coal zone
A	3	A	65.5	1709.0	1693.5	Fractures
A	3	B	34.5	1744.0	1725.5	Fractures
B	1	A	684.0	1363.5	1336.5	Sandstone (> 50%)
B	1	B	492.0	1560.5	1518.5	Sandstone (> 50%)
B	2	A	354.5	1682.5	1665.5	Hazard coal zone
B	2	B	311.0	1731.5	1708.0	Fractures
B	3	A	269.0	1766.5	1750.0	Hazard No. 7 coal
B	3	B	243.5	1788.5	1776.5	Interbedded
B	4	A	227.0	1807.5	1793.5	Hazard No. 8 coal
B	4	B	205.0	1829.0	1813.0	Shale/sandy shale
B	5	A	179.0	1856.5	1843.5	Hazard No. 8 rider coal
B	5	B	149.5	1896.0	1870.5	Fractures
B	6	A	91.5	1952.0	1930.5	Fractures
B	6	B	64.0	1977.0	1956.0	Interbedded
C	1	A	260.0	1361.0	1333.5	Interbedded
C	1	B	173.5	1448.5	1419.5	Shale (Magoffin Member)
C	2	A	130.5	1481.0	1462.0	1/3 in Magoffin Shale
C	2	B	70.5	1547.5	1521.0	Sandstone (> 50%)
C	3	A	24.0	1583.5	1567.5	Fractures
C	4	A	17.0	1585.5	1576.0	Fractures

Table 5.—Water-Level Elevations for Piezometers in Edd Fork—Nest A.

Date	*A1A Elev. (ft.)*	*A1B Elev. (ft.)*	*A2A Elev. (ft.)*	*A2B Elev. (ft.)*	*A3A Elev. (ft.)*	*A3B Elev. (ft.)*
13–Aug–92	1387.0	1515.5	1588.9	1691.9	1695.0	Dry
27–Aug–92	1384.4	1508.2	1589.0	1691.9	1695.3	Dry
28–Aug–92	1383.8	1506.6	1589.4	1692.2	1695.3	Dry
10–Sep–92	1381.5	1498.4	1589.1	1692.7	1695.5	Dry
23–Sep–92	1373.5	1455.1	1589.8	1692.8	1695.0	Dry
24–Sep–92	1373.5	1455.1	1588.8	1692.8	1695.4	Dry
25–Sep–92	1373.5	1455.1	1588.8	1692.8	1695.5	Dry
01–Oct–92	1371.3	1455.4	1588.7	1692.5	1695.3	Dry
15–Oct–92	1372.0	1460.6	1588.7	1692.7	1695.0	Dry
28–Oct–92	1372.1	1460.7	1588.7	1692.3	1695.5	Dry
12–Nov–92	1372.2	1460.8	1589.1	1692.4	1695.0	Dry
03–Dec–92	1370.7	1434.6	1589.4	1692.7	1695.0	Dry
15–Dec–92	1370.8	1434.7	1589.7	1693.0	1695.5	Dry
06–Jan–93	1371.2	1434.9	1589.2	1693.4	1695.9	Dry
02–Feb–93	1371.7	1435.0	1589.1	1693.2	1695.5	Dry

Table 6.—Water-Level Elevations for Piezometers in Edd Fork—Nest B.

Date	*B1A Elev. (ft.)*	*B1B Elev. (ft.)*	*B2A Elev. (ft.)*	*B2B Elev. (ft.)*	*B3A Elev. (ft.)*	*B3B Elev. (ft.)*	*B4A Elev. (ft.)*	*B4B Elev. (ft.)*	*B5A Elev. (ft.)*	*B5B Elev. (ft.)*	*B6A Elev. (ft.)*	*B6B Elev. (ft.)*
13–Aug–92	1378.6	1650.3	1688.0	1725.9	1755.4	1783.4	1797.2	1835.3	1853.3	1877.2	Dry	Dry
27–Aug–92	1377.3	1637.3	1688.4	1725.8	1755.4	1785.4	1797.1	1833.7	1853.4	1877.2	Dry	Dry
28–Aug–92	1377.3	1636.6	1688.7	1725.8	1755.4	1785.5	1797.2	1833.7	1853.5		1931.4	Dry
10–Sep–92	1376.5	1627.2	1689.2	1725.8	1755.4	1785.5	1797.5	1832.2	1853.5	1877.5	1931.3	Dry
23–Sep–92	1375.9	1619.9	1690.7	1725.8	1755.4	1783.4	1797.4	1826.2	1853.5	1876.8	Dry	Dry
24–Sep–92	1375.9	1619.9	1690.7	1725.8	1755.4	1783.4	1797.4	1826.2	1853.5	1876.8	Dry	Dry
25–Sep–92	1375.9	1579.8	1690.7	1725.8	1755.4	1783.4	1797.4	1819.3	1853.5	1876.8	Dry	Dry
01–Oct–92	1373.2	1582.1	1690.7	1725.6	1755.4	1783.3	1797.3	1819.6	1853.4	1876.7	Dry	Dry
15–Oct–92	1374.2	1586.0	1690.7	1725.6	1755.4	1783.4	1797.2	1819.8	1853.4	1876.6	Dry	Dry
28–Oct–92	1374.5	1588.5	1690.8	1725.9	1755.4	1783.5	1797.1	1819.9	1853.3	1876.3	1931.6	Dry
17–Nov–92	1374.1	1590.1	1690.7	1725.6	1755.3	1783.4	1797.0	1820.0	1853.5	1876.5	Dry	Dry
03–Dec–92	1374.2	1582.1	1688.1	1725.7	1755.3	1780.4	1797.2	1817.7	1853.4	1876.5	Dry	Dry
15–Dec–92	1373.9	1583.7	1688.9	1725.6	1755.4	1780.5	1797.4	1817.9	1853.6	1876.8	Dry	Dry
06–Jan–93	1373.5	1583.4	1689.1	1725.6	1755.4	1780.5	1798.7	1818.0	1853.6	1876.8	Dry	Dry
02–Feb–93	1373.3	1580.1	1689.5	1725.7	1755.4	1780.5	1798.0	1818.2	1853.5	1876.9	Dry	Dry

Some examples of strata that are located in adjacent test intervals have conductivity values that vary over several orders of magnitude. One example is illustrated in Figure 29. The two test intervals at the top of the hole have conductivities that differ by two orders of magnitude. This difference in conductivity is attributed to a fracture located within one of the test intervals. Another example (Figure 29) shows the highly conductive nature of coal seams. The interbedded zone at a depth of about 260 feet has a conductivity that is 150 times less than the coal bed immediately below it.

Few data are available to compare the effect of topographic position to hydraulic conductivity distribution. Figures 28, 29, and 30 show that calculated conductivities have a greater range of values at depth in the ridge and valley-side settings compared to the valley bottom. However, coal beds and fractures are underrepresented in the valley-bottom core hole. The lack of fractures may reflect conditions in an isolated hole and may not be representative of the valley bottom in general. However the lack of fractures is consistent with an investigation by Hill (1988) where V-shaped valleys contained highly competent (unfractured) strata under high compressive stress.

Water Levels

Piezometers constructed for this study have screened intervals that range from approximately 12 to 27 feet in length. Piezometers in coal seams have the shortest intervals. Deep piezometers in tight formations have longer intervals. Piezometer B1B has an open interval of about 40 feet because of a problem during construction.

Static water levels for piezometers, open to an interval as opposed to a point, generally represent a composite head over that interval. The composite head is commonly considered as the average water level at the midpoint of the open interval. The assumption that head represents the average head in the open interval is strictly valid only for homogeneous porous-media where hydraulic properties within the open interval are similar. Coal-field strata are not homogeneous; therefore, interpretation of water-level data must consider the effects that layered strata and fractures have on the system.

Piezometers located deep within the ridge interior below drainage are less likely to exhibit extremes in conductivity. The screened interval is commonly saturated and fractures are less common, at least at a single piezometer. Water levels in this situation probably represent a composite average over the interval.

Fractures and highly conductive coal beds located within a monitored zone exert a strong influence on static water levels. Fractures and coal seams may control water levels in the interval so that head is not a composite of the interval. Nonetheless, examination of water level elevations relative to interval midpoints provide useful information of the distribution of hydraulic head with depth. To maintain consistency for this discussion, head in the piezometer is presumed to represent head at the interval midpoint. In reality, for relatively short monitored intervals, potential error is on the order of a few feet. Relative to the scale of the head changes in this system which is on the order of hundreds of feet, this error is negligible. Effects of fractures and coal seams on head is discussed in more detail in later sections.

Graphs showing water-level elevation and piezometer-interval midpoint elevation for each piezometer within a nest are shown in Figures 31, 32, and 33. The line of zero pressure head, where head is equal to elevation, and the static water elevation for the core hole at each site are shown on each plot.

Table 7.—Water-Level Elevations for Piezometers in Edd Fork—Nest C.

Date	*C1A Elev. (ft.)*	*C1B Elev. (ft.)*	*C2A Elev. (ft.)*	*C2B Elev. (ft.)*	*C3A Elev. (ft.)*	*C3B Elev. (ft.)*
13–Aug–92	1371.6	1562.2	1525.4	1567.0	1577.8	1579.9
27–Aug–92	1370.8	1562.1	1525.8	1567.0	1579.8	1581.3
28–Aug–92	1370.8	1562.1	1526.2	1567.4	1582.8	1582.4
10–Sep–92	1370.3	1562.0	1526.2	1567.3	1577.1	1581.3
23–Sep–92	1370.0	1528.3	1526.4	1566.7	1576.4	1581.5
24–Sep–92	1343.8	1425.4	1526.1	1566.7	1576.5	1581.3
25–Sep–92	1356.7	1425.4	1526.4	1567.1	1577.0	1580.6
01–Oct–92	1368.1	1425.7	1526.3	1566.5	1576.5	1580.4
15–Oct–92	1368.6	1425.6	1526.5	1566.5	1576.5	1580.9
28–Oct–92	1368.9	1427.7	1526.4	1566.5	1576.8	1580.4
11–Nov–92	1368.9	1425.7	1526.5	1566.2	1577.3	1581.0
03–Dec–92	1367.1	1424.5	1526.5	1566.2	1577.2	1581.7
15–Dec–92	1367.6	1424.5	1526.7	1566.7	1579.6	1582.4
06–Jan–93	1367.7	1424.6	1526.5	1566.2	1578.7	1582.2
02–Feb–93	1368.2	1424.6	1526.3	1565.8	1577.2	1580.9

Table 8.—Percent Reacting Values (meq/L) for Water Samples from Edd Fork Piezometer Nests.

Constituent	*A1A*	*A1B*	*A2A*	*A2B*	*B2A*
LABORATORY ANALYSES					
% Calcium	1.46	1.91	49.21	40.62	36.01
% Magnesium	0.51	1.13	30.58	51.76	23.57
% (Sodium + potassium)	98.03	96.96	20.21	7.62	40.41
% Chloride	1.88	2.05	1.07	1.10	1.59
% Sulfate	7.68	21.88	27.47	63.70	25.36
% Bicarbonate	90.44	76.07	71.46	35.20	73.05
Total dissolved solids (mg/L)	426.43	652.30	234.88	201.71	219.72
% Error	4.50	6.44	4.62	3.11	3.46
FIELD ANALYSES					
pH	8.37	8.34	7.46	6.52	7.40
T (degrees C)	13.1	15.2	16.9	15.6	13.2
Sp. cond. (micro S)					

Constituent	*B3A*	*B5A*	*B5B*	*C1A*	*C1B*
LABORATORY ANALYSES					
% Calcium	37.332	42.31	42.36	0.69	1.61
% Magnesium	36.98	0.41	54.56	0.41	0.70
% (Sodium + potassium)	25.79	3.28	3.08	98.90	97.69
% Chloride	0.92	0.32	0.80	3.87	1.61
% Sulfate	72.33	89.22	82.74	19.66	29.88
% Bicarbonate	26.75	10.46	16.45	76.47	68.50
Total dissolved solids (mg/L)	634.59	1,512.44	990.38	450.55	633.92
% Error	4.09	4.06	12.71	3.51	3.21
FIELD ANALYSES					
pH	6.56	6.69	6.36	8.48	8.86
T (degrees C)	12.7	14.4	13.4	16	14.3
Sp. cond. (micro S)	757	1,502	889	575	837

Constituent	*C2A*	*C2B*	*C3A*	*C4A*	*SWC*
LABORATORY ANALYSES					
% Calcium	1.69	56.68	33.84	42.60	46.32
% Magnesium	0.72	27.85	38.32	33.89	51.83
% (Sodium + potassium)	97.59	15.47	27.83	23.51	1.85
% Chloride	2.13	0.00	0.63	6.29	0.57
% Sulfate	1.44	12.05	52.22	46.35	91.22
% Bicarbonate	96.43	87.95	47.15	47.35	8.21
Total dissolved solids (mg/L)	398.34	110.51	24.13	36.21	823.20
% Error	5.46	8.09	5.99	15.04*	1.77
FIELD ANALYSES					
pH	8.87	7.21	5.73	6.32	7.56
T (degrees C)	14.2	13.9	17.5	16.3	13.7
Sp. cond. (micro S)	582	188	48.5	80.8	921

* High error is the result of low total dissolved solids.

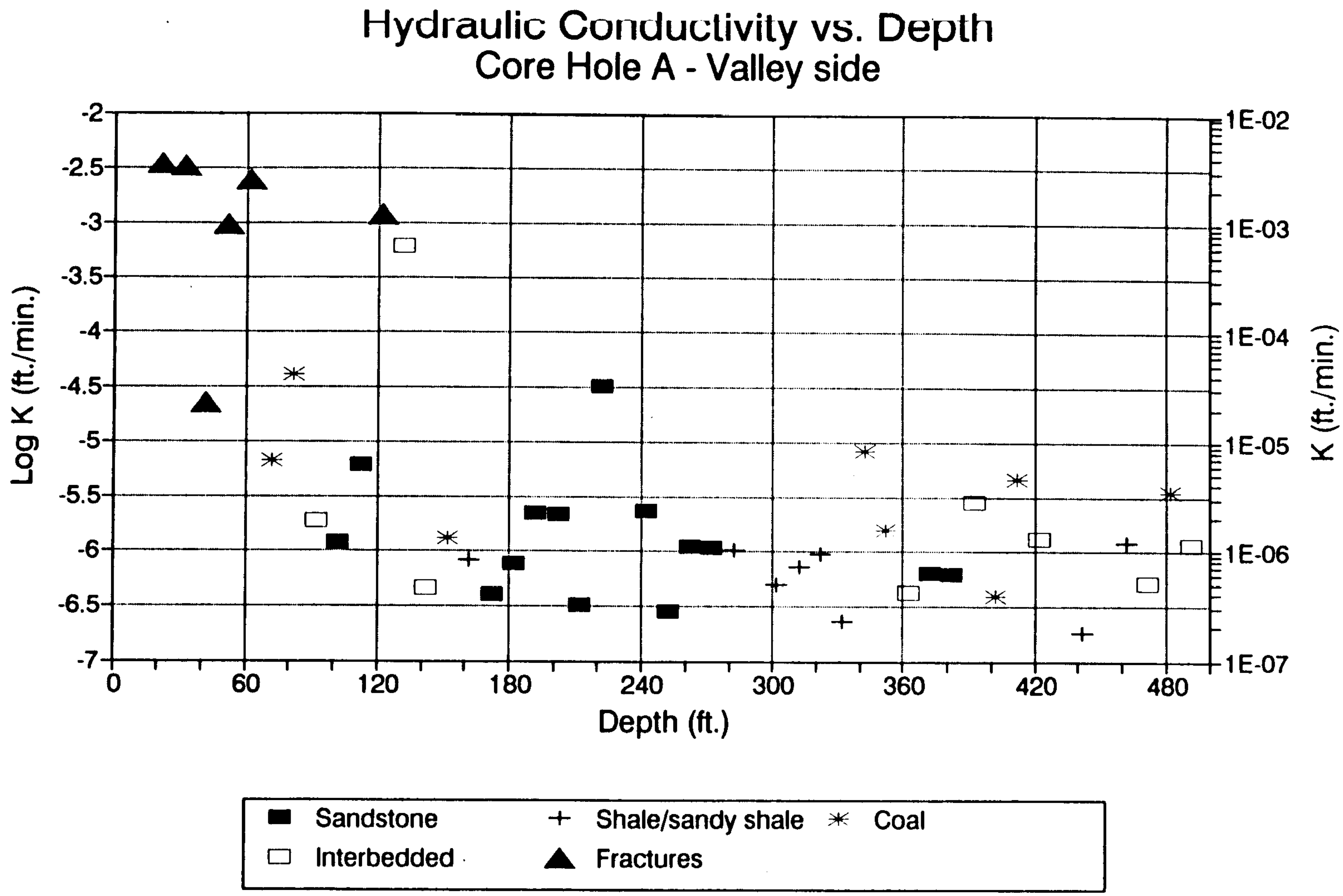
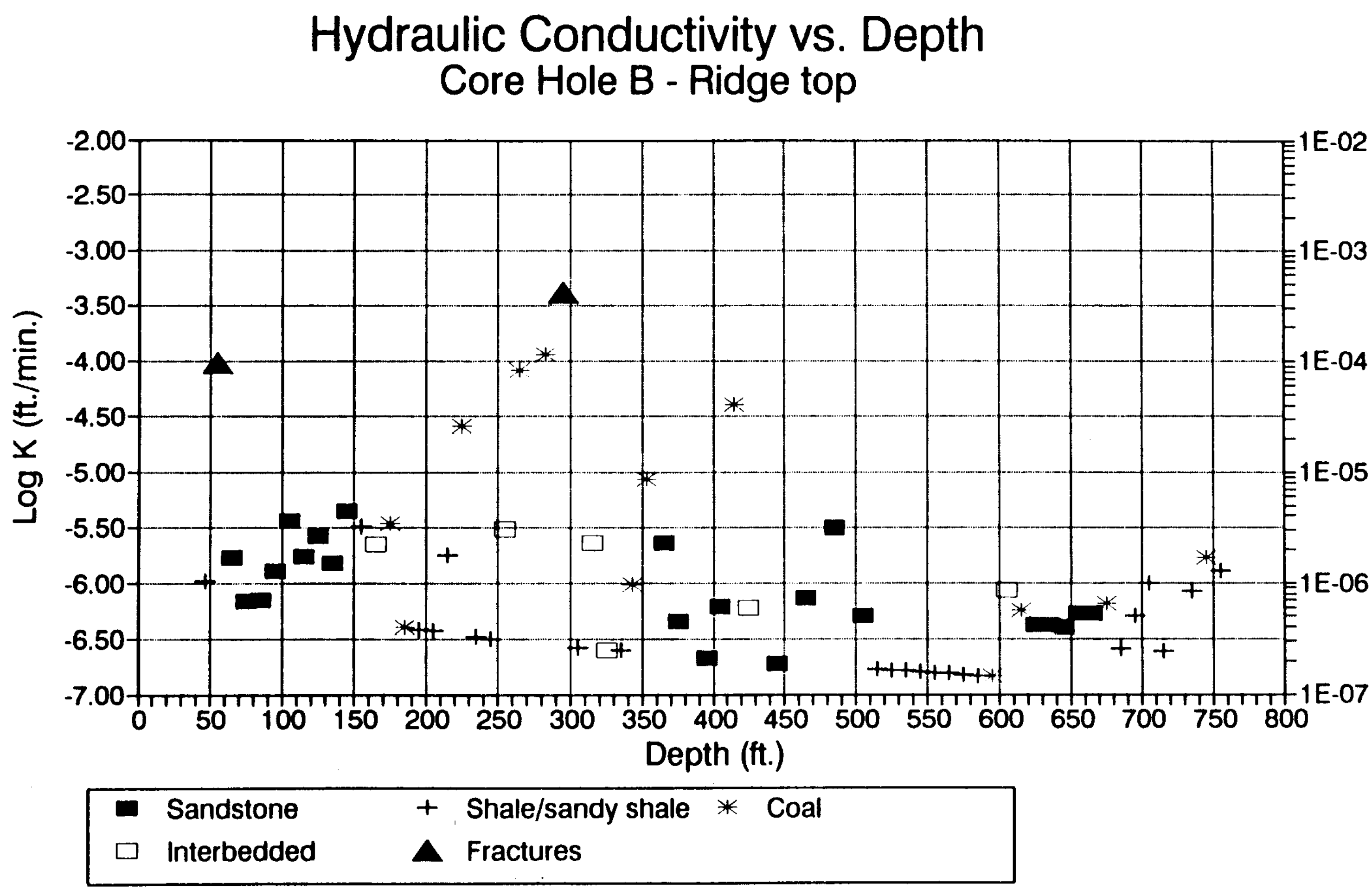


Figure 28. Distribution of hydraulic conductivity with depth for core hole A.



NOTE: Strata from 0 to 40 feet has been removed by mining.

Figure 29. Distribution of hydraulic conductivity with depth for core hole B.

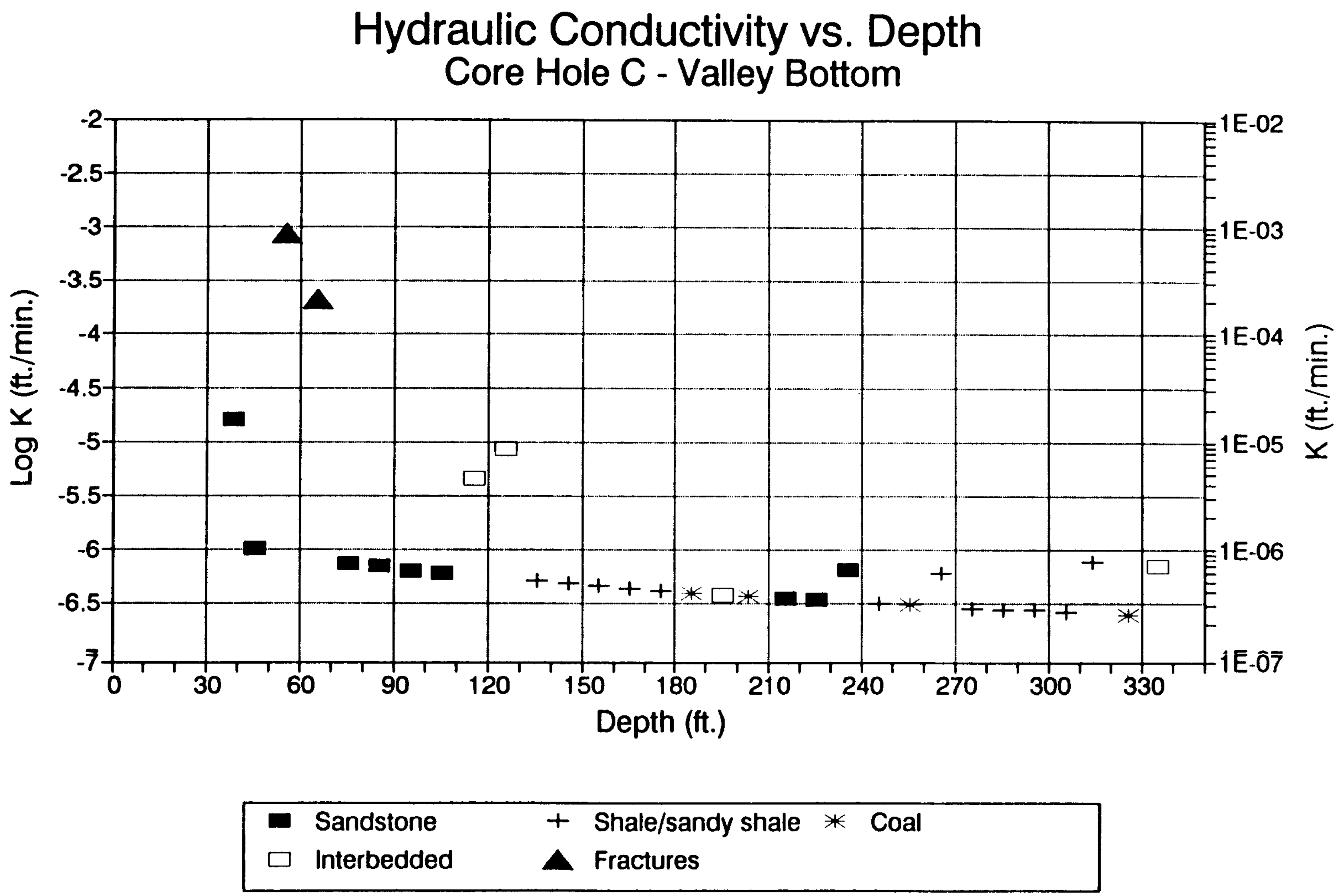


Figure 30. Distribution of hydraulic conductivity with depth for core hole C.

Table 9.—Summary of Calculated Hydraulic Conductivity Values for Core Holes in Edd Fork.

	Fracture	*Coal (Above Drainage)*	*Coal (Below Drainage)*	*Sandstone*	*Shale/sandy shale*
Number of samples	10		13	45	43
Maximum value (ft./min.)	4E-03	2E-04	8E-06	3E-05	6E-04
Minimum value (ft./min.)	2E-05	1E-06	2E-07	2E-07	3E-07
Average value (ft./min.)	4E-04	9E-06	8E-07	1E-06	4E-07
Median value (ft./min.)	9E-04	9E-06	6E-07	7E-07	4E-07

Figure 31 illustrates head relative to depth for the ridgetop piezometer nest. Water levels in the upper part of the ridge down to at least the Hazard Number 7 Coal (Piezometer 133A) plot along the line of zero pressure head, regardless of lithology of the piezometers. Head decreases nearly linearly with depth, indicating near vertical flow. Piezometer 13213, located just below this coal bed, also plots along this line, but the water level is probably controlled by a fracture zone near the middle of the interval. This fracture may or may not represent a composite head over the interval. With increasing depth, pressure head becomes a component of total head, and water levels rise above the top of the sandpacked interval. The static water level for the core hole at site B is also shown in Figure 32. Core hole water level is approximately equal to the elevation of the Hazard Number 7 coal zone that is apparently capable of draining water that flows into the open bore hole.

Figure 32 illustrates head and depth relationships in the valley-side piezometer nest. Water levels for all piezometers, except those in shallow fractures and piezometer Al B, rise above the level of the monitored zone. A loss of head with depth is observed in piezometers at this site.

Figure 33 shows head/depth relationships below the level of Edd Fork at nest C. The two upper piezometers are completed in the highly weathered zone less than 25 feet below the surface. These piezometers represent unconfined conditions. All piezometers at nest C, except for C4A (and C3A after rainfall events), have water levels that are below the level of Edd Fork and that are progressively deeper with increasing piezometer depth. The static water level of the open core hole is 10 feet below the level of the creek, indicating a loss of head with depth.

A similar head/depth analysis for three topographic settings was done by Harlow and LeCain (1992) in the southwest Virginia coal field. Data, obtained from short term pressure-injection tests, primarily in coal zones, show that downward gradients are generally less steep in the ridge and valley-side settings than in Edd Fork. Valley-bottom data indicate that head with depth is similar to the open core hole water levels signifying very slight downward gradients. Approximate core hole locations suggest that most core holes tested by Harlow and LeCain are closer to major streams than test holes in Edd Fork. One ridgetop hole and one valley-bottom hole, both located far from major streams, showed a greater head loss with depth, similar to core holes A and B. Low-conductivity strata are not represented in the data of Harlow and LeCain because of the long time required for heads to equilibrate within test intervals. Data from Edd Fork augments the Virginia data by providing head data for low-conductivity formations and for strata located above core-hole static water levels. Strata in the ridge at Edd Fork, above the core-hole static water level, show a one-foot-per-foot decrease in head with depth. Intervals tested by Harlow and LeCain (1992) were located only below core-hole water levels.

Figure 34, showing piezometer heads and interval depths for Edd Fork on one graph, displays the relationships among piezometers completed in the same stratigraphic intervals but in different topographic positions. Piezometers at the same elevation and those with, similar heads are tightly clustered, indicating that heads are nearly equal for intervals screened at similar elevations. There is no large pressure head component in the ridge interior driving ground-water flow toward the valley. Figure 35 shows head contours throughout the cross section assuming the system is homogeneous and isotropic. The cross section shows there is an overall loss of head with depth, but, it does not necessarily reflect the movement of ground water within the ridge. It ignores the effects of heterogeneity and anisotropy bedded strata and fractures on the flow system. These effects will be discussed later in this section.

Three-dimensional ground-water flow is not accurately reflected in a two-dimensional cross section. There is certainly a component of flow perpendicular to the cross section, parallel to Edd Fork. The cross section is oriented, however, nearly perpendicular to Beech Fork, the probable direction of regional ground-water flow.

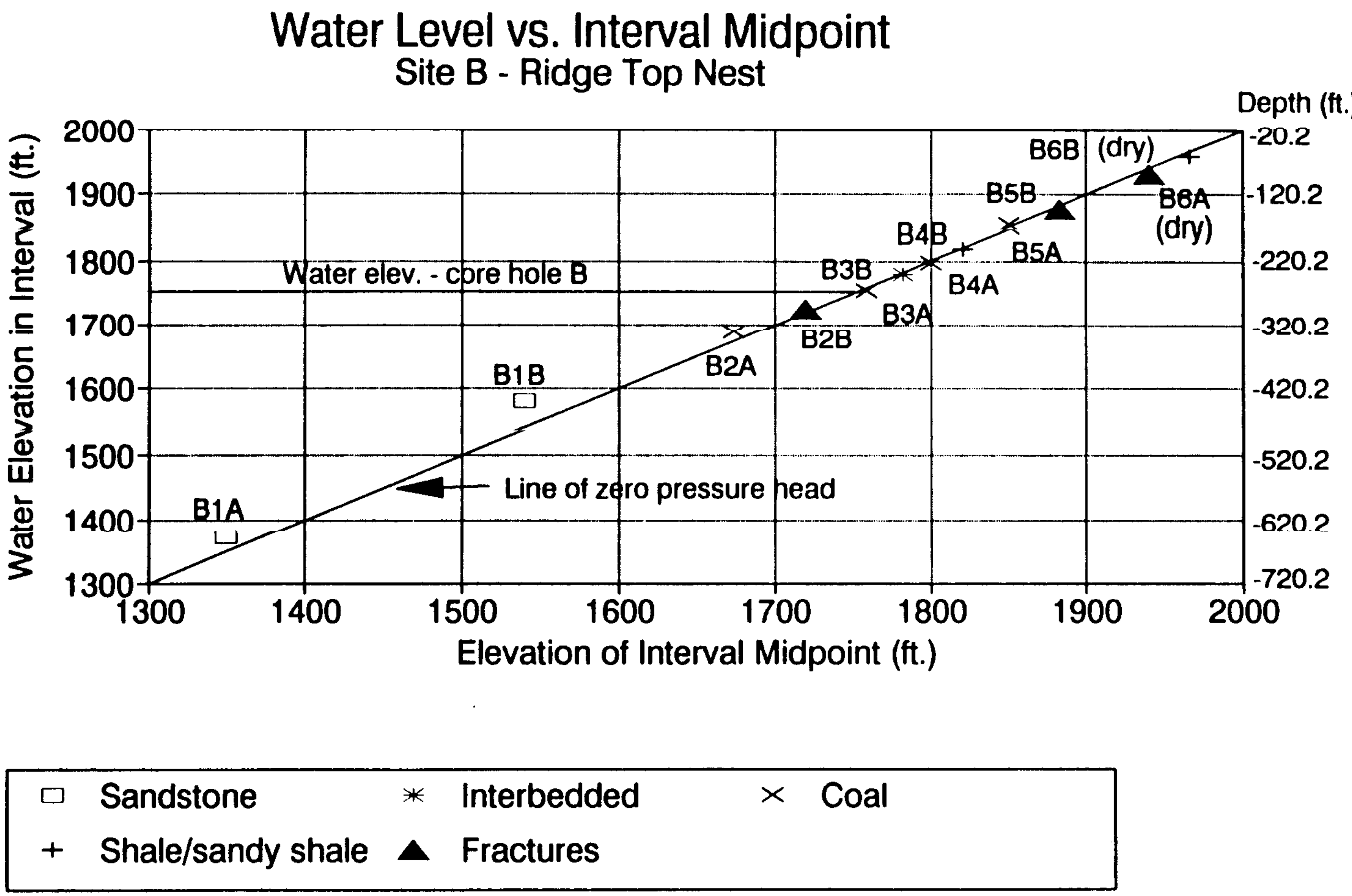


Figure 31. Water-level elevations plotted against piezometer midpoint elevation for piezometer nest B.

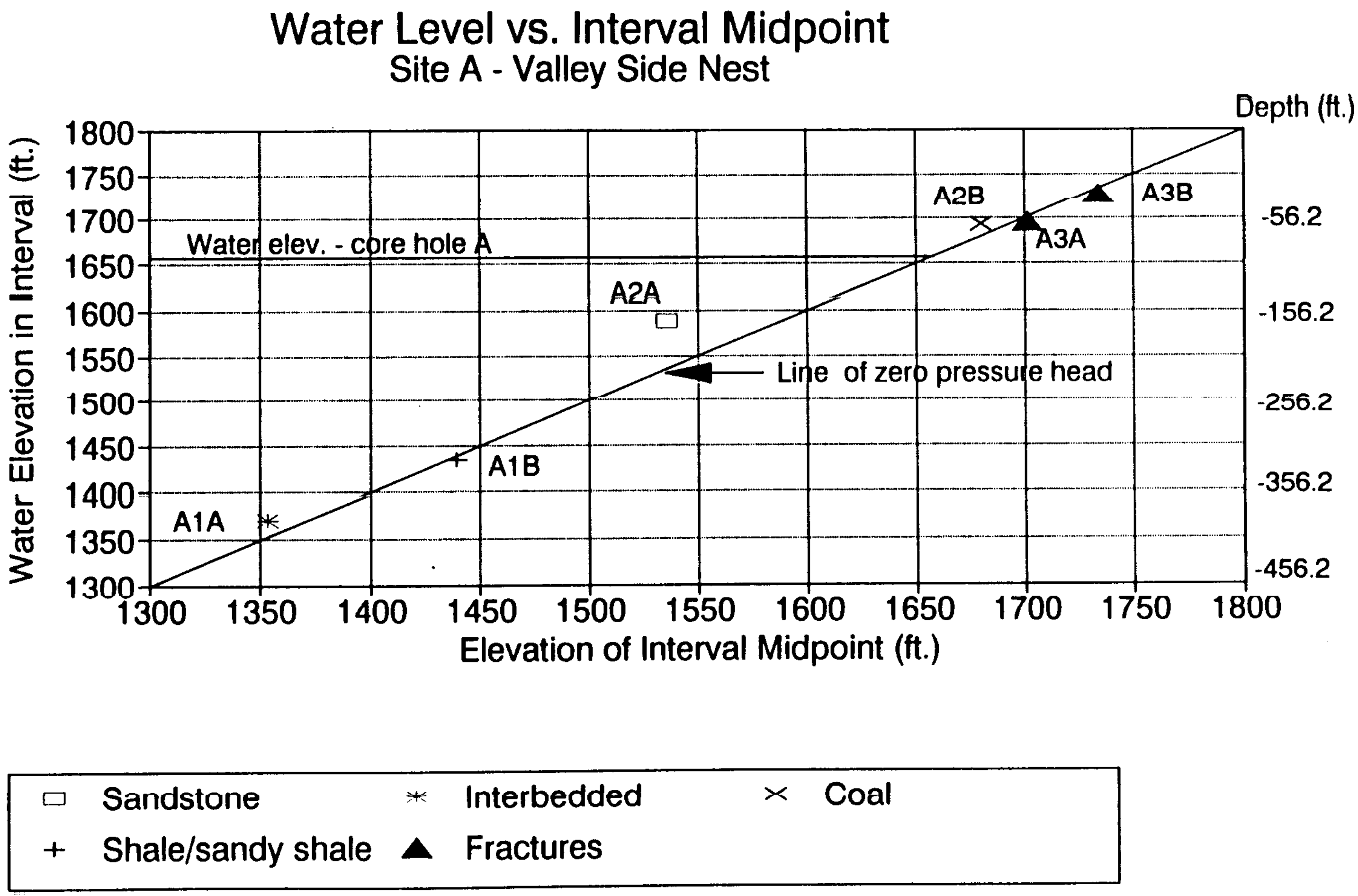


Figure 32. Water-level elevations plotted against piezometer midpoint elevation for piezometer nest A.

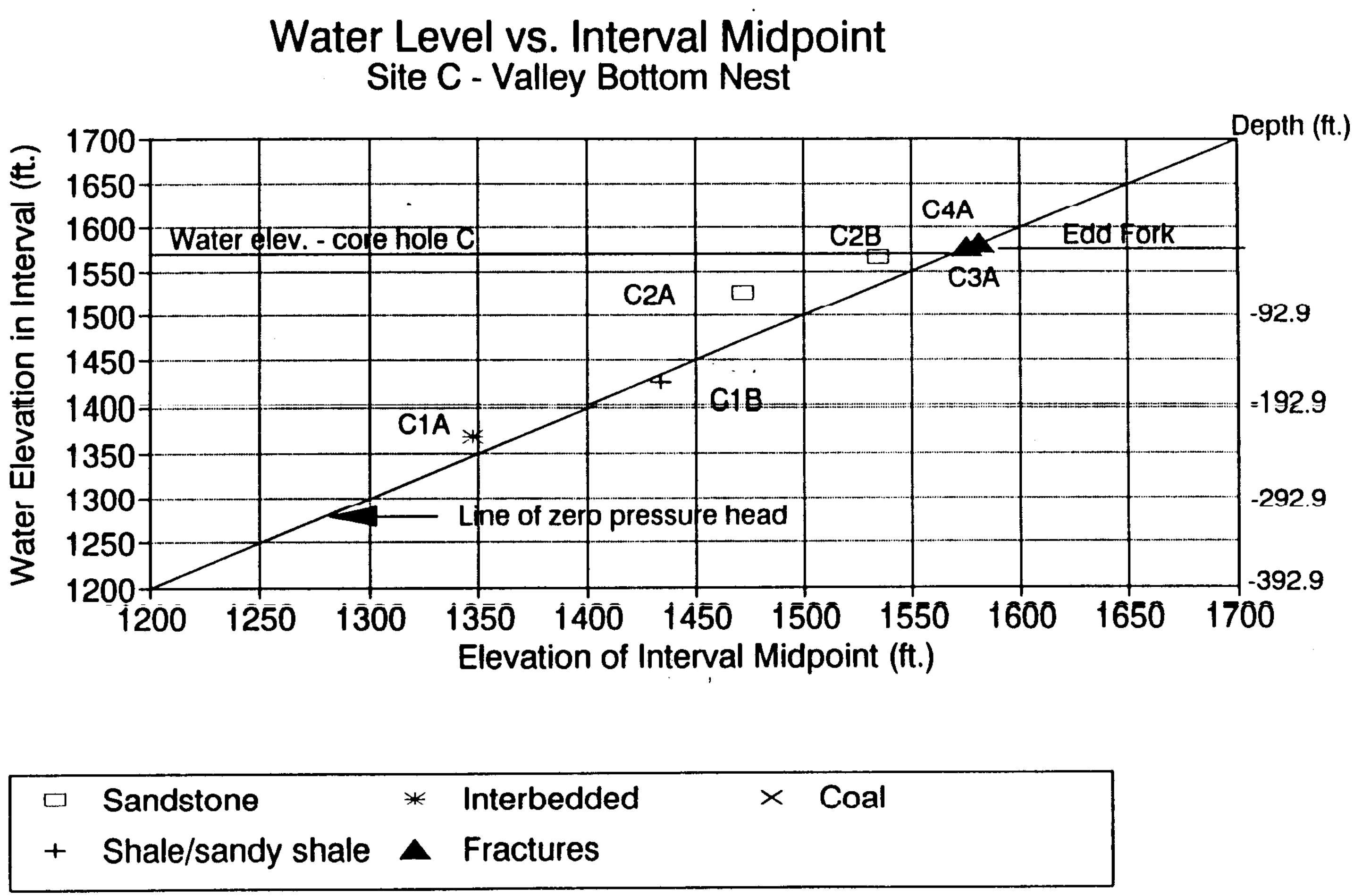


Figure 33. Water-level elevations plotted against piezometer midpoint elevatin for piezometer nest C.

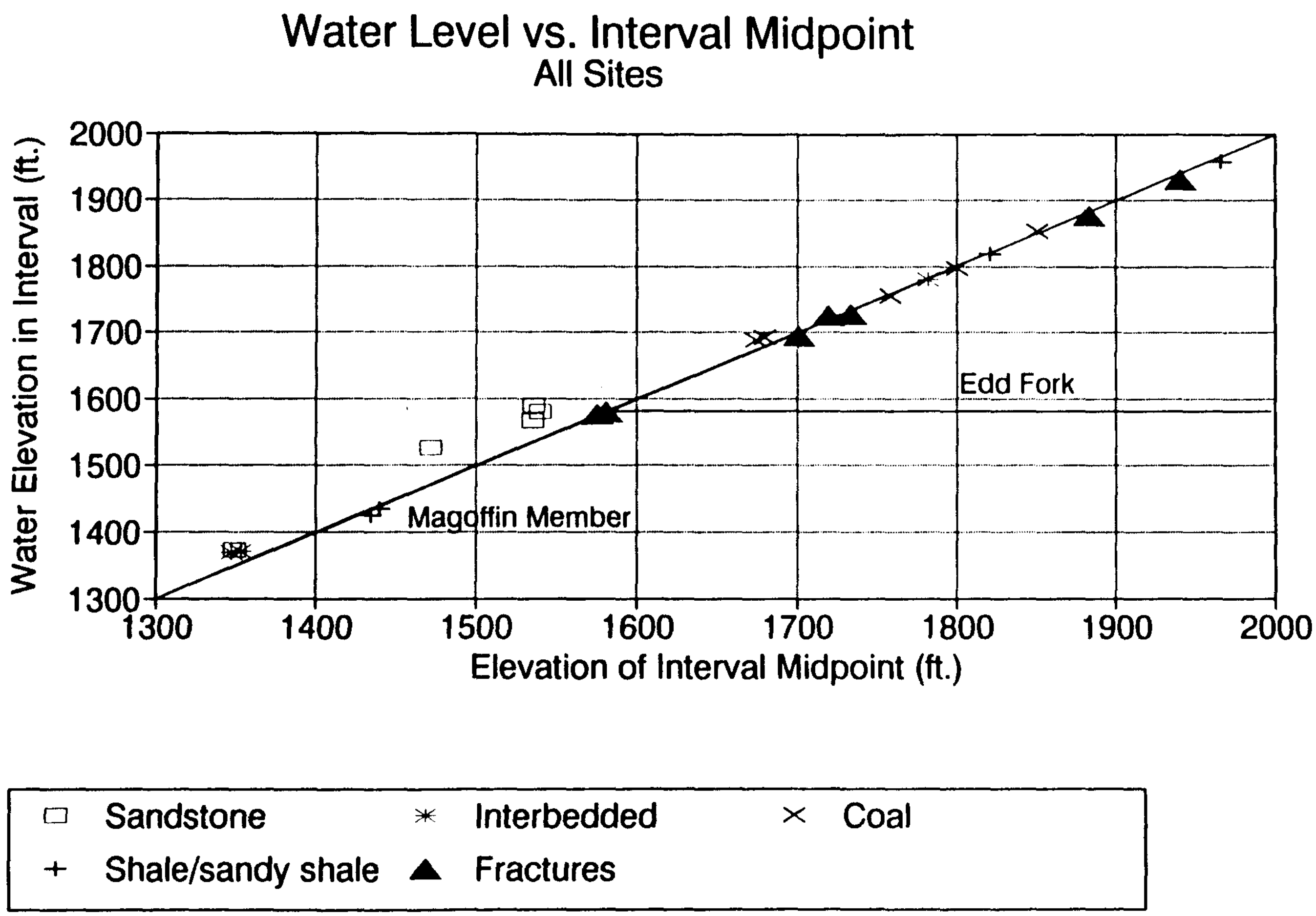


Figure 34. Water-level elevations plotted against piezometer midpoint elevations for all piezometers.

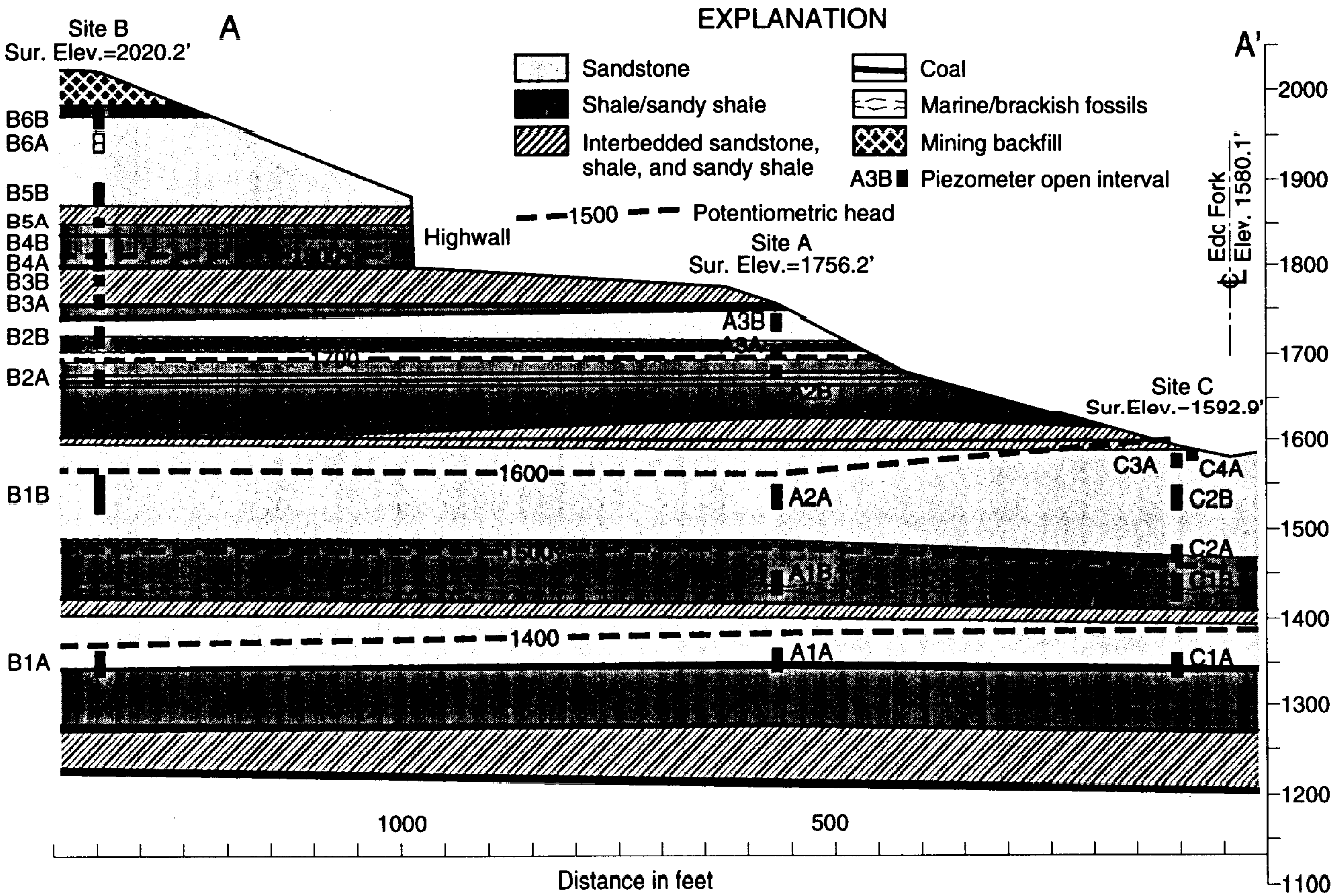


Figure 35. Water-level elevations for cross section A–A' assuming homogeneous and isotropic media (see Figure 21 for location).

Water Quality

Water-quality data are different between piezometers located in the strata above the Magoffin Member and piezometers located within or below the Magoffin Member. Bienkowski (1990) also identified a difference in water quality between domestic wells above and below the Magoffin. Water from piezometers above the Magoffin Member in Edd Fork primarily contains ions of sulfate, bicarbonate, calcium, and magnesium. Water from piezometers located in or below the Magoffin primarily contain sodium and bicarbonate ions and is noticeably deficient in calcium and magnesium. Wunsch (1992) attributes this change in water type in eastern Kentucky to cation exchange reactions along the flow path.

Ground-Water Zones

Hydraulic conductivity variations resulting from lithologic changes, fractures, and depth from the surface impart significant heterogeneity to the system. Water-level positions with respect to depth and lithology illustrate that the system does not function in a homogeneous manner. Water quality differences relative to the Magoffin Member suggest that the Magoffin may influence water quality.

It would be difficult and cost prohibitive to characterize individual heterogeneities within a flow system, and, any attempt to do so would probably only be valid for a site-specific area. Prior to understanding all individual components in a system, it is beneficial to identify zones that have similar characteristics and describe general behavior. From the general analysis, one may identify specific elements that exert the greatest influence on the ground-water flow system.

The ground-water flow system in Edd Fork may be divided into zones on the basis of water quality and hydraulic properties. Two zones are differentiated on the basis of water quality differences: (1) the above-Magoffin-Member zone and (2) the below-and-including-Magoffin-Member zone. Three additional zones may be differentiated on the basis of fracture occurrence and hydraulic properties. They are (3) the shallow-fracture zone, (4) the elevation-head zone, and (5) the pressure head zone. Figure 36 illustrates the location of these zones in Edd Fork. A description of these zones in the study area follows.

Zones Differentiated by Water Quality

The Magoffin Member, a widespread shale/sandy shale unit is present throughout much of the coal field. The thickness in the Edd Fork watershed is approximately 70 feet and the upper contact is located approximately 125 feet below the elevation of Edd Fork. Horizontal hydraulic conductivity values calculated from pressure-injection tests are in the 1 $X10^{-7}$ to $5x10^{-7}$ feet per-minute range, although there are several zones that did not take measurable quantities of water. Consequently, actual horizontal conductivity values may be smaller than estimated from pressure-injection tests.

Above-Magoffin-Member Zone

The above-Magoffin-Member zone overlies the Magoffin Member and contains typical coal-bearing strata dominated by sandstone. Several coal beds, from the Haddix Coal through the Hazard Number 8 Rider seam, are present above the Magoffin Member in the study area.

Analyses of water samples from nine piezometers, shown on the Piper diagram in Figure 37, illustrate representative water quality for strata located above the Magoffin Member. Maximum and minimum constituent values measured in piezometers; completed above the Magoffin Shale are included with the piper diagram. It is apparent from the maximum and minimum constituent values that water quality is variable over short vertical and horizontal distances in this zone. Water is generally calcium-magnesium-sulfate- bicarbonate type.

Below-and-Including-Magoffin-Member Zone

The below-and-including-Magoffin-Member zone, encompasses strata from the top of the Magoffin Member to the saline-fresh-water interface. The location of the interface is inferred at an elevation between 1,000 and 1,200 feet MSL (Hopkins, 1966) in the vicinity of the study area. This elevation is probably realistic for Beech Fork, where salty water is documented in wells drilled adjacent to Beech Fork, downstream of the study area. Analyses from three wells near Hyden, approximately 14 miles downstream of the site, reported chloride values of 232,128, and 940 mg/L, in wells that are 85,120, and 210 feet deep, respectively (drill logs for brine study on file at the Kentucky Geological Survey). The elevation of the interface below the Edd Fork watershed is not documented.

Water-quality data are available for two piezometers within the Magoffin Member and for three piezometers below the Magoffin Member. The Piper diagram (see Figure 37) contrasts the sodium-bicarbonate-type water characteristic of the below-and-including-Magoffin-Member zone, with the calcium-magnesium-sulfate-bicarbonate-type water found in the above-Magoffin-Member zone. Maximum and minimum constituent values below the Magoffin are also listed in Figure 37. In general, Water quality in this zone shows less variation

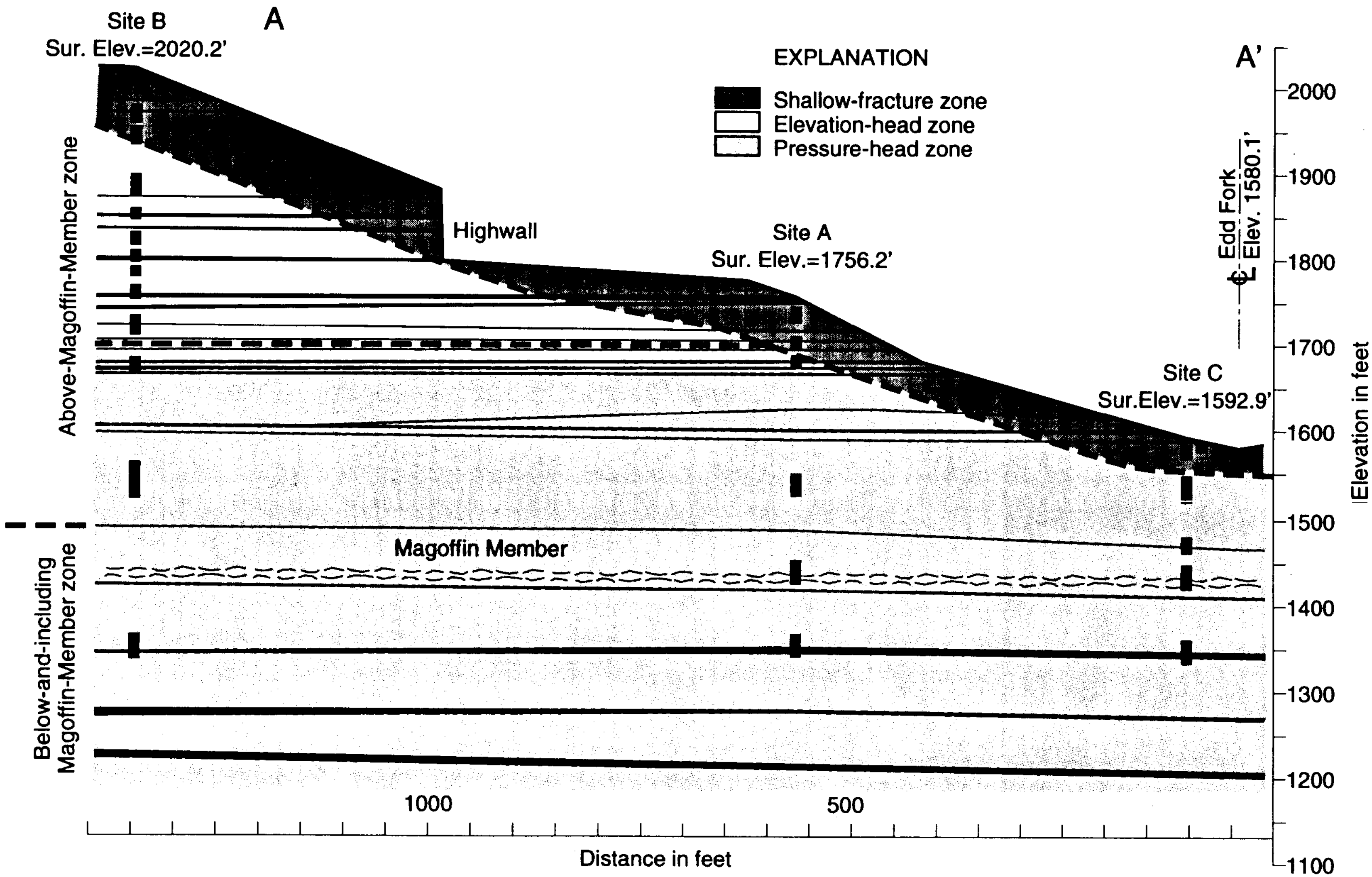


Figure 36. Ground-water zones in Edd Fork.

Ranges (mg/L)

	pH	TDS	Ca	Mg	Na	K	SO4	HCO3	Cl
ABOVE-MAGOFFIN									
max	7.46	1610	191	149	52.8	11.2	1050	193	4.59
min	5.73	30	2.30	1.58	0.914	1.82	9.59	11	1.00
BELOW & INCLUDING MAGOFFIN									
max	8.87	652	4.0	1.45	232	3.47	159	552	11.0
min	8.34	384	1.04	0.377	155	2.05	5.36	377	5.36

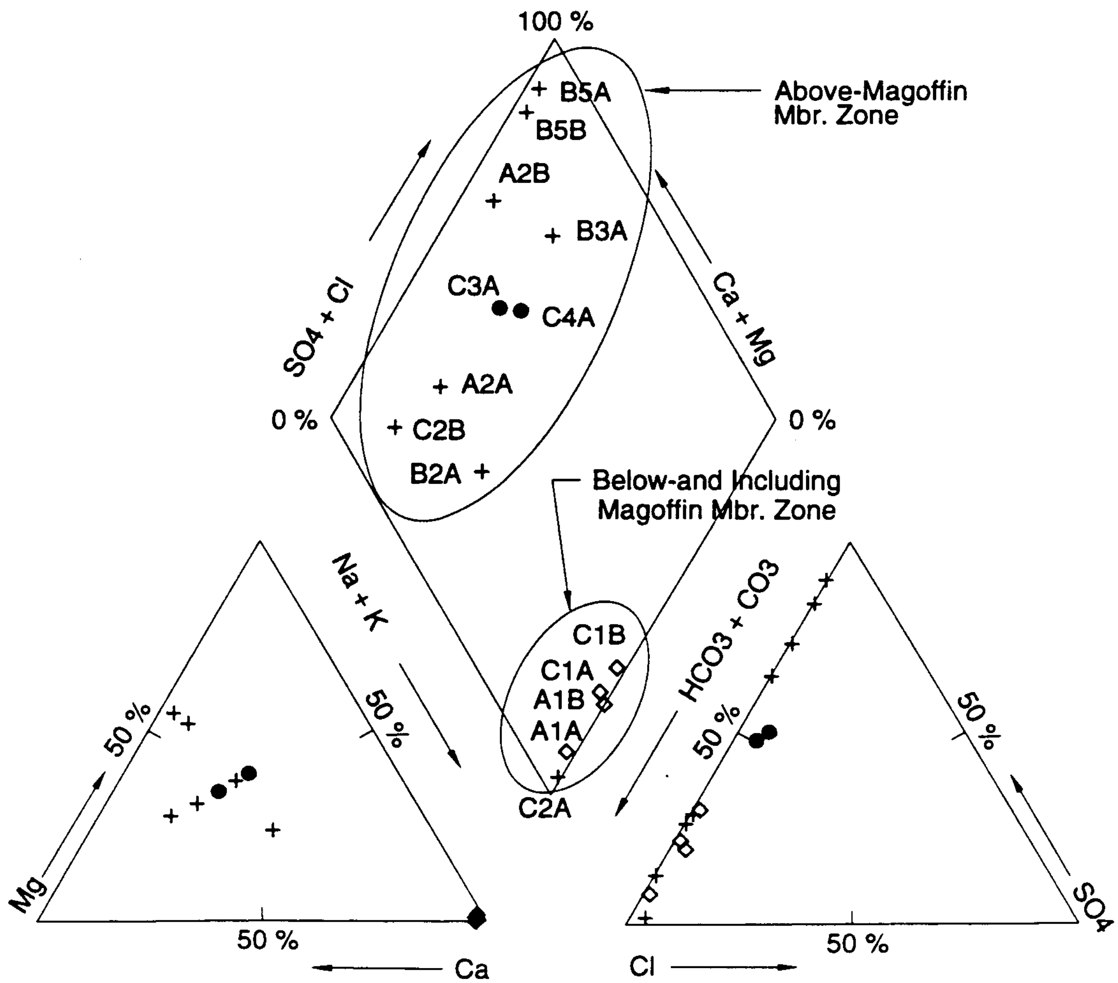


Figure 37. Piper diagram showing water quality in Edd Fork piezometers.

in composition and total dissolved constituents than water above the Magoffin.

Zones Based on Hydraulic Properties

Shallow-Fracture Zone

Fractures after ground-water flow by providing discrete conduits for water movement. The apparent effects of fractures diminish with depth; fracture frequency and openness probably decline.

Information on the depth of the shallow-fracture zone is available from core- and bore-hole data. Drill data show that the upper4O feet of the fracture zone on ridgetops surrounding Edd Fork has been removed by surface mining. Approximately 40 feet of mine spoil covers what is left of the shallow-fracture zone in these areas. The rock type immediately below the mine spoil is sandstone. A weathered and fractured zone is present at a depth between 50 and 60 feet. Drill cuttings from six piezometer bore holes at site B show a variable amount of weathering. Lateral discontinuity within tens of feet suggests that weathered zones may coincide with vertical joints.

The valley-side location shows numerous fractured and weathered zones extending to the base of a sandstone unit 60-feet below the surface. Fractures are mostly high-angle and weathered bedding planes. Drilling circulation was lost in a high-angle fracture at 30 feet while coring. An open fracture with an aperture of approximately

Fractures at site C, adjacent to Edd Fork, extend to a depth of approximately 60 feet. The upper 30 feet is highly weathered. Because the shallow-fracture zone is defined on the basis of hydraulic characteristics, the lower boundary of this zone may not extend into the deeper fractures at 50 to 60 feet. Water-level data, discussed later in this section, indicate that deeper fractures may be associated with regional flow. The lower boundary of the shallow-fracture zone is transitional and depths are not absolute.

Shallow fractures less than 60 feet deep, are shown by pressure-injection data to be the most conductive zones in the study area. Eight fractured test intervals have equivalent-porous-media conductivities that range from $4x10^{-3}$ feet per minute to $2x10^{-5}$ feet per minute (data in Appendix B). The median value, $9x10^{-4}$ feet per minute, is approximately 1,000 times greater than the median conductivity calculated for unfractured sandstone and shale (see Table 9). The fracture-dependent flow in this system is apparent from the variation in conductivities in adjacent test intervals. For example, in core hole A, the test interval from 37 to 47 feet has a calculated conductivity which is approximately 1,000 times less than the fractured sandstone in the overlying interval.

The presence of numerous shallow fractures created drilling problems at site A and resulted in a sustained loss of drilling fluid circulation until the fracture zone could be cased. Drill cuttings were apparently forced into open fractures. Cuttings flowed back into the hole on several occasions at the end of a drill run but no cuttings were detected in adjacent boreholes. A trace of air movement was detected in core hole A while drilling bore hole A2. Interconnection between adjacent bore holes may result from drilling along strike of near-vertical fractures.

One piezometer, B6B, installed in the shallow-fracture zone in the ridgetop, has a total depth of 64 feet. Although this piezometer is shallow, no fractures were observed in this interval during the drilling of bore hole B6. This piezometer never contained water during the monitoring period even though the bore hole appeared to produce minor amounts of water after drilling.

Ground-water movement and storage in the shallow fracture zone along the ridge has the potential to be impacted by past surface mining. The natural surface material has been replaced by approximately 40 feet of compacted overburden that may promote runoff rather than infiltration; however, infiltration studies in this material have not been conducted. Very little water was observed in the ridgetop overburden during drilling. Active mining may have also plugged fractures near the surface, resulting in less recharge to the fracture zone. Water that does find its way into the overburden may be stored and released slowly into the underlying rock.

Two piezometers, AM and A3B, are located in fractured sandstone at the valley-side nest. Two water-bearing fractures, encountered during the drilling of bore hole A3 were selected for monitoring. Piezometer A3B is the shallower of the two piezometers, having a total depth of 33.5 feet. Water does not accumulate in this piezometer. *A* perennial seep, located downslope of nest *A* at an elevation corresponding to piezometer *AM,* indicates that water flows through this sandstone. Piezometer *AM* has a total depth of 65.7 feet. The hydrograph of piezometer *AM* (Figure 38) is typical for a shallow-fracture zone piezometer; water accumulates in response to rainfall. No more than a foot of water has been measured in this piezometer; however, higher water levels having a very short duration may occur.

Piezometer nest *A* is located on undisturbed ground; however, it is situated below an unbackfilled contour surface-mine bench. Past mining may impact the shal-

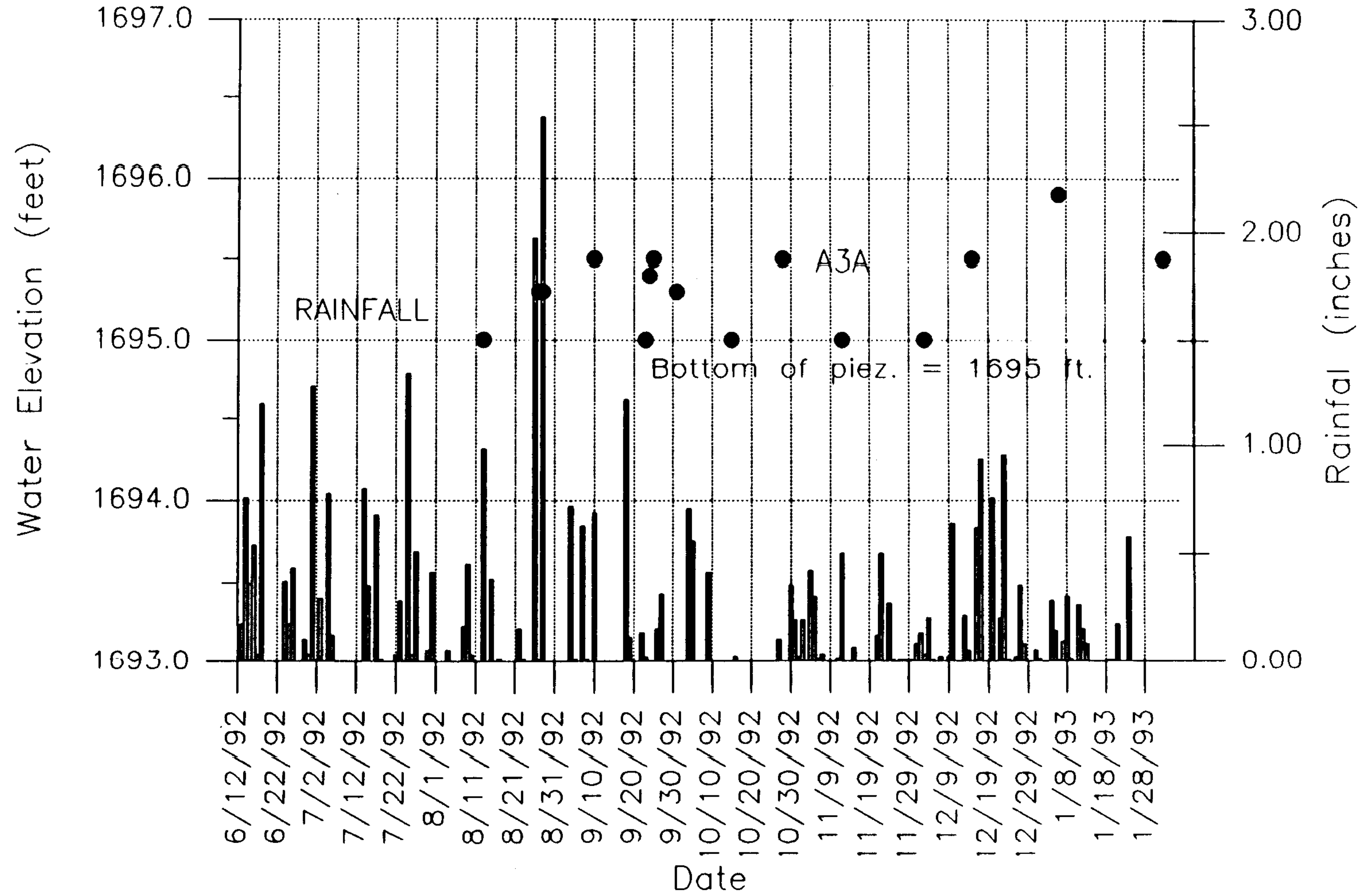


Figure 38. Rainfall data and hydrograph for piezometer A3A.

low-fracture zone at this location. Relatively impermeable underclay allows water discharging from the Hazard Number 8 Coal, at the base of the highwall, to flow across the bench, rather than infiltrate into the groundwater system. Some of this water probably reinfiltrates just beyond the edge of the bench, but some of this flow discharges as surface water directly into Edd Fork. The bench may create a depressed water surface in the fracture zone. A lowering of ground-water levels in the surface-fracture zone was observed at a study area in Knott County, Kentucky (Kipp and Dinger, 1987) after contour mining commenced above a piezometer nest. Water levels rebounded to pre-mining levels after backfilling was completed.

Two shallow piezometers, C3A and C4A, located in the shallow-fracture zone adjacent to Edd Fork, contain several feet of water and fluctuate directly with precipitation (Figure 39). These wells show the greatest range in water levels of all piezometers on the site; fluctuations as much as 6 feet have been measured in piezometer C3A. Piezometer C4A is 17 feet deep and has water levels that range from a few tenths of a foot to several feet above the level of Edd Fork. The water level in this well reflects the water table. Piezometer C3A, completed at the base of the highly weathered zone, has a total depth of 24 feet. Water levels in this piezometer are generally three feet below the level of Edd Fork.

A 4.5-inch rain in late August caused a water level increase in both piezometers. Piezometer C4A showed a measured rise of 1.5 feet. The deeper piezometer, C3A, showed a measured increase of 5 feet above the normal static water level. The water level in the deep piezometer rose to approximately the same elevation as in the shallow piezometer. The total water level rise is unknown because water levels were not continuously recorded.

Very little water quality data is available for the shallow-fracture zone at the Edd Fork site. Water from C3A and C4A is very low in dissolved constituents, 30 and 52 mg/L TDS respectively, indicating either rapid flow of precipitation through the system or flow through highly weathered rocks that have few reacting surfaces. Major ions are present in nearly equal percentages (see Table 8).

Elevation-Head Zone

The elevation-head zone lies below the shallow-fracture zone and extends into the sandstone unit below the Hazard Number 7 Coal. The base of the elevation-head zone is transitional, but, in general, is located at the approximate elevation where pressure head is a part of the total head. The location of the bottom boundary is determined in part by the position of the Hazard Number 8 coal seam. Vertical distance above drainage may also be a factor. Maximum depth to the top of this zone from the ridge top is approximately 300 feet (see Figure 36).

The elevation-head zone in Edd Fork contains three coal beds, the Hazard Number 8 Rider through Hazard Number 7 Coal seam, that are sandwiched between less conductive strata. Coal-bearing intervals in core hole B have conductivities that range from $1x10^{-4}$ feet per minute to $4xl0^{-7}$ feet per minute. The lowest conductivities were calculated for two thin splits of the Hazard Number 8 Rider coal. Coal seams having a thickness of at least 1.9 feet have equivalent-porous-media hydraulic conductivities that range from $1X10^{-4}$ to $3x10^{-5}$ feet per minute. These values are at least ten times greater than the horizontal conductivity of surrounding sandstone and shale.

Even though this zone lies below the shallow-f racture zone, open fractures are not uncommon in the elevation-head zone. The distribution of fractures, however, is not well-known. In coal-bearing rocks of Pennsylvania, Nickelson and Hough (1967) found that adjacent lithologies show different joint patterns and that joints in underclays are absent or poorly developed. The distribution and interconnection of fractures among lithologic units undoubtedly play an important role in vertical ground-water flow in this zone.

Possible fracture interconnection was noted during and after well construction. Piezometer B2B is completed in a fracture zone at the same depth as a fracture interval logged in core hole B. Bentonite slurry, pumped into holes B1 and B2, dropped to a level of 30 feet below the top of the hole during well construction. Slurry was later recovered from piezometer B2 during purging and sampling. Bentonite either migrated laterally from bore hole B1 to bore hole B2 along fractures or else slurry from bore hole B2 bypassed the bentonite seal (probably along a vertical fracture) and entered the piezometer below the seal.

Eight piezometers, B2B, B3A, B3B, B4A, B4B, B5A, B5B, and B6A are located in the elevation-head zone. Table 10 summarizes hydraulic characteristics of these piezometers. Piezometers B5B and B6A are in the ridge-capping sandstone unit. Piezometers B3A, B4A, and B5A encompass the upper split of the Hazard Number 7 Coal, the Hazard Number 8 Coal, and the upper split of the Hazard Number 8 Rider Coal, respectively. The remaining three piezometers, B2B, B3B, and B4B, are in strata between coals.

The lithology of monitored intervals and the presence of fractures affect the response of piezometers. Two piezometers are located in the ridge-capping sand

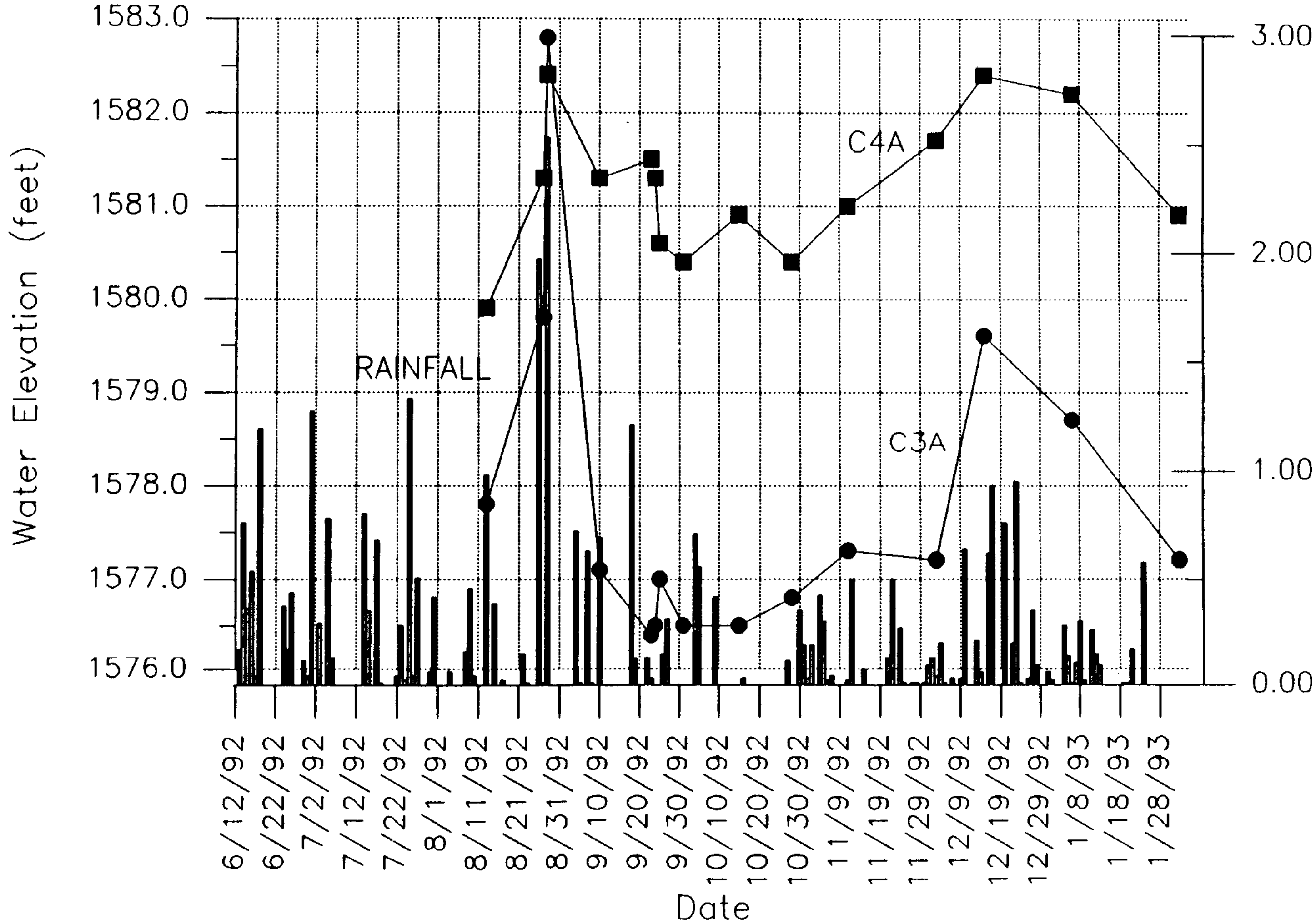


Figure 39. Rainfall data and hydrograph for piezometers C3A and C4A.

stone. Piezometer B6A, located in a fractured sandstone interval, remained dry throughout the study period even though bore hole B6 made approximately 025 gallons of water per minute during drilling. Fractures my allow water to drain to a lower level, preventing water accumulation in the piezometer. Piezometer B5B bottoms at the base of the ridge-capping sandstone. Bore hole B5 showed significant weathering at this depth that was not observed in the adjacent core hole. The hydrograph for piezometer B5B is shown in Figure 40. Water levels show a delayed response to rainfall, but generally rise during wet periods and decline during dry periods. Piezometer B5B consistently contains about 4 feet of water, and produces enough water to bail three well volumes and collect samples, indicating that fractures are supplying water to this piezometer.

The water table in the ridge is probably located within this sandstone unit at a depth somewhere between piezometers B6A and B5B. The water surface in piezometer B5B does not necessarily represent the water table; water may be draining to a lower head via fractures encountered in the open interval.

Piezometers B3B and B4B are completed primarily in sandy shale. Hydrographs are shown in Figures 41 and 42. It is difficult to determine, given the data available, whether or not these piezometers have reached equilibrium; however, these piezometers are characteristic of the piezometers in low-conductivity rocks. A discussion of piezometers located in tight formations is included in a later section.

Piezometer B2B is open to sandstone and sandy shale; however, an open fracture is present within the monitored interval at a depth of 295 feet. The water level in this piezometer is located at the elevation of this fracture and is seasonally constant, varying only a few tenths of a foot (Figure 43). Although this piezometer is deep, the fracture produces water and head re-equilibrates within hours of bailing.

Piezometers B3A, B4A, and B5A are completed in coal beds. All three seams apparently transmit water and re-equilibrate within hours after an external stress. Water levels for these piezometers are shown in Figures 44, 45, and 46.

Water levels in piezometers open to both coal and rock are controlled by the most conductive zone. Piezometer B5A is located in a coal seam that does not have a conductivity significantly greater than surrounding strata. The water level in this piezometer stands four feet above the top of the coal seam, indicating that the coal cannot drain water that cascades into the well bore from the overlying sand-packed interval. Piezometer B4A is located in the Hazard Number 8, the thickest coal seam on the site. The static water level in this piezometer is about two feet below the top of the coal seam. This coal effectively drains water that enters the well bore from the overlying sand pack. Because this piezometer monitors the entire coal interval, a water level located below the top boundary of the coal indicates that a free water surface exists in this piezometer. There may or may not be a free-water surface within this coal throughout the ridge, depending on the amount of vertical flow entering the coal seam. Piezometer B3A is the deepest coal-seam piezometer in the elevation-head zone. The water level in this piezometer coincides with the upper boundary of the coal seam, indicating that the coal seam is in equilibrium with water entering the piezometer from non-coal strata.

Table 10.—Summary of Piezometric Data for the Elevation-Head Zone.

Piez. No.	*TD (ft.)*	*Approx. Static Water Level (ft.)*	*Approx. Static Water Elev. (ft.)*	*Normal Water Level Fluct. (ft.)*	*Distance Below Sand Pack (ft.)*	*Time to Equilibrate*	*Monitored Interval*
B5A	179.0	169.5	1,853.5	< 1	3.0	min.–hrs.	coal
B4A	227.0	224.5	1,797.0	2	10.5	min.–hrs.	coal
B3A	269.0	266.0	1,755.5	< 1	11.0	min.–hrs.	coal
B5B	149.5	146.5	1,876.5	< 1	19.5	min.–hrs.	fracture
B4B*	205.0	201.5	1,820.0	< 1	9.0	months	rock
B3B*	243.5	238.0	1,783.5	1	5.0	months	rock
B2B	311.0	295.5	1,725.5	1	6.0	min.–hrs.	fracture
B6A	92.0	Dry	—	—	—	—	rock

* Values are estimates based on information to date.

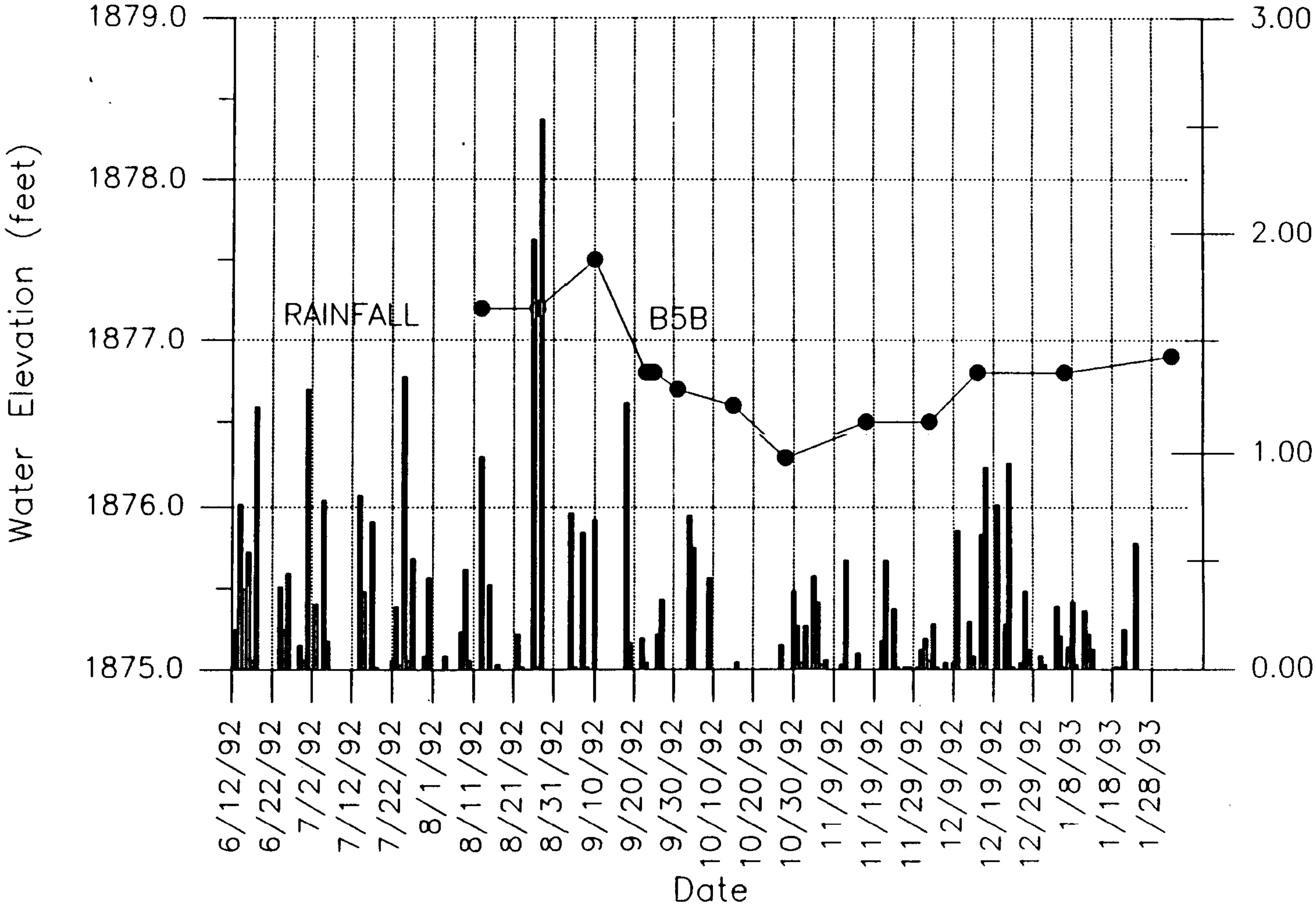


Figure 40. Rainfall data and hydrograph for piezometer B5B.

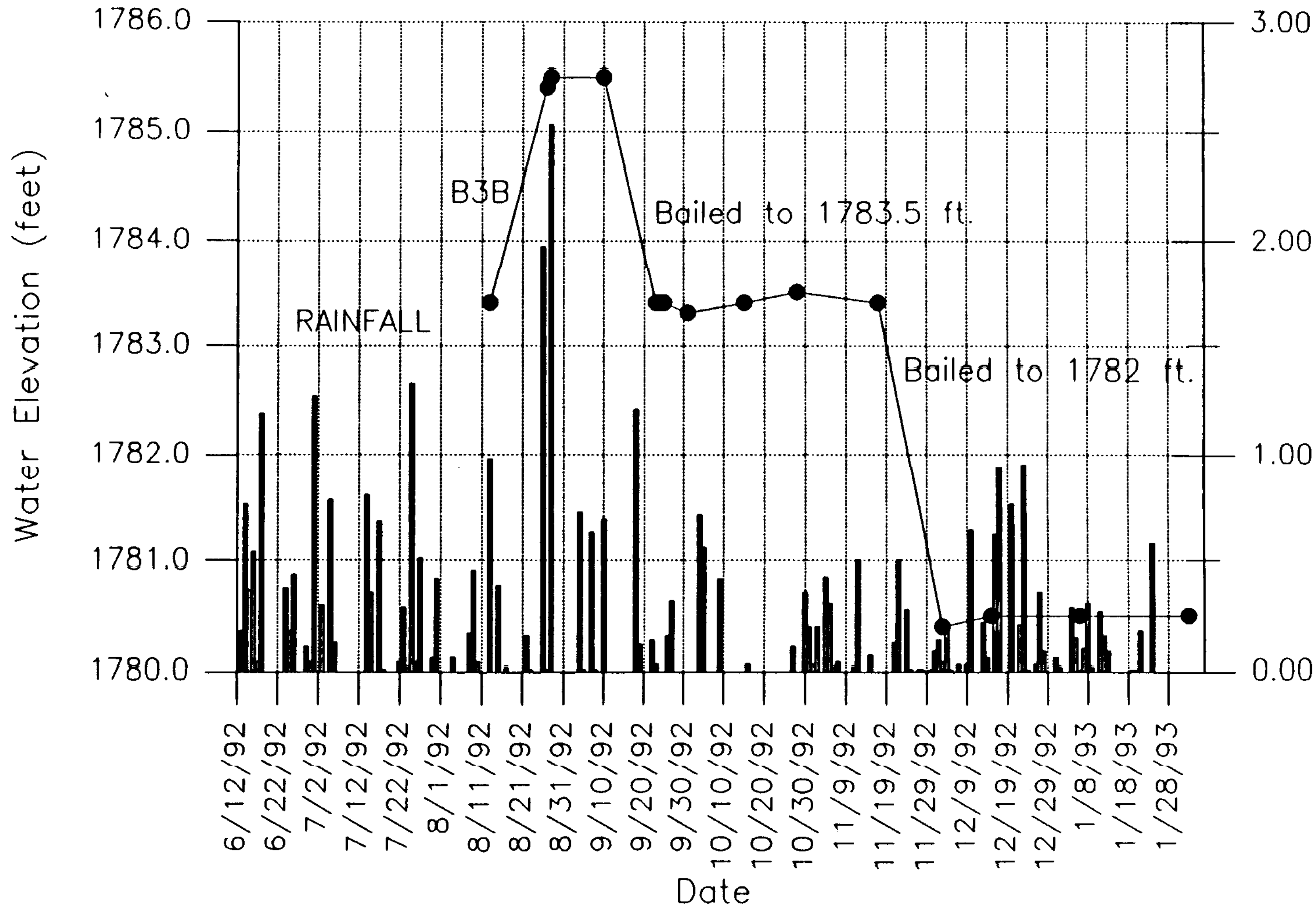


Figure 41. Rainfall data and hydrograph for piezometer B3B.

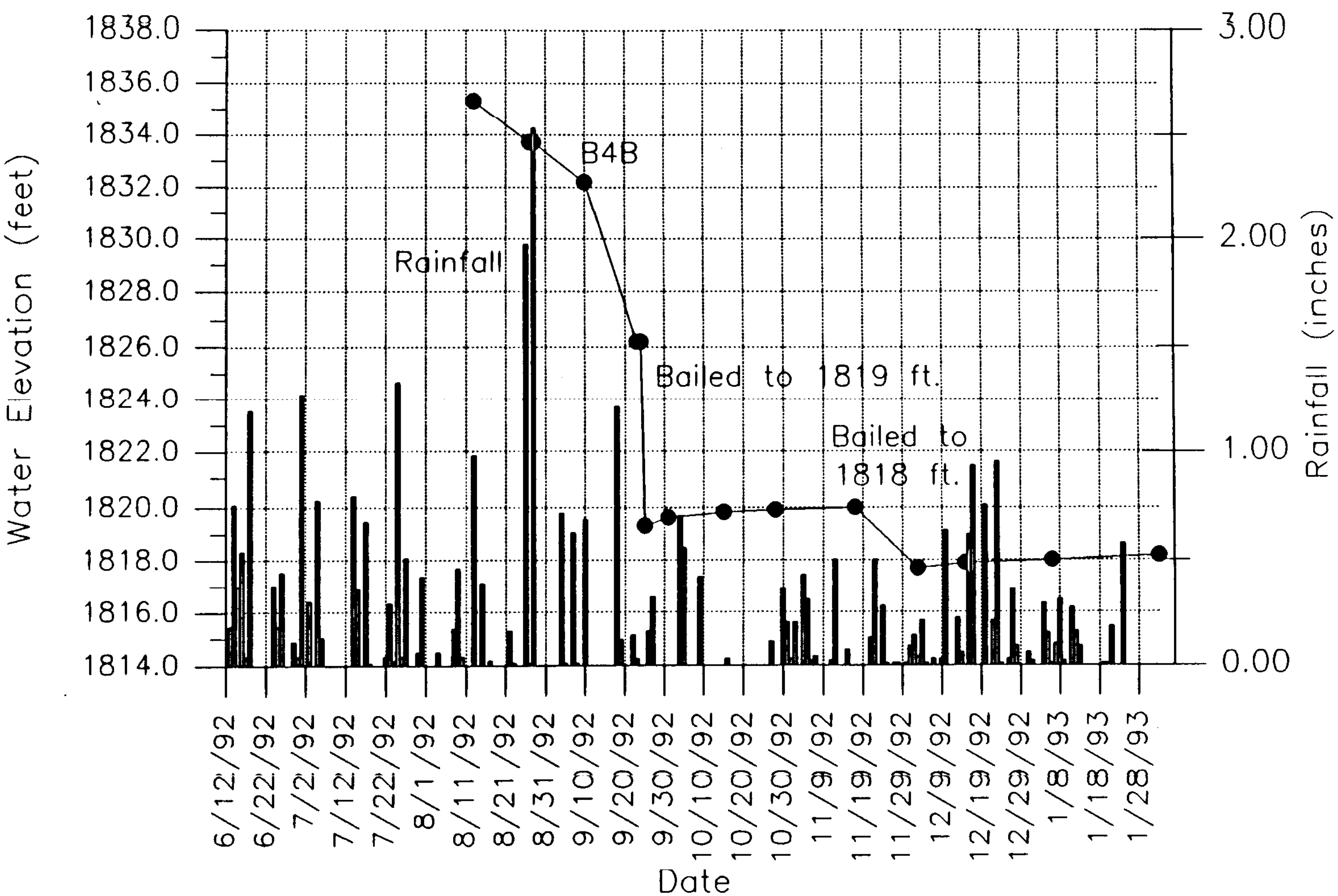


Figure 42. Rainfall data and hydrograph for piezometer B4B.

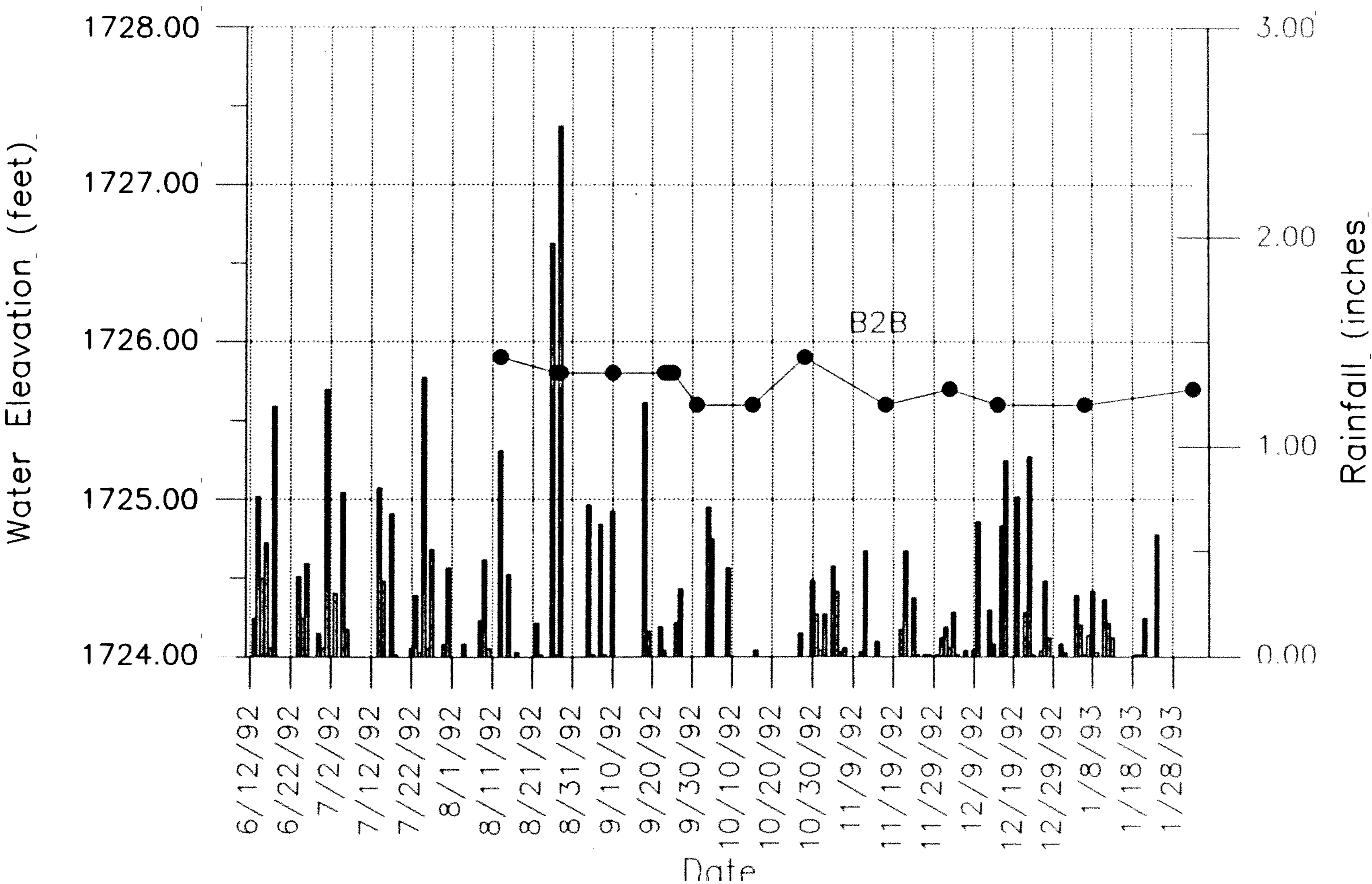


Figure 43. Rainfall data and hydrograph for piezometer B2B.

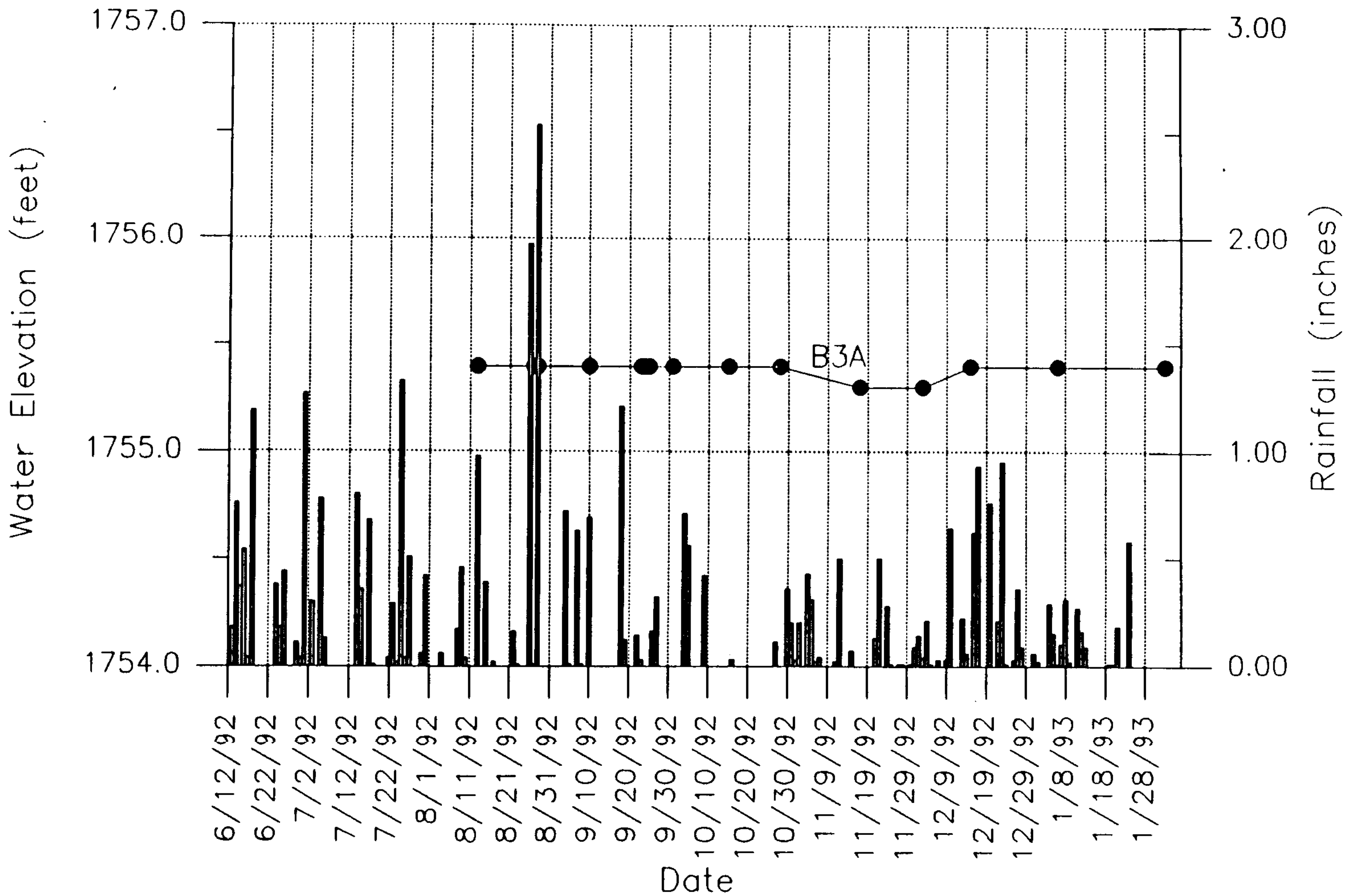


Figure 44. Rainfall data and hydrograph for piezometer B3A.

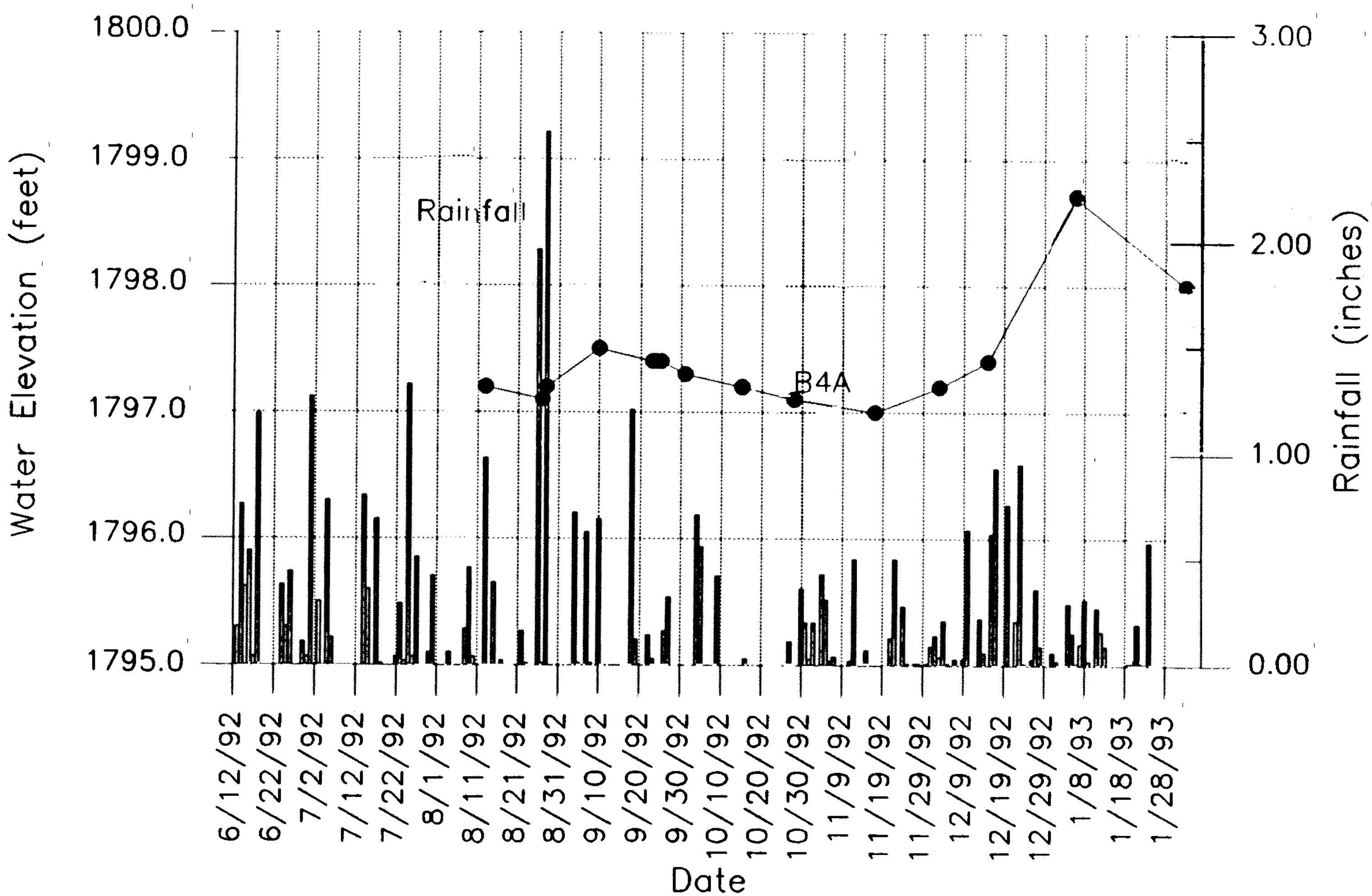


Figure 45. Rainfall data and hydrograph for piezometer B4A.

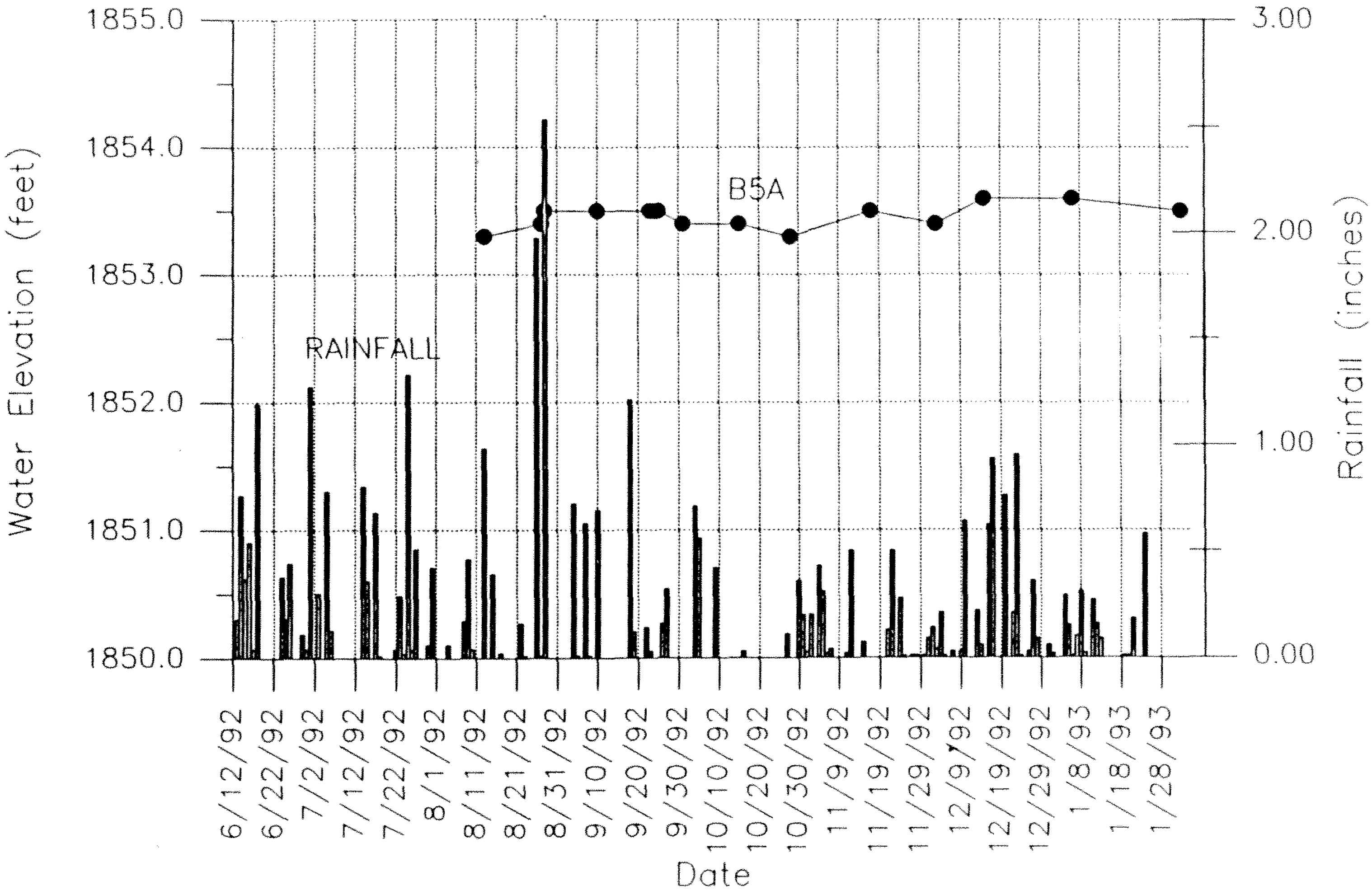


Figure 46. Rainfall data and hydrograph for piezometer B5A.

Coal seams affect head in overlying strata. Because coals are more conductive than other strata, head throughout the elevation-head zone is dissipated by coal beds. As a result, piezometers in this zone have water levels that are near the midpoint of the monitored interval. Piezometer B4B has a head that is two feet below the interval midpoint. It is located above the Hazard Number 8 Coal that contains a free-water surface over at least a part of the area. Piezometer B3B has a water level very close to the interval midpoint. It is located above the Hazard Number 7 split, a coal seam that maintains a water level at or near the top of the coal. Strata in the elevation-head zone are mostly saturate .

Water levels within screened intervals in piezometers above coals do not represent free-water surfaces, rather, water levels represent the average potentiometric surface over the interval. Because piezometers in coal seams completely encompass the monitored interval, a static head within the coal seam indicates that the coal bed contains a free-water surface.

Pressure-Head Zone

Ground-water beneath the elevation-head and shallow-fracture zones generally has pressure head as a component of total head. Widespread confining units, depending on topographic position, may be an exception. The pressure-head zone is projected to extend to the base of the fresh water system at the fresh-saline water interface. The fresh-saline boundary is the limit of fresh ground-water flow; thus, the interface makes a convenient lower boundary for this investigation. It is recognized that saline ground water has a pressure head component.

Eleven piezometers are located in the pressure-head zone. Two piezometers are in the Hazard Coal zone, three piezometers are completed in a sandstone unit above the Magoffin Member, one is located at the upper contact of the Magoffin Member, two are within the Magoff in Member, and three are below the Magoffin Member.

Table 11 shows the wide variation in the time required for piezometers in this zone to equilibrate after an imposed stress. Equilibration times range from nearly instantaneous in fractured intervals to many months in strata below drainage or deep within the ridge core. Coal beds in this zone required a longer time to reach equilibrium than the shallower coal beds. All piezometers were allowed to equilibrate naturally for two months following installation, then were pumped or bailed to evacuate standing water.

Piezometers at similar elevations in different topographic positions have different water-level responses. Figure 47 shows hydrographs for piezometers in the Hazard Coal zone. Water levels in piezometer A2B, located near the valley wall, generally fluctuate with precipitation. The storm in late August produced a 0.3 foot rise in water level in this piezometer. Water levels fell in late October and recovered during the end of the year as rainfall increased. Piezometer B2A is located in the ridge core. Water levels in this piezometer respond more subtly to pressure changes that are transmitted through the coal bed. The hydrograph indicates a consistently higher head in A2B, the shallow piezometer, and may reflect recharge conditions. The drop in water level in piezometer B2A in November reflects purging and gradual recovery.

Table 11.—Summary of Piezometric Data for the Pressure-Head Zone.

Piez. No.	*TD (ft.)*	*Approx. Static Water Level (ft.)*	*Approx. Static Water Elev. (ft.)*	*Normal Water Level Fluct. (ft.)*	*Distance Below Sand Pack (ft.)***	*Time to Equilibrate*	*Monitored Interval*
B2A	354.5	5.0	1,691.0	1	7.0	month	coal
A2B	85.5	66.5	1,692.5	1	5.0	days	coal
B1B*	492.0	438.0	1,583.0	?	23.0	> 6 mos.	sandstone
A2A	233.5	170.0	1,589.0	1	40.0	days	fracture
C2B	70.5	28.0	1,566.0	1	18.0	min.	fracture
C2A	130.5	68.0	1,526.0	1	45.0	min.	contact
A1B*	328.0	323.0	1,435.0	?	(–18)	> 6 mos.	Magoffin
C1B*	173.5	170.0	1,425.0	?	(–24)	> 6 mos.	Magoffin
B1A*	684.0	648.0	1,374.0	?	10.0	> 6 mos.	below Mag.
A1A	415.0	385.5	1,372.0	1	5.0	month	below Mag.
C1A	260.0	226.0	1,369.0	1	8.0	month	below Mag.

* Values are estimates based on information to date.
** Negative number means water level below top of sandpack.

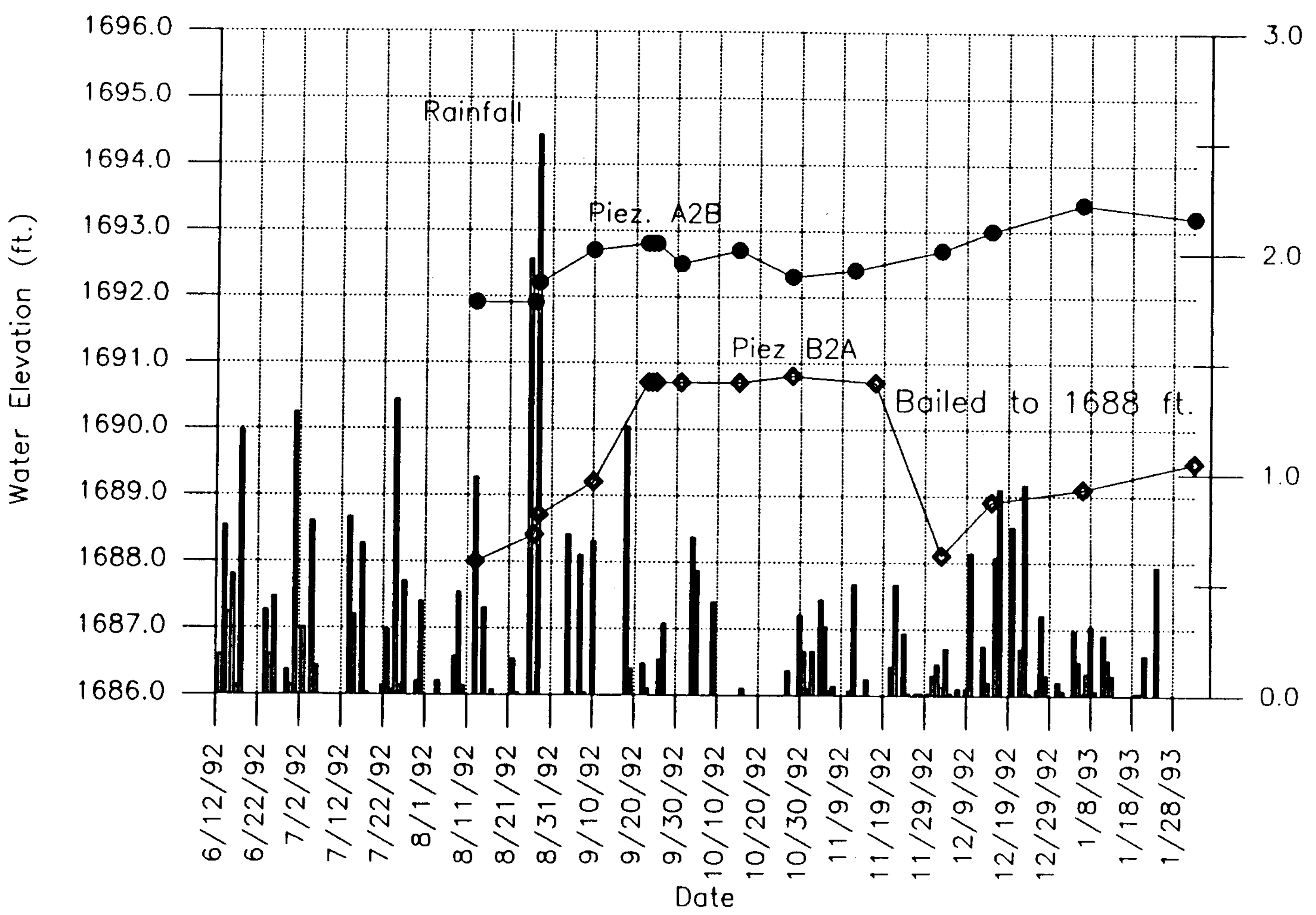


Figure 47. Rainfall data and hydrograph for piezometers A2B and B2A, located in the Hazard coal zone.

Figure 48 shows water levels for three piezometers located in the sandstone overlying the Magoffin Member. Piezometers A2A and C2B, located in fractures, equilibrate within days and minutes, respectively. Piezometer B1B, in the ridge core, may still be in the equilibration process after six months. Piezometer C2A, is located at the contact between the sandstone above the Magoffin and the Magoffin Member. The rapid response of this piezometer to precipitation and pumping stresses suggests that fractures, although not noted from core logs, are present in the open interval (Figure 49).

Three piezometers are completed below the Magoffin Member and two piezometers are located within the Magoffin Member. Hydrographs for piezometers located below the Magoffin are shown in Figure 50 and hydrographs for the two piezometers located within the Magoff in are shown in Figure 51. Water-level responses indicate very low conductivity in the Magoffin. A discussion of the four piezometers in the pressure-head zone located in low-conductivity strata follows.

Piezometers A1 B, B1 A, B1B, and C1B illustrate the difficulty interpreting water-level data in low-conductivity strata. It is unclear from available data whether or not static water levels in these piezometers reached equilibrium during the study period (approximately 6 months).

Piezometer B1A (Figure 50) was allowed to decline naturally following construction. A three-feet drop in water level during late September coincides with a small volume of water removed from the piezometer during an unsuccessful purging attempt. In general, the hydrograph shows an exponential water-level decline that eventually flattens out toward the end of the study period.

Piezometer B1B (Figure 48) was partially purged in late September. Prior to purging, the water level showed an exponential decline similar to piezometer B1A. Following the initial purging, the piezometer partially rebounded. The piezometer was purged again in mid November to collect water samples. Water levels did not rebound after the second purging. The initial rebound may represent an adjustment to the artificially high head in the immediate vicinity of the well. In low-conductivity strata, head does not change rapidly unless connected by fractures. If the strata in the vicinity of the piezometer equilibrated to the post-construction water level, water levels lowered by bailing would tend to rebound to this artificial head. After the second purging attempt, heads had begun to adjust to the actual formation head and did not rebound.

Piezometer A1B is located in the Magoffin Member. Water levels declined exponentially after construction. The well was partially bailed to approximately two feet below the level of the sand pack. Water levels rebounded to a level several feet above the sand pack. This rebound probably represents an adjustment to an artificially high head in the vicinity of the piezometer as described above. This piezometer was bailed again in late September and was lowered to level that was about 18 feet below the top of the sand pack. The sand pack was probably partially dewatered during the final bailing and heads did not rebound significantly.

Piezometer C1B located in the Magoffin Member (Figure 51) responded differently. Following well construction, the water level in piezometer C1B remained at an artificially high level and did not decline over time. The piezometer was partially bailed in mid September and pumped in late September. The volume of water removed by pumping was approximately equal to the volume of water contained in the well bore and gravel pack. After pumping in late September, water levels did not rebound.

Water levels for the two Magoffin piezometers have remained within the screened interval several months after purging. Heads measured in these piezometers near the end of the study period may be representative of the head within the Magoffin Member or may represent piezometers in poorly conductive strata that have not equilibrated.

Ground-Water Flow System

Piezometric data provide point-specific information that may be used to infer behavior of the larger system. In Edd Fork, piezometric data are used to define three zones that exhibit similar hydraulic characteristics. The ground-water flow system in the Edd Fork watershed is composed of three hydraulically distinct zones; the shallow-fracture zone, the elevation-head zone, and the pressure-head zone. Boundaries separating these zones are transitional but can be inferred from water level data.

The shallow-fracture zone functions as both a recharge zone and a discharge zone. Recharge from precipitation infiltrates vertically through the soil layer into the underlying fracture system. Water migrates vertically and laterally through the upper, unsaturated part of the fracture system as gravity drainage. Some percolating water exits the valley wall as springs where fractures or coal beds intersect the surface. Discharge from springs reinfiltrates into the system downslope or flows along the surface and discharges directly to Edd Fork.

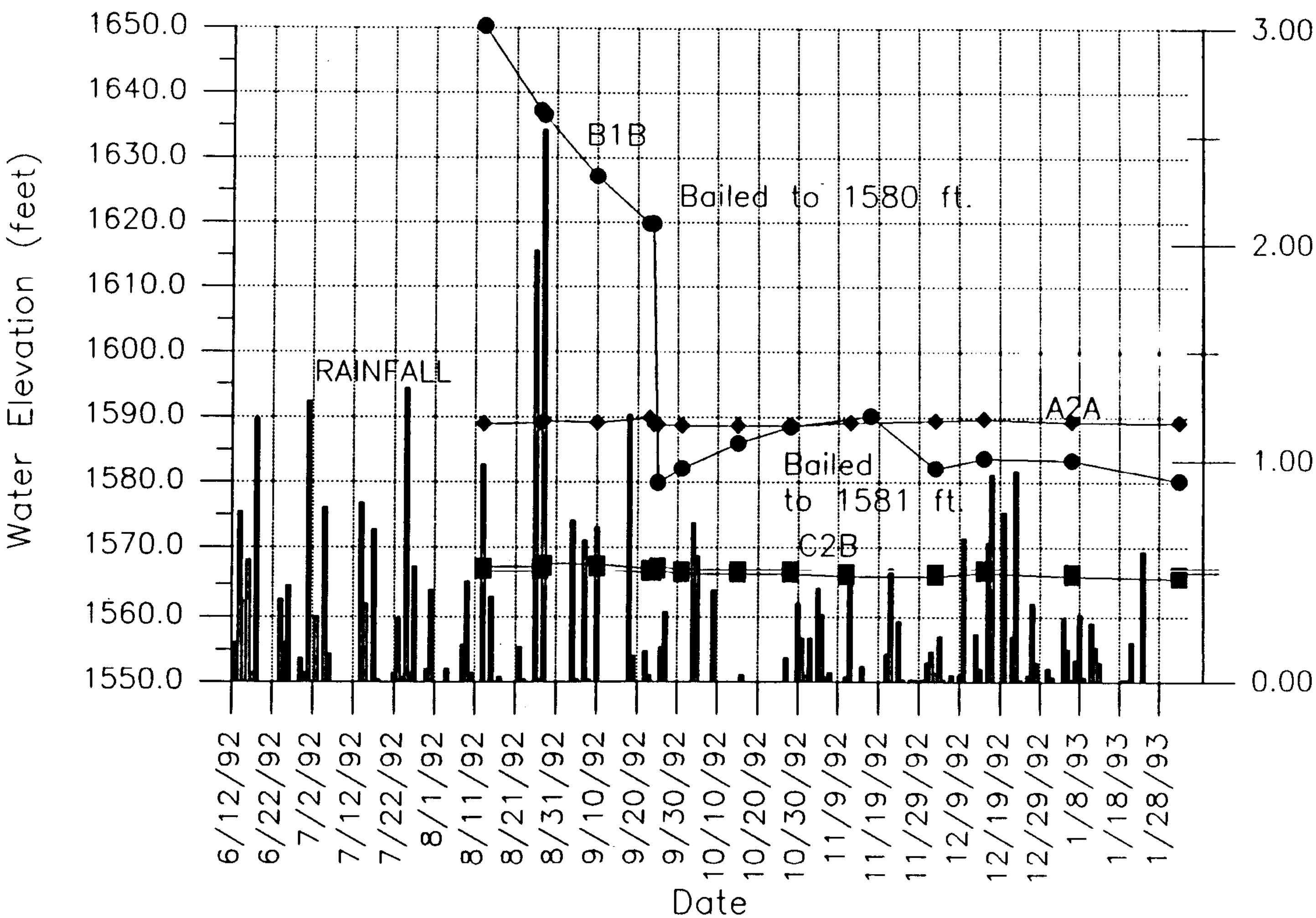


Figure 48. Rainfall data and hydrograph for piezometers B1B, A2A, and C2B, located in the sandstone above the Magoffin Member.

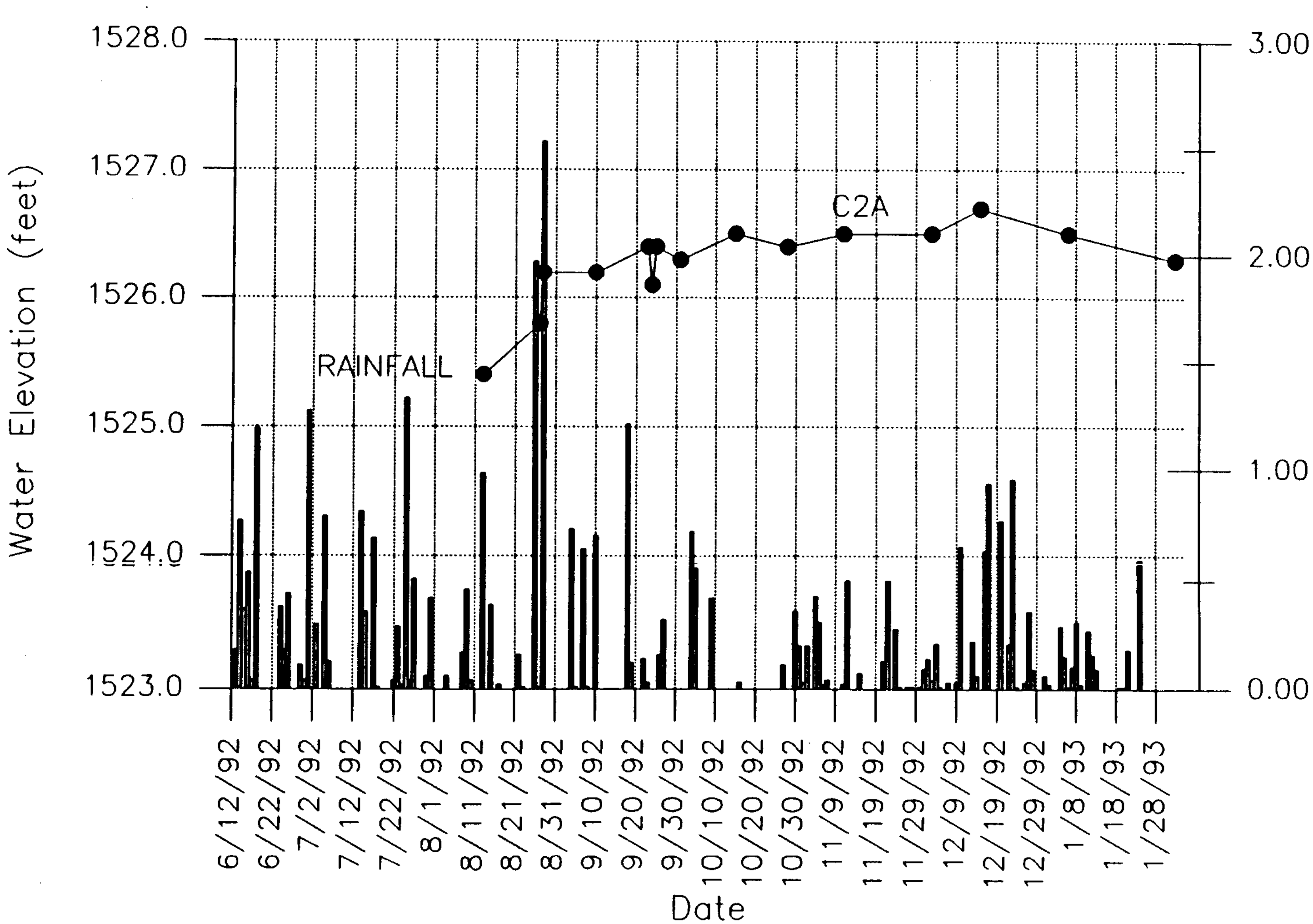


Figure 49. Rainfall data and hydrograph for piezometer C2A.

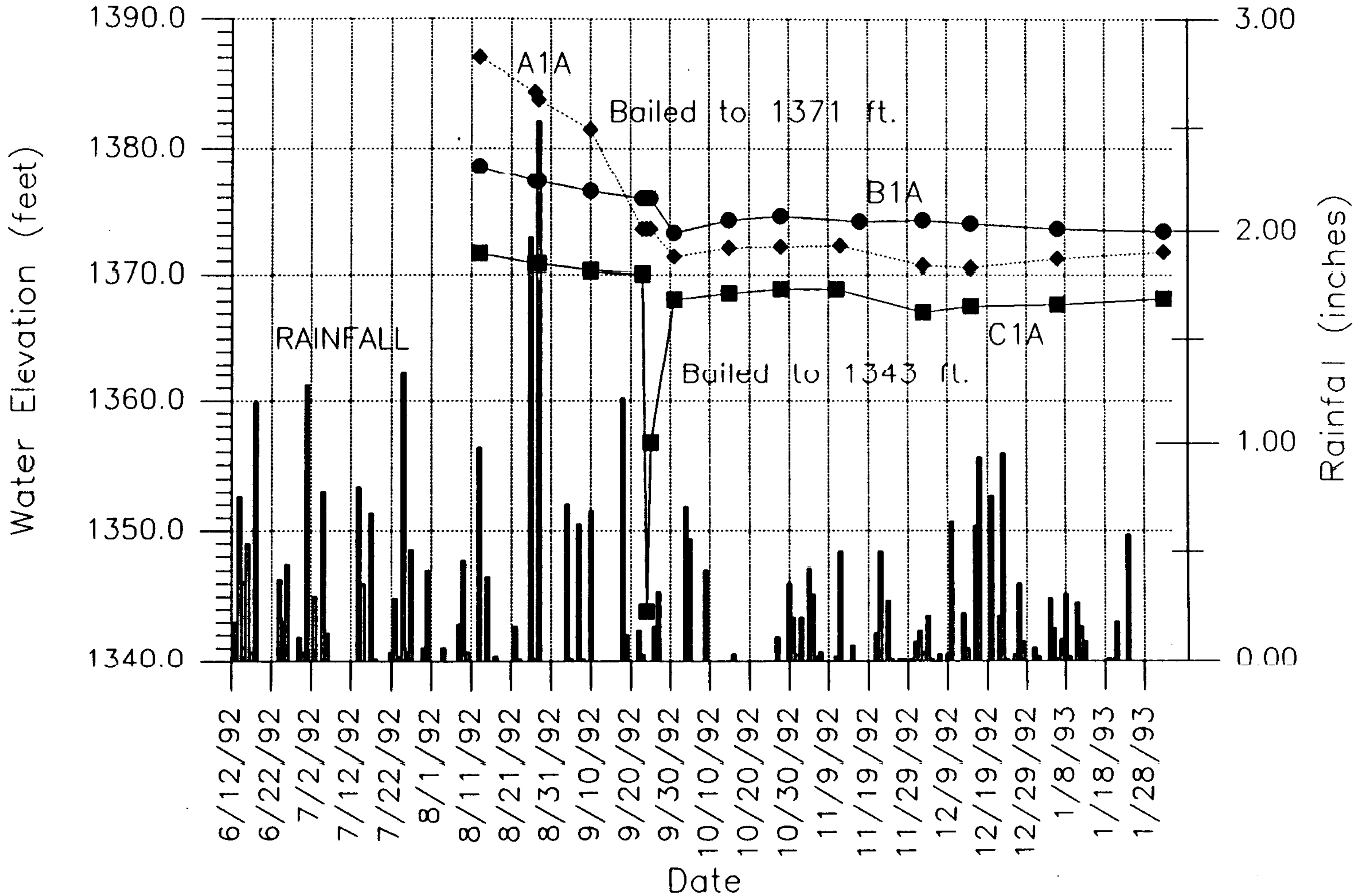


Figure 50. Rainfall data and hydrograph for piezometers A1A, B1A, and C1A, located below the Magoffin Member.

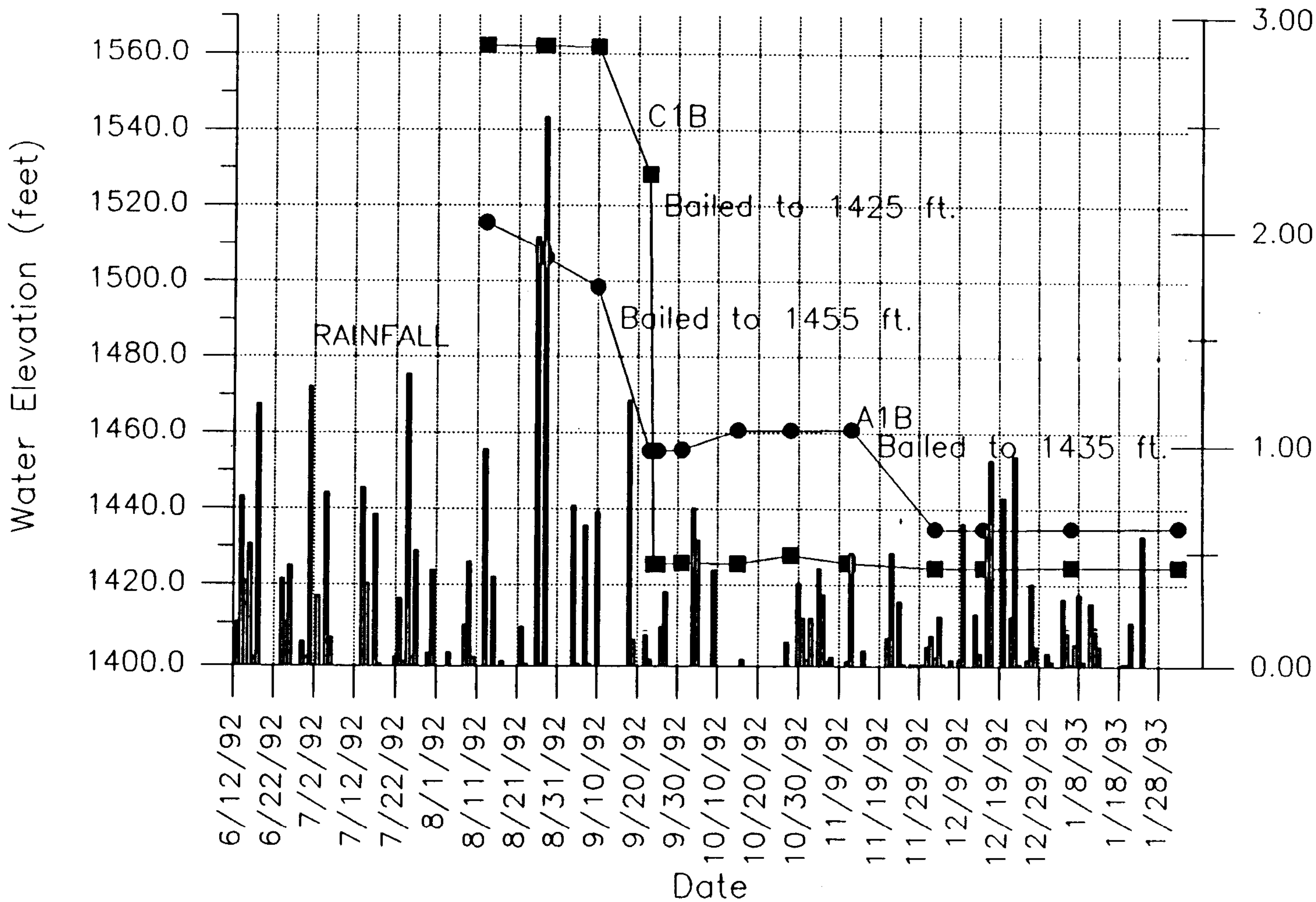


Figure 51. Rainfall data and hydrograph for piezometers A1B and C1B.

A water table that intersects Edd Fork in the valley bottom is present within the shallow-fracture zone along the valley slope between site A and site C. The water table surface fluctuates seasonally, as well as in response to specific rainfall events. It is probable that mining activity in the watershed has depressed the elevation of the saturated zone in the ridge tops and on hillslopes beneath mining benches in a manner similar to Wolfpen Branch.

The shallow-fracture zone comprises the local flow system in the Edd Fork watershed, contributing subsurface flow to Edd Fork. Mine spoil located throughout the watershed undoubtedly stores and releases water that helps to sustain flow during dry periods. Edd Fork probably does not contribute much recharge to unfractured strata below the shallow-fracture zone. Because ground-water flow is three dimensional, there is also a component of flow in this zone that is approximately parallel to Edd Fork and may discharge downstream to Edd Fork or to Trace Branch.

Water that does not discharge through the shallow-fracture zone, percolates into the elevation-head zone, partially through vertical fractures and partially via intergranular flow. The elevation-head zone is saturated except for the Hazard Number 8 Coal bed. Unconfined conditions are indicated because head is equal to elevation. Flow throughout this zone is nearly vertical in non-coal rock but is more nearly horizontal in coal beds. Near-vertical, downward gradients in rock are in response to more conductive coal beds that divert part of the flow horizontally toward valley walls. Water either discharges as springs, evidenced by sustained flow from the Hazard Number 8 Coal seam at the base of the highwall, or it reenters the shallow-fracture zone. Saturated conditions in the ridge core indicate that some water moves downward to recharge deep strata. Vertical fractures present above drainage probably provide vertical recharge conduits and promote greater flow than would occur intergranularly.

Below the elevation-head zone, ground water is confined. The top of the pressure-head zone extends to about 150 feet above the level of Edd Fork (Figure 38). Upper boundaries are the elevation-head zone or the shallow-fracture zone. Vertical gradients in the pressure-head zone are less steep than in the elevation-head zone, but flow has a strong vertical component. Head data in the valley-bottom sandstone unit indicate that flow is downward, although there is a lateral component of flow under Edd Fork. On the basis of head data, there is a regional system, flowing downward and laterally, that does not discharge to Edd Fork. Because flow is three dimensional, there is probably a third component of flow in this sandstone parallel to Edd Fork, towards Trace Branch.

The Magoffin Member, a thick, shale/sandy shale sequence, is located below the level of Edd Fork. Because strata are saturated below the Magoffin, some flow must pass through the Magoffin to recharge the regional flow system. The Magoffin, therefore, is a leaky, confining unit. Because it is laterally extensive and has a steep vertical gradient, significant quantities of water may pass through this unit. Ground-water below the Magoffin Member is sodium-bicarbonate type, indicative of slow-moving water that has a long residence time. Cation-exchange reactions are primarily responsible for conversion of water from calcium-magnesium type to sodium type (Wunsch, 1992). Slow flow through a clayrich unit such as the Magoffin would accomplish this exchange. As a result of this water-quality difference, two ground-water zones, the above-Magoffin-Member zone and the below-and-including-Magoffin-Member zone are distinguishable. Bienkowski (1990), also found a difference in quality above and below the Magoffin in the Eastern Kentucky Coal Field where the Magoffin Member is present.

Continued generation of sodium-bicarbonate-type water along the flow path may be expected where calcite continues to dissolve and host sites for cation exchange are available. Sodium-chloride type water, however, is generally considered connate or formation water in eastern Kentucky (McGrain and Thomas, 1951). High chloride content in fresh ground water near stream valleys, probably results from mixing with chloride-rich water at depth.

Fracture permeability probably exists at depth, either in discrete fractures or as coal cleat. If fractures play a part in determining the depth of fresh-water flow, -fractures are probably closed, are less abundant, or are poorly connected with greater depth of the flow system. The fresh-saline water interface may represent an area where no fracture permeability is present; therefore, no flushing of connate water occurs.

SUMMARY OF EASTERN KENTUCKY GROUND-WATER INVESTIGATIONS

Objective

Ground-water data from three previous investigations in eastern Kentucky will be summarized. Groundwater zones will be identified using data from the following sites:

1. Ground Water Geochemistry and its Relationship to the Flow System at an Unmined Site [Star Fire]

in the Eastern Kentucky Coal Field (Wunsch, 1992).

2. A Conceptual Model of Ground-Water Flow in the Eastern Kentucky Coal Field (Kipp and others, 1983) and Stress-relief Fracture Control of Ground-Water Movement in the Appalachian Plateau (Kipp and Dinger, 1987)

3. Data from Test Drilling to Trace Movement of Ground Water in Coal-Bearing Rocks near Fish trap Lake, Pike County, Kentucky (Davis, 1986) and Movement of Ground Water in Coal-Bearing Rocks near Fishtrap Lake in Pike County, Kentucky (Davis, 1987).

Location

Locations of all study areas, including Edd Fork, are shown on Figure 52. The Edd Fork, Star Fire, and Wolf Den Branch sites encompass approximately the same stratigraphic interval within the Breathitt Formation. The Fishtrap Lake site lies below the Magoffin Member, the lower in the Breathitt Formation.

Methods

Three studies were summarized and data evaluated in order to describe ground-water zones similar to those in Edd Fork. Drill data, pressure-injection test data, water-level data, and water-quality data were available from publications regarding these sites. The types of data available depend on the original intent of the study. Consequently, the level of detail varies from site to site. These three particular study areas were selected for the following reasons: (1) these studies represent the coal hydrology studies completed in the Eastern Kentucky Coal Field; (2) all sites are located in the Breathitt Formation; (3) study areas encompass different topographic and drainage positions; (4) a wide variety of detailed information is available; and (5) individuals involved in data

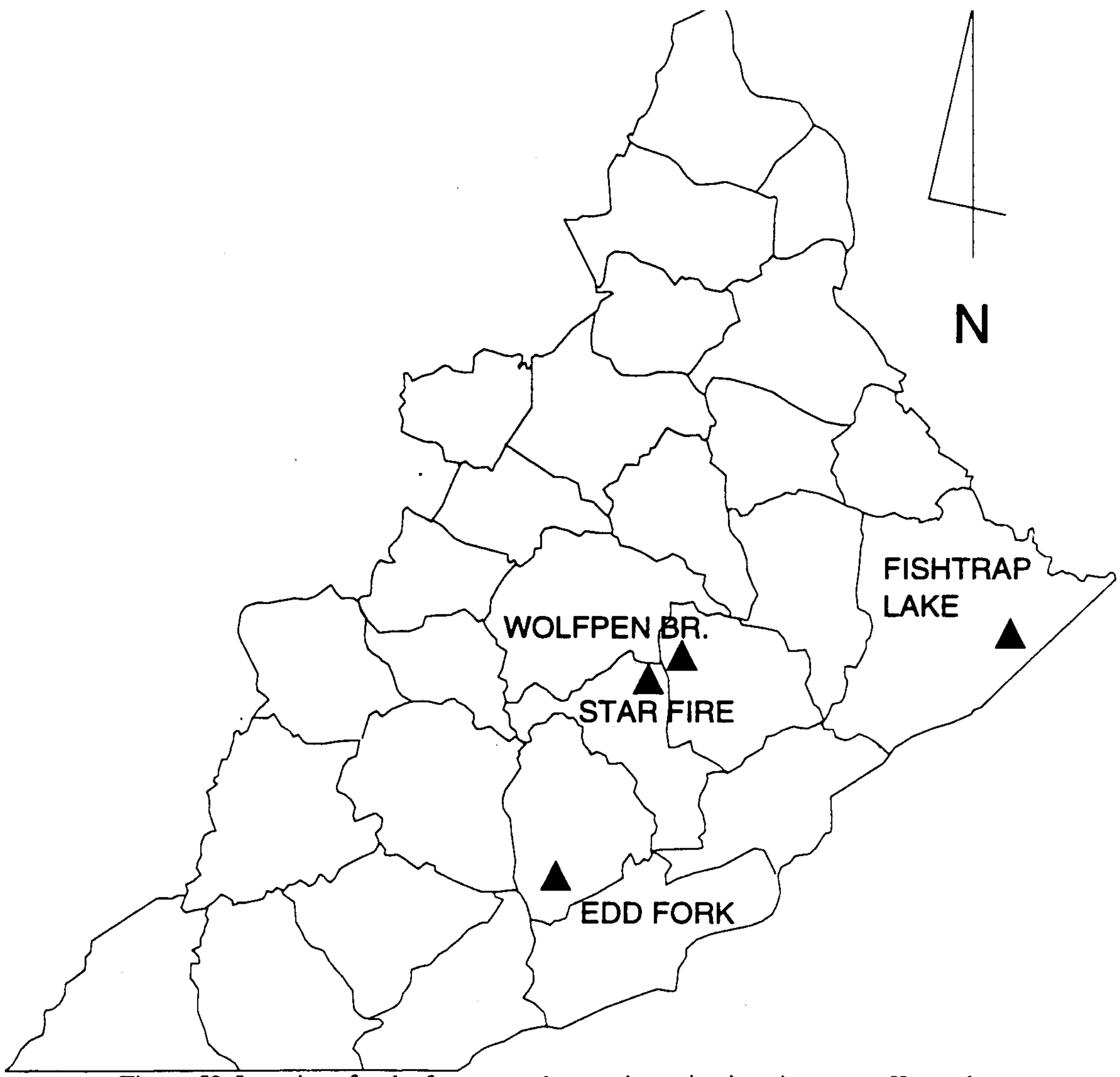


Figure 52. Locations for the four ground-water investigations in eastern Kentucky.

collection are available to verify accuracy or limitations of the data.

Data Description and Summary

Star Fire Site, Perry County

A one-year study by Wunsch (1992) provides a detailed description of geochemical facies that may be present in a ridge setting adjacent to a third-order stream in eastern Kentucky. Geochemical evolution of ground-water in the ridge is related to the ground-water flow system. The site is located on the Vest and Noble, Kentucky 7.5 minute quadrangles. The site and monitoring points are shown on Figure 53. One core hole was drilled to characterize stratigraphy. Estimates of hydraulic conductivity were obtained from pressure-injection tests conducted in the core hole using 5-foot intervals. The variation of conductivity with depth is shown in Figure 54. Sixteen piezometers were installed in rotary bore holes at various sites on the ridge. A summary of piezometer data is presented in Table 12. Figure 55 shows piezometer screened intervals in cross section. Figure 56 shows the relationship of water levels to piezometer interval depth for all piezometers. Water quality data, representing an average of samples collected during the study, are shown on the Piper diagram in Figure 57. The author of this dissertation recognizes that water quality varied within each piezometer over the course of the Star Fire study; however, average values are useful for identifying major ionic differences. The reader is referred to Wunsch (1992) for a detailed geochemical evaluation of the Star Fire site.

GROUND-WATER ZONES

The Magoffin Member is above drainage at the Star Fire site. Average water-quality data show that waters above and below the Magoffin Member are different types. Calcium and magnesium are the dominant cations in strata above the Magoffin. Sodium is the predominant cation, except in shallow valley-bottom piezometers, in ground-water below the Magoffin Member.

Three zones differentiated on the basis of hydraulic properties are also present. The shallow-fracture zone is identifiable from core- and bore-hole logs, down-hole camera examinations, electric logs, pressure-injection tests, and piezometric data. These data indicate that a highly fractured zone extends to a depth of about 60 feet along ridges and valley walls. No data are available in the valley bottom. Pressure-injection tests (Figure 54) show conductive fractures in the upper 60 feet. Three piezometers are located in the shallow-fracture zone. Piezometer 14A shows water-level fluctuations characteristic of shallow-fracture piezometers. Piezometer 21B is dry, indicating unsaturated conditions (Wunsch, 1992). Piezometer 41B exhibits water quality that is a mixture of rapidly infiltrating water and older water from the ridge interior (Wunsch, 1992).

Table 12.—Summary of Screened Intervals for the Star Fire Site.

Piezometer No.	*Surface Elev. (ft.)*	*Total Depth (ft.)*	*Min. Water Level Elev. (ft.)*	*Max. Water Level Elev. (ft.)*	*Water Level Fluctuation (ft.)*	*Monitored Interval**
11A	1283.7	418	901.7	905.9	4.2	ss
11B	1283.7	195	1093.4	1094	0.6	c
11C	1283.7	48.5	1237	1248.1	11.1	c
12A	1283.8	167	1122	1122.3	0.3	f
13A	1284.7	102	1184.2	1185.8	1.6	c
13B	1284.7	50	1233.8	1236.1	2.3	c
14A	1284.2	40	1245.6	1252.2	6.6	f
21A	1152.1	67	1088	1090.3	2.3	c
21B	1152.1	47	dry	dry	—	f
22A	1152.9	290	898.6	905.2	6.6	ss
22B	1152.9	200	987.2	991.8	4.6	sh
31A	1003.7	140	865.3	872.5	7.2	ss
31B	1003.7	100	914.7	918.4	3.7	f
41A	925	172.7	839.6	843.3	3.7	ss
41B	925	70	862.6	867.8	5.2	ss

* ss–sandstone; c–coal; f–fracture; sh–shale

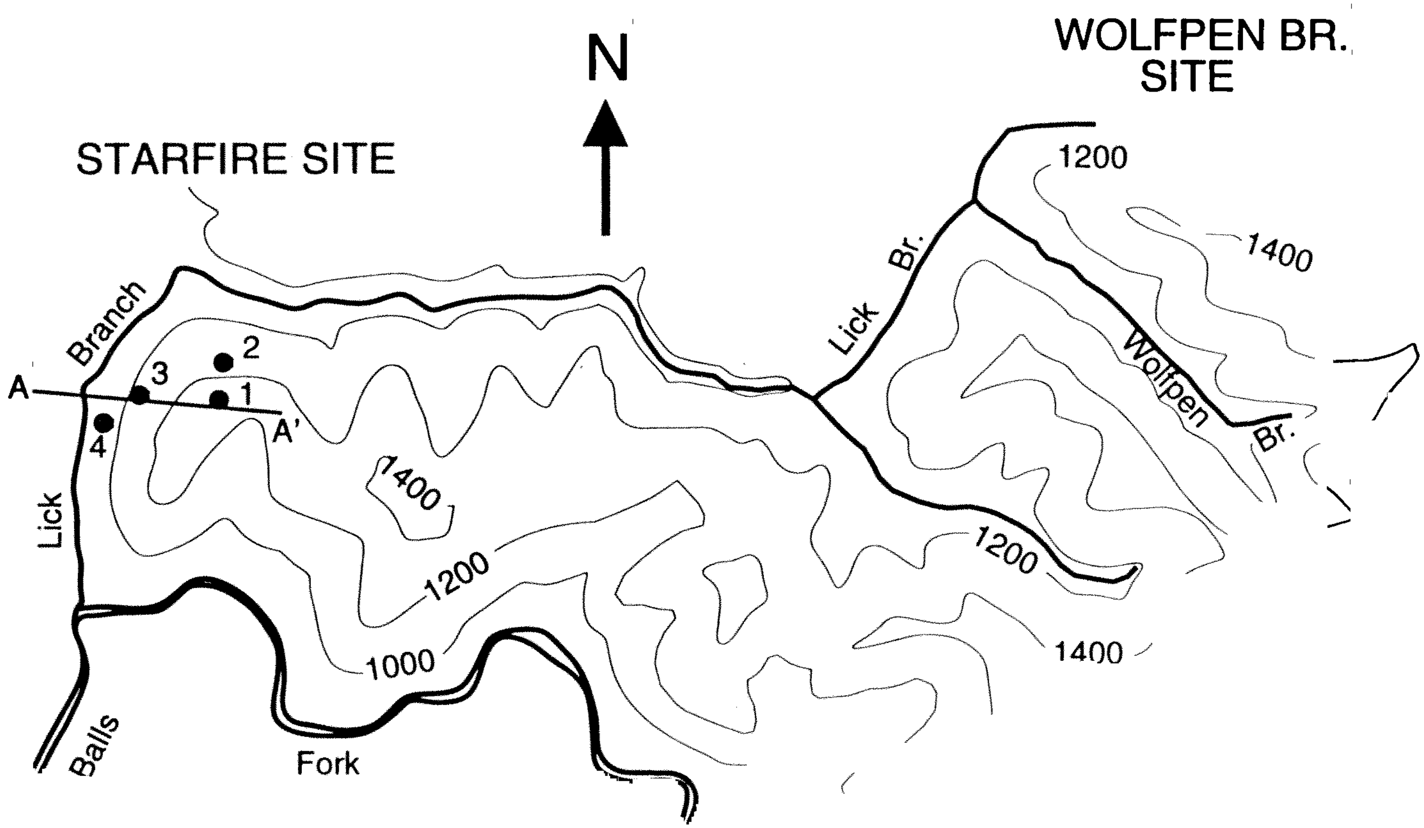


Figure 53. Locations of monitoring points at the Star Fire site (modified from Wunsch, 1992).

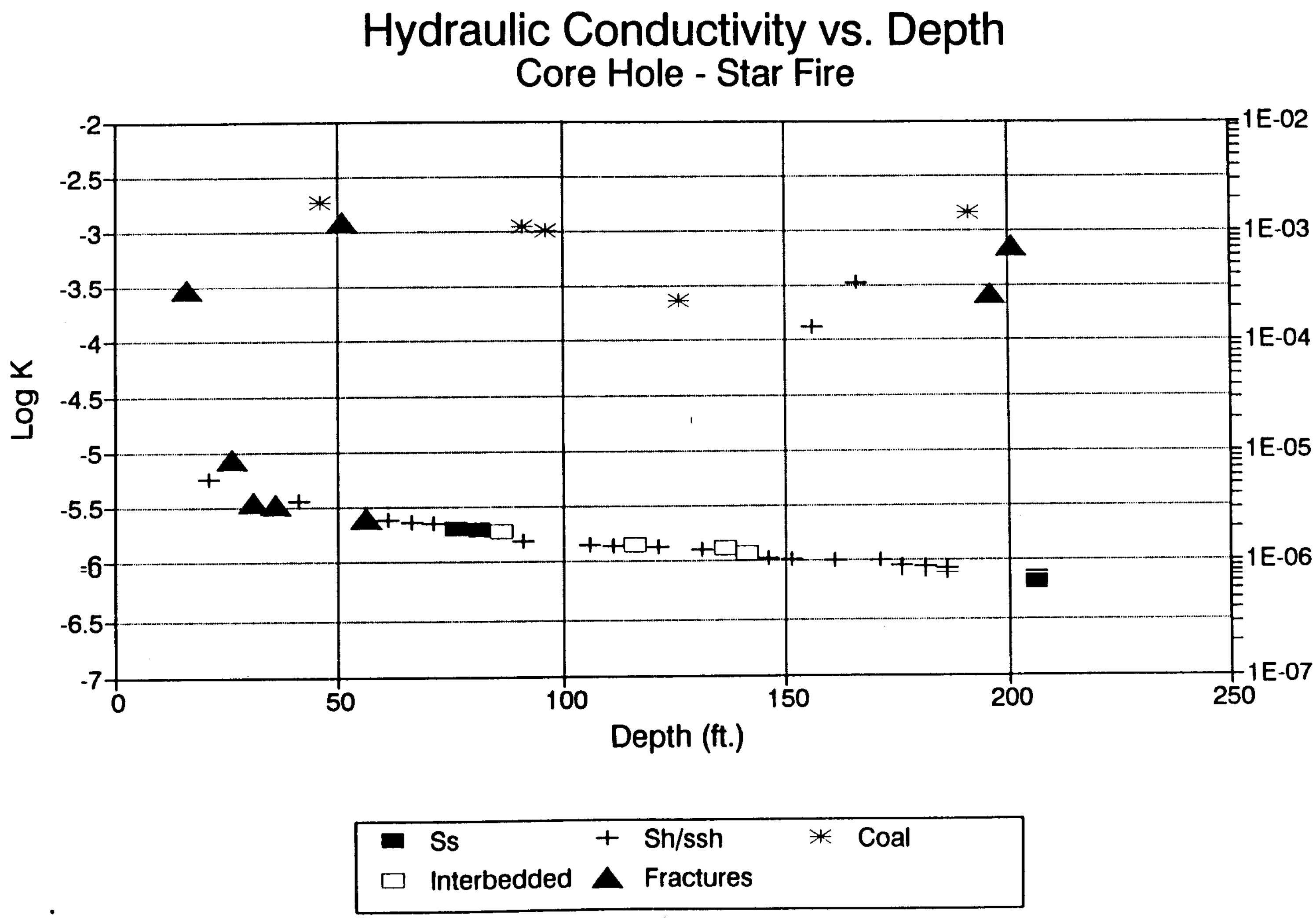


Figure 54. Distribution of hydraulic conductivity with depth for the Star Fire site.

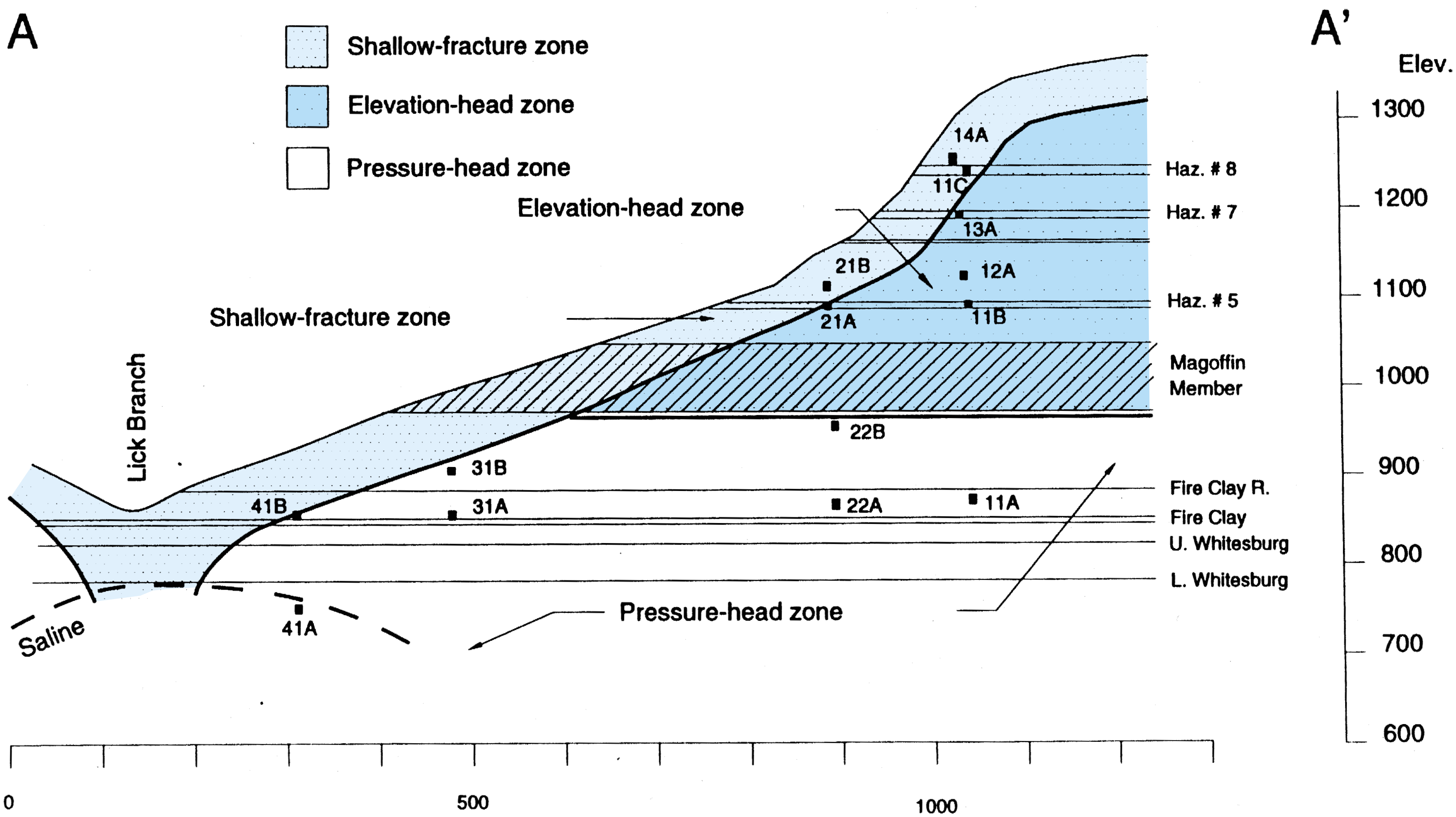


Figure 55. Cross–section A–A' of the Star Fire site showing piezometric intervals and ground-water zones (cross section modified from Wunsch, 1992).

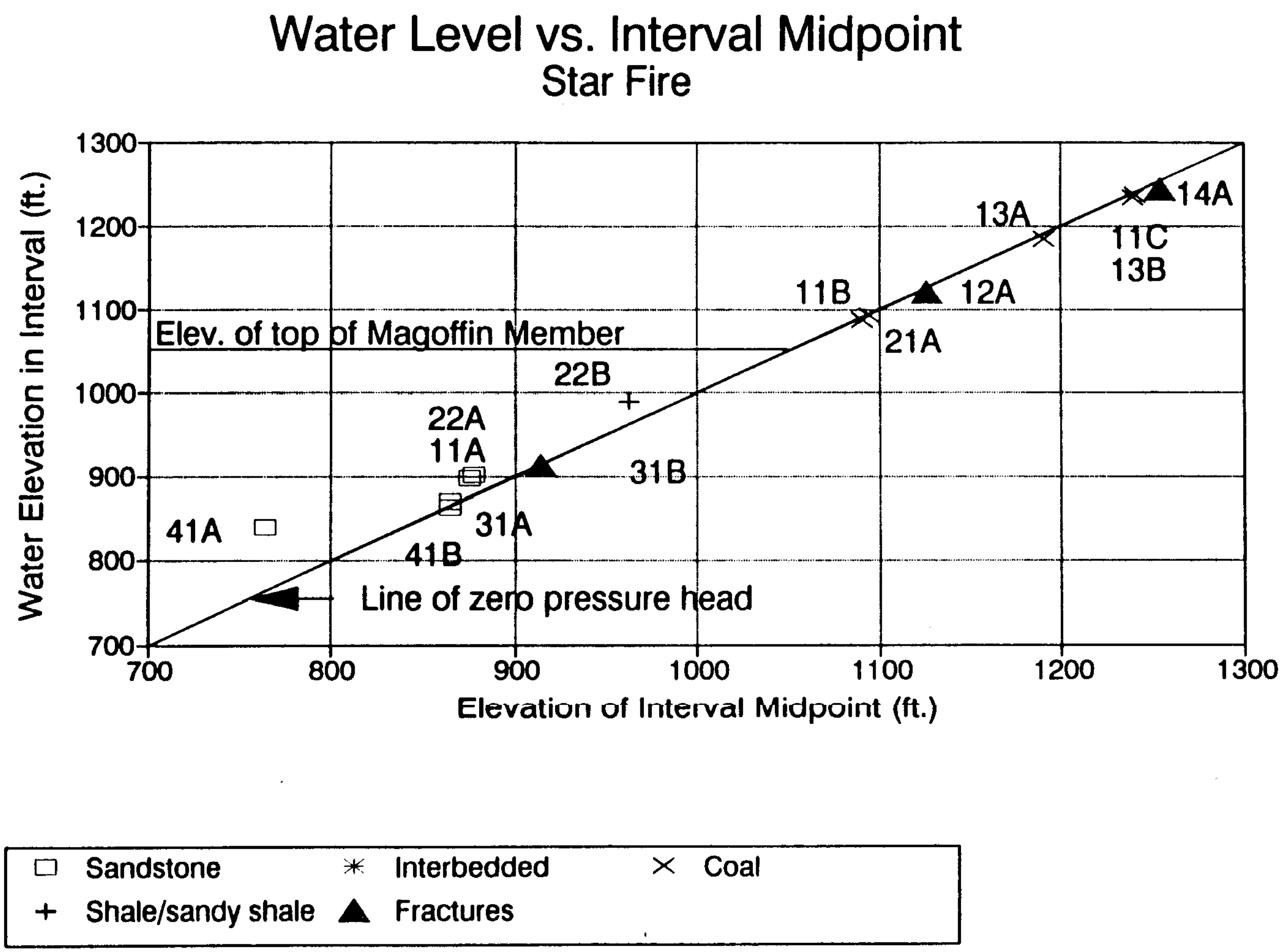


Figure 56. Water-level elevations plotted against piezometer midpoint elevations for the Star Fire site.

Ranges (mg/L)									
ABOVE-MAGOFFIN	pH	TDS	Ca	Mg	Na	K	SO4	HCO3	Cl
max	6.92	746.13	84.3	70.7	22.8	11.9	332	590	7.14
min	5.37	140.43	10	4.54	3.64	0.94	7.0	71	1.00
BELOW & INCLUDING MAGOFFIN									
max	8.93	1200.5	49	19.20	326.0	6.44	602	572	50.7
min	6.56	381.3	0.69	0.19	59.0	0.62	0	190	1.00
MIXED									
max	6.97	663.94	62.4	58.3	103.0	35.2	103.0	429	35.2
min	6.48	557.72	12.3	7.3	1.76	2.83	79.6	371	1.00
BRINE									
avg.	7.07	24873	249	61.1	4785	26.9	10.9	429	8041

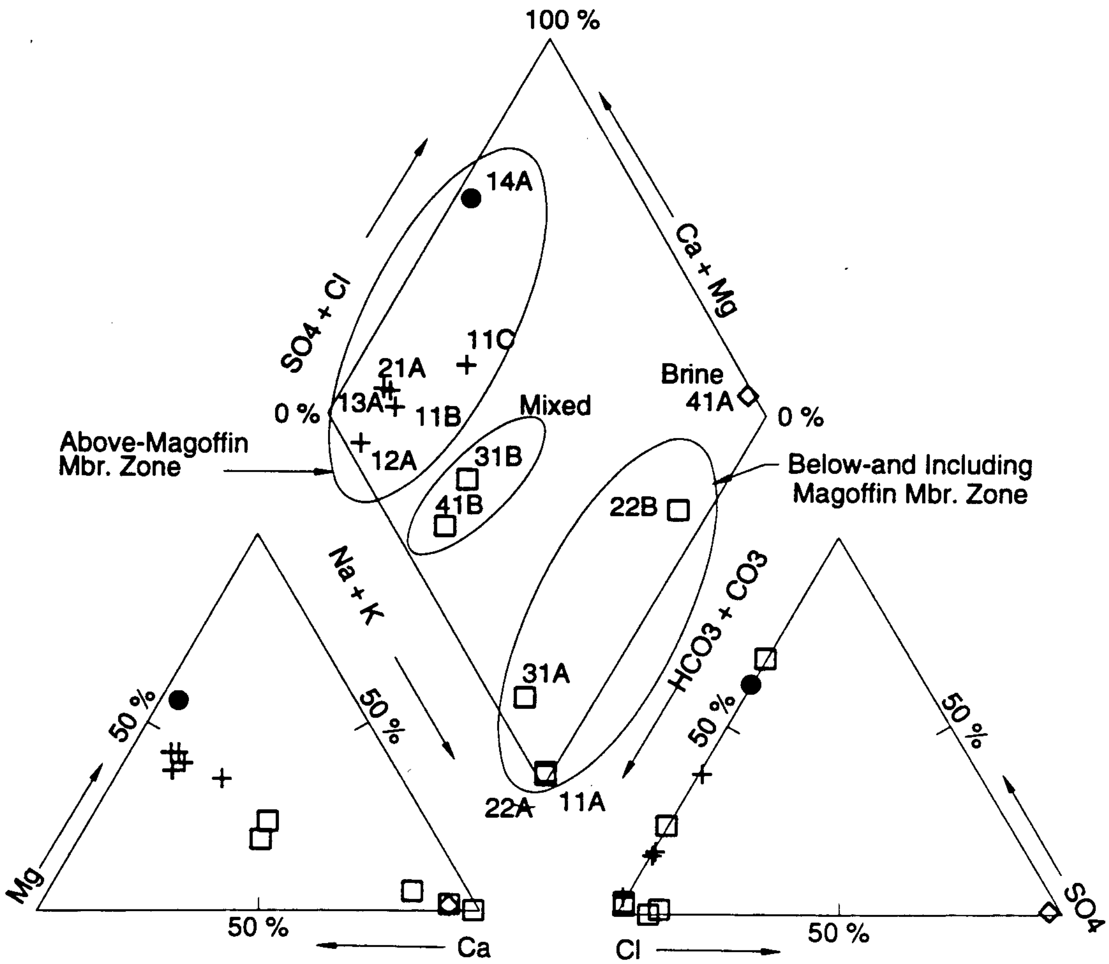


Figure 57. Piper diagram showing 12-month water-quality averages for the Star Fire site.

Piezometric data support the existence of an elevation-head zone that extends approximately to the top of the Magoffin Member. No piezometers were placed within the Magoffin; however, because it is above drainage and head drops approximately one-foot per foot between piezometers above and below it, heads are likely to be at or near the interval midpoint. For this reason, the Magoffin Member is included as part of the elevation head zone.

A downward gradient of approximately one-foot per foot is present between piezometers 13A and 11B. As described by Wunsch (1992), flow is predominantly vertical through the ridge; however, coals divert some of the flow laterally. Water levels from piezometers completed in coal beds indicate that coal seams are partially drained. Coal seams at this site are thicker than coal seams at Edd Fork and may transmit a greater volume of water. Everywhere below the Magoffin Member, head in the system includes both elevation-and pressure head components.

Similar data collection procedures conducted at sites with different stream orders invites comparison of results for the Edd Fork and Star Fire sites. The sites encompass nearly the same stratigraphic interval; the primary difference is that the Magoffin Member is below drainage at Edd Fork and above drainage at Star Fire. Both sites show water-quality differences between piezometers above and below the Magoffin. The pH is generally higher in strata in and below the Magoffin Member than in strata above the Magoffin Member. Calcium and magnesium are the dominant cations above the Magoffin Member. Hydraulic conductivity profiles obtained from core hole pressure-injection tests show that fractures and coals are highly conductive zones; whereas, unfractured sandstone and shale have low conductivity. The hydraulic gradient in the ridge interiors is downward at both sites. Gradients continue downward beneath the first-order stream at Edd Fork; however, the third-order stream at Star Fire is identified as a discharge zone. Saline water is encountered at a depth of about 100 feet below creek level at Star Fire. Water obtained from 260 feet below the level of Edd Fork is fresh water. Deep piezometers; in the ridge interiors indicate fresh water at both sites.

Wolfpen Branch Site, Knott County

A study, conducted in 1982 by the Kentucky Geological Survey, was designed to collect ground-water data from a small drainage basin prior to, during, and after surface mining. Results were used to develop a conceptual model of ground-water flow in the basin and to assess the effects of mining and reclamation on groundwater flow and quality.

Wolfpen Branch is located on the Vest, Kentucky, 7.5 minute quadrangle, approximately one mile upstream from the Star Fire site on Lick Branch. The site and monitoring points are shown on Figure 58.

Table 13.—Summary of Screened Intervals for the Wolfpen Branch Site.

Well No.	*Total Depth (ft.)*	*Surface Elev. (ft.)*	*Top of Open Interval (ft.)*	*Bottom of Open Interval (ft.)*	*Approx. Yield (gpm)*	*Monitored Interval**
50	292.7	1072	7.3	292.7	> 10	f
51	50.0	1070	8.2	50.0	> 10	f
52	94.3	1066	49.0	94.3	< 1	M
60	210.0	1181	92.4	210.0	< 1	ss, c, M
61	86.0	1181	15.0	86.0	< 1	ss, c
62	155.0	1182	87.0	155.0	< 5	ss
70	98.5	1133	35.5	98.5	> 10	ss
71	33.0	1132	16.0	33.0	1–5	c
80	174.6	1202	114.0	174.6	< 1	ss
81	115.0	1203	52.6	115.0	< 1	ss, c
82	52.0	1203	10.0	52.0	5–10	f
83	52.0	1204	10.0	52.0	5–10	f

* ss–sandstone; c–coal; f–fracture; M–Magoffin Member

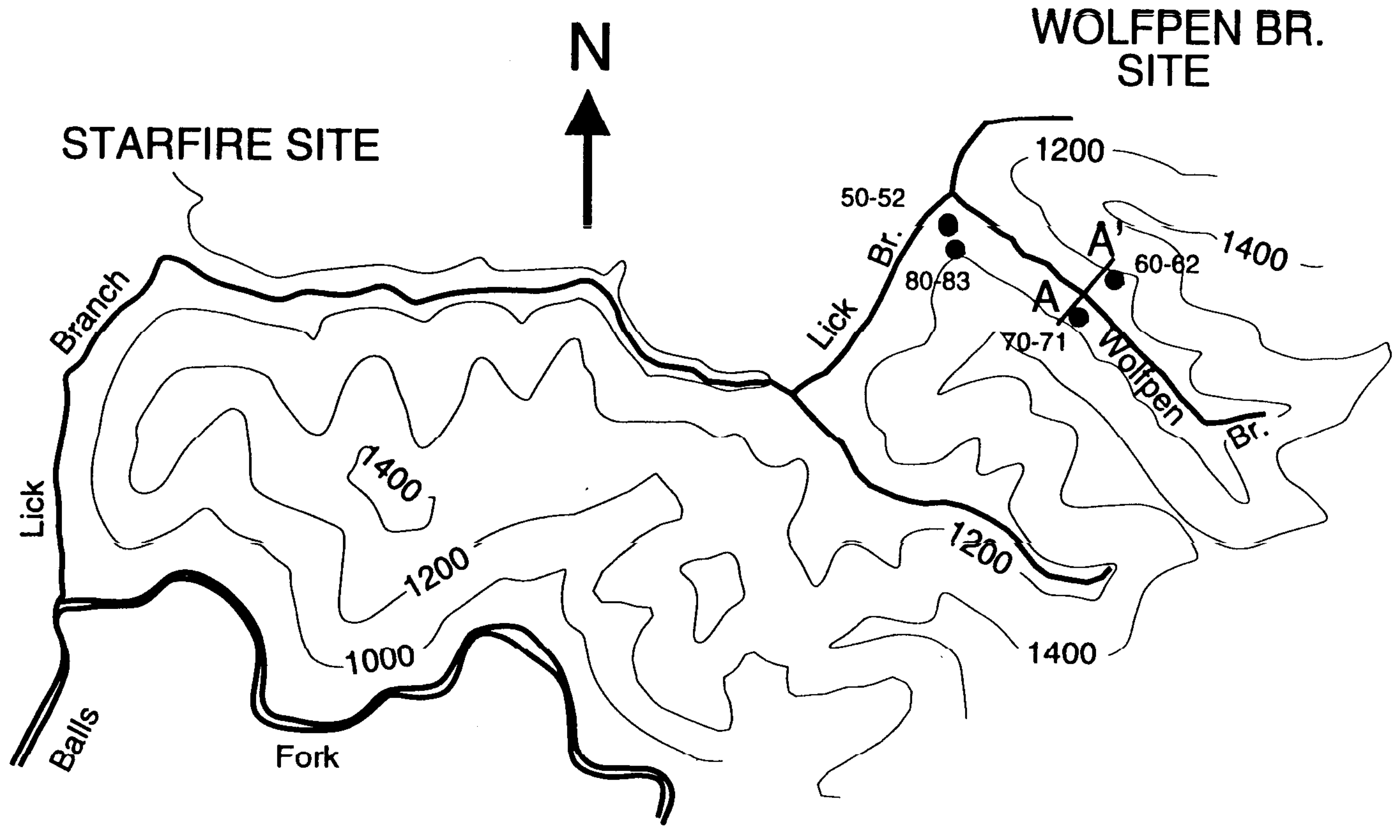


Figure 58. Location map for the Wolfpen Branch site showing monitoring points, cross section A–A', and the proximity of this site to the Star Fire site.

Four core holes were drilled at each of four nest sites to characterize stratigraphy and locate fracture zones. Thirteen monitoring wells were installed in sandstone units at various topographic locations. Wells in this study had long screen intervals that encompass entire lithologic intervals, rather than short screens that provide head data at discrete points in the system. A conceptualized cross section showing relative well locations is shown in Figure 59. A summary of well data is shown in Table 13. The partial Piper diagram (Figure 60) shows only cations because analyses of major anions are not available. The reader is referred to Kipp and Dinger (1987) and Kipp and others (1983) for additional information on this study area.

GROUND-WATER ZONES

The Magoffin Member is below the level of both Wolfpen Branch and Lick Branch. Water quality from four wells above the Magoffin show that the ground water contains the cations calcium and magnesium. One well above the Magoffin completed in a coal bed, contains appreciable sodium. One well, located in the Magoffin Member, indicates that ground water is high in sodium and depressed in calcium and magnesium. No data are available for ground water below the Magoffin. These limited analyses indicate there is a water quality difference in wells located in above the Magoffin Member and within the Magoffin Member; however, there are no quality data from below the Magoffin Member.

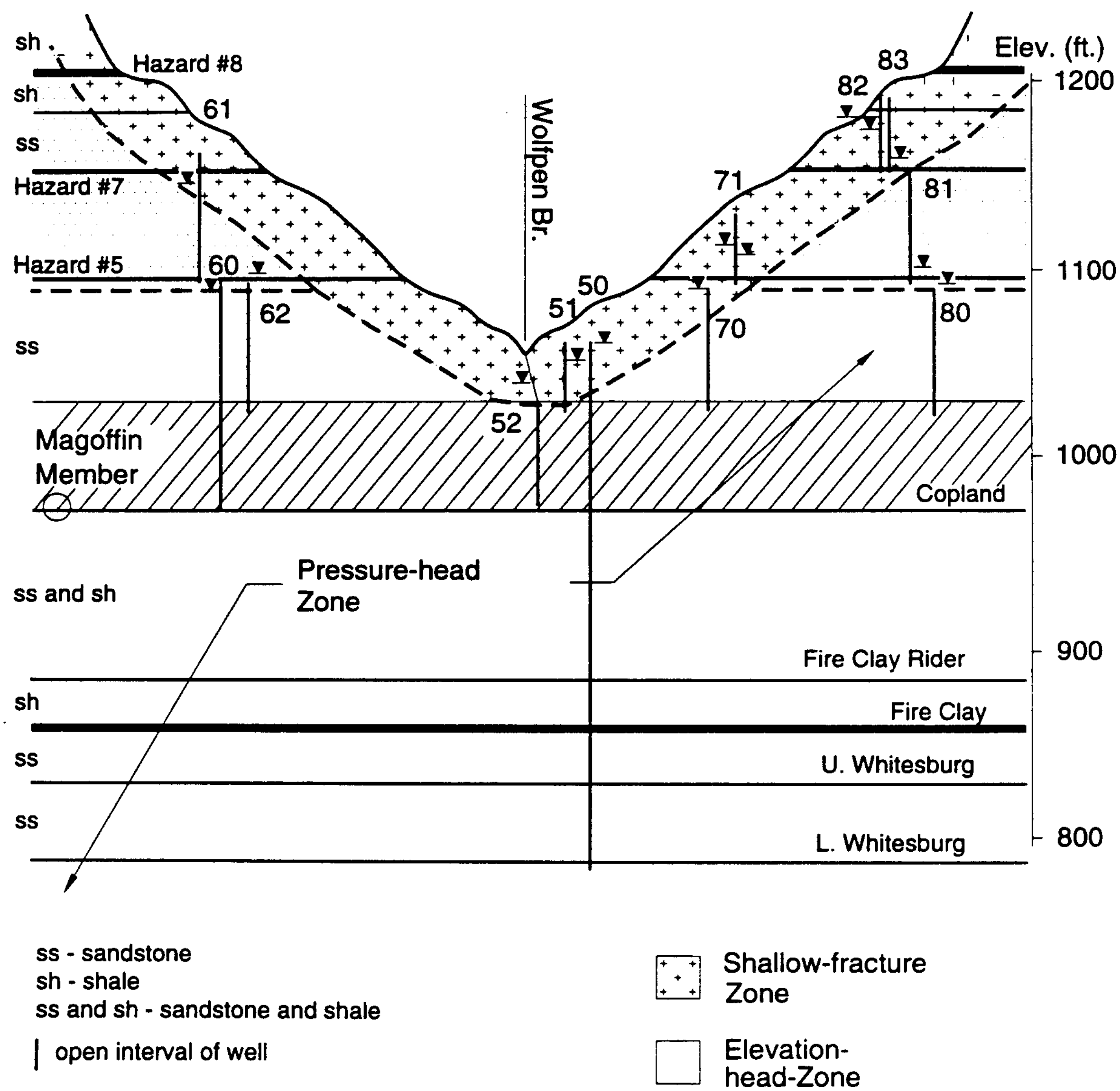


Figure 59. Cross section A–A' (see Figure 58 for location) showing screened intervals, water levels, and ground-water zones at the Wolfpen Branch site (modified from Kipp and others, 1983).

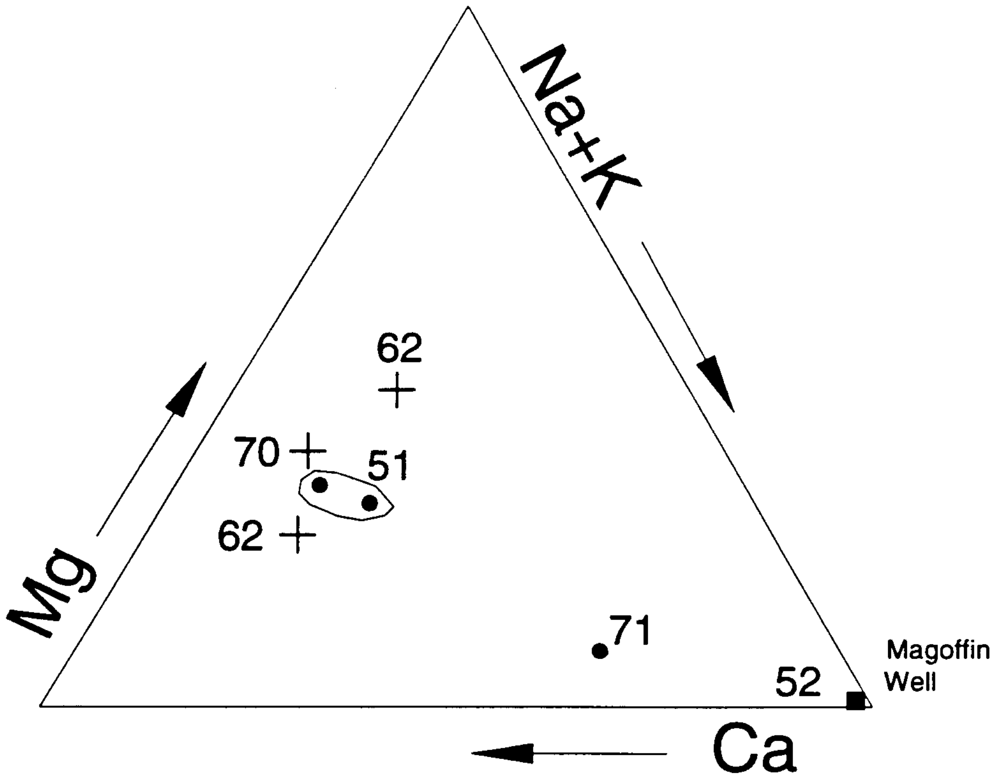


Figure 60. Cation distribution for sampled wells at the Wolfpen Branch site.

Core data indicate that the shallow-fracture zone exists at this site. The most extensive fracturing is at depths less than 70 feet on the valley walls. Fractures at site 50, near the confluence of Lick Branch and Wolfpen Branch, extend to the top of the Magoffin Member, 40 feet below the surface.

Three wells, 51, 82, and 83 are screened through the entire thickness of the shallow-fracture zone. Water cascades into these wells from fractures located above the water level in the well. Direct inflow to wells via fractures results in water levels that fluctuate rapidly in response to precipitation events. Continuous water level measurements for well 51 also recorded diumal evapotranspiration effects (Kipp and Dinger, 1987). Two wells, 82 and 83, are identically constructed except that well 83 intercepts a fracture near the base of the open interval. The water level in this well is 15 to 20 feet lower than the water level in well 82. Water in the well is drained by the fracture; however, water cascades in from the overlying Hazard No. 7 Coal seam.

Three wells, 61, 71, and 81, terminate in the Hazard Number 5A Coal seam. Water levels are within the open interval. This may indicate that the coal bed is draining the wells in a similar manner to that at Edd Fork and Star Fire. The base of the elevation-head zone is probably associated with this coal bed because all other wells are located in the pressure-head zone.

Three wells, 62, 70, and 80, are open to a sandstone unit between the Magoffin Member and the Hazard 5A Coal bed. Water levels in these wells rise above the top of the sandstone, indicating that pressure head is a component of total head conditions exist.

Piezometers 50 and 52 are located approximately 100 feet from the confluence of Wolfpen Branch and Lick Branch (Figure 58). Wolfpen Branch is a first-order stream; however, Lick Branch is a third order stream. Well 52 is completed in the Magoffin Member. The Magoffin Member intersects Lick Branch, a stream that is probably a regional discharge zone in this vicinity, on the basis of the findings in the Star Fire investigation. A 292 feet-deep open well, completed to a greater depth than well 50, has a higher head than well 50, indicating that there is an increase in head with depth. This supports a regional discharge zone in the vicinity of Lick Branch.

Fishtrap Lake Site, Pike County

This study, conducted by the U.S.G.S. in 1985 and 1986, was initiated to investigate hydraulic connection in fractured bedrock using dye traces and to make a determination whether or not ridge-top and hill-side land uses are geologically isolated from lower aquifers. The site is located on the Lick Creek 7.5 minute quadrangle map along a ridge adjacent to Levisa Fork and Grapevine Creek (Figure 61). Grapevine Creek is a third-order

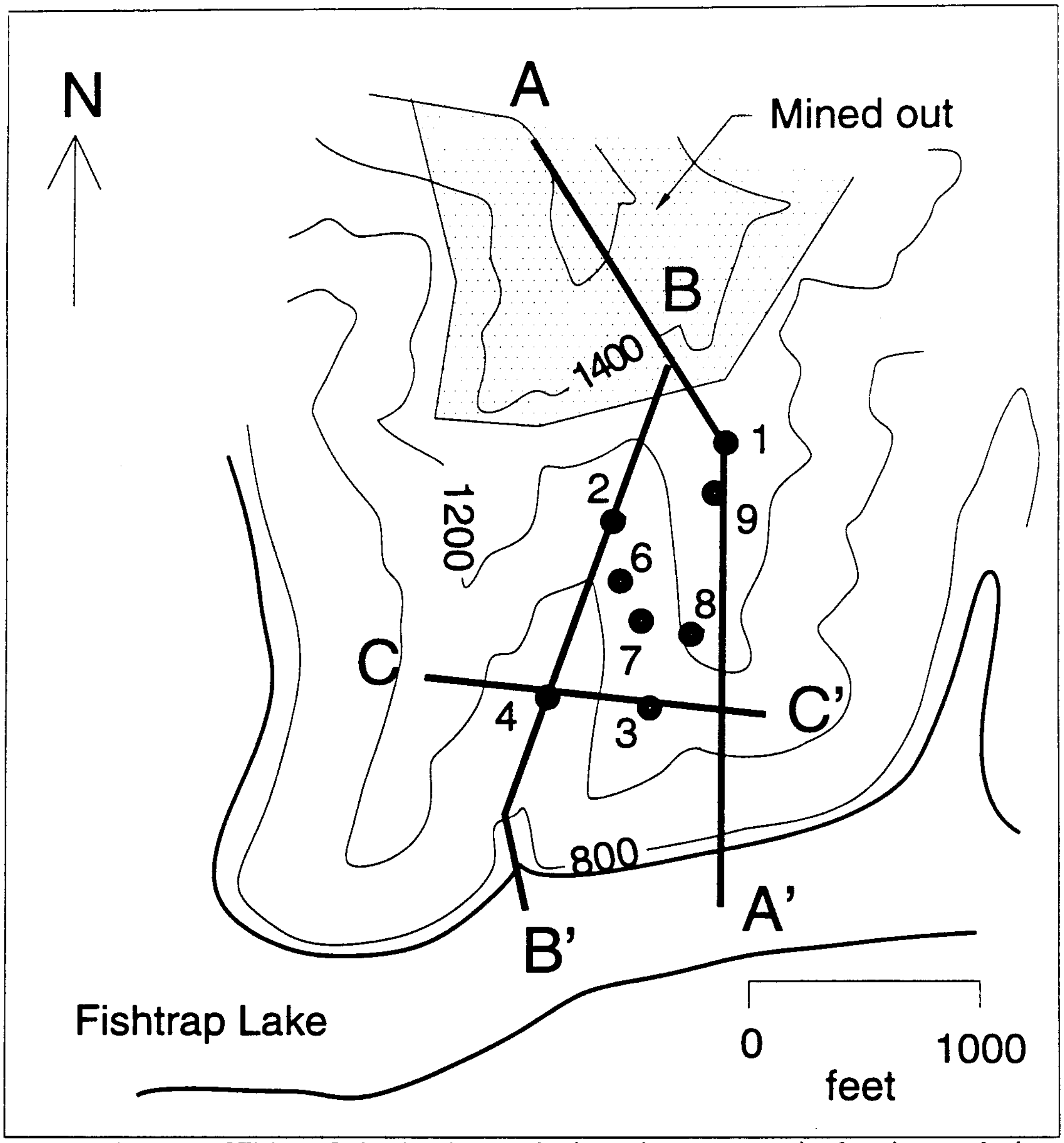


Figure 61. Location map of Fishtrap Lake showing monitoring points, cross-section locations, and mine works.

stream and Levisa Fork is a major river. Both streams are part of the artificially impounded Fishtrap Lake.

Eight core holes were drilled in various topographic positions along the ridge to characterize stratigraphy and determine fracture locations (Figure 61). Selected intervals from all holes were pressure-injection tested to determine approximate hydraulic properties. Equivalent-porous-media-conductivity values were calculated by the author of this dissertation from field data. Hydraulic conductivity in relation to depth is plotted in Figure 62. Small-diameter, multiple-completion piezometers were installed in the core holes. The upper sections of several holes were left as open-hole wells in shallow fractures. Piezometer and well data are summarized in Table 14. Piezometer intervals are illustrated in cross section in Figures 63, 64, and 65.

After completion of the study, it was reported that the boundary of a mined-out coal seam was located within a few hundred feet of Hole 1 (U.S.G.S., 1990). Cross section A-A: (Figure 63) and the site map (Figure 61) show the proximity of the mine to drill holes on the upper part of the ridge. Two of three piezometers in nest 1 are stratigraphically above the mine. Water-level and dye injection data indicate that all three piezometers in the nest are hydraulically connected. There is a possibility that nest 1 was affected by mining, and therefore; it will not be included in the analysis. Piezometer 9P is also close to the mine and will not be used. The remaining piezometers are stratigraphically below the mine and data are probably not impacted by mining.

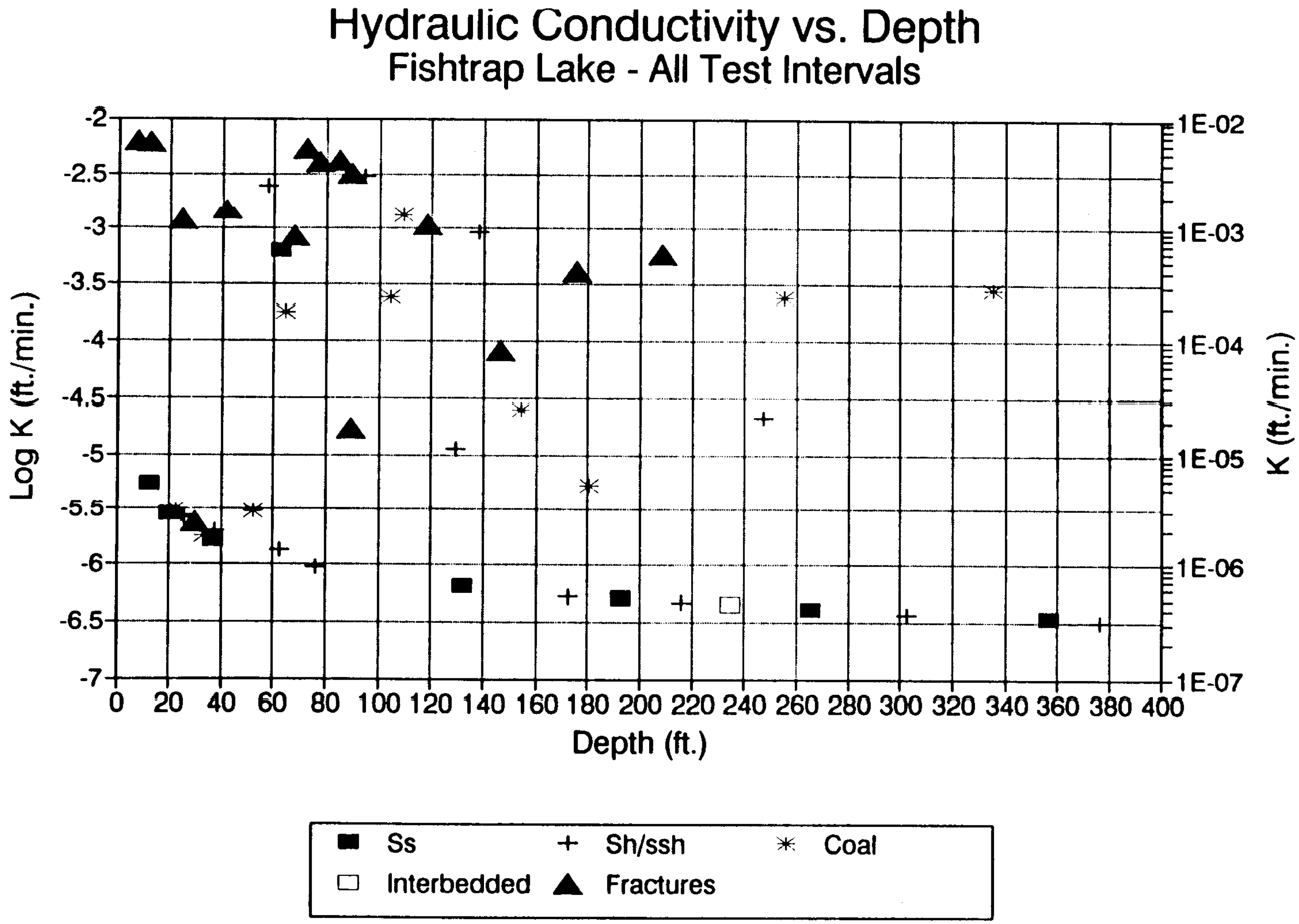


Figure 62. Distribution of hydrraulic conductivity with depth for all core holes at the Fishtrap Lake site.

Table 14.—Summary of Screened Intervals for the Fishtrap Lake Site.

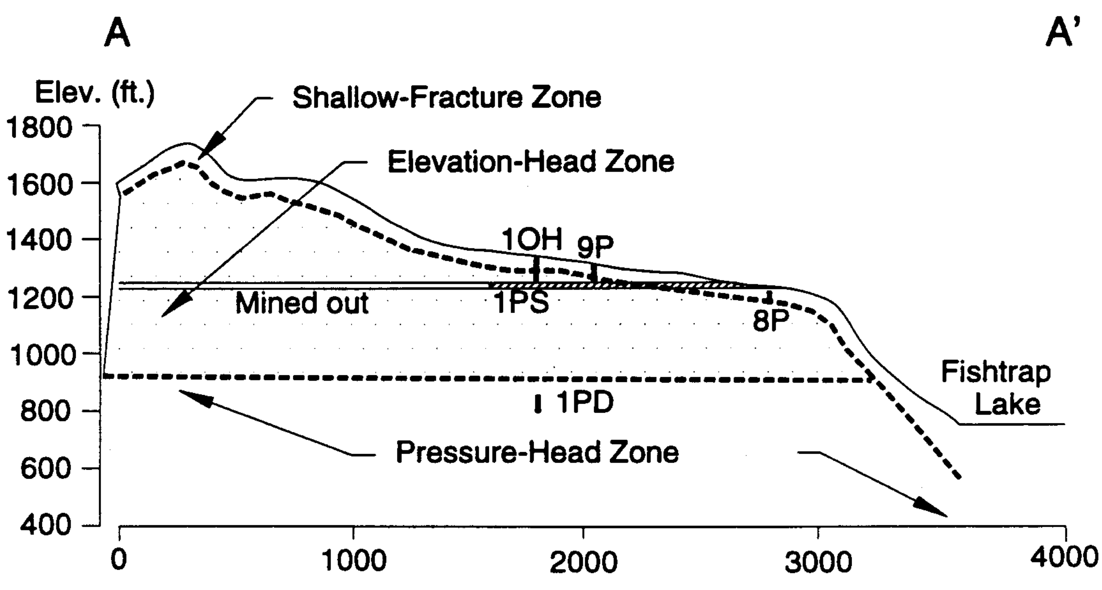
Piez. No.	*Total Depth (ft.)*	*Surface Elev. (ft.)*	*Top of Monitored Interval Elev. (ft.)*	*Bottom of Monitored Interval Elev. (ft.)*	*Min. Water Level Elev. (ft.)*	*Max. Water Level Elev. (ft.)*	*Monitored Interval**
1OH	61.0	1358.5	1353.5	1297.5	1301.2	1307.9	sf
1PS	209.5	1358.5	1168.0	1142.5	dry	1167.1	f
1PD	333.5	1358.5	1028.5	1019.5	1138.7	1178.5	c
2OH	25.0	1059.5	1048.5	1031.5	1047.0	1052.2	sf
2P	183.0	1059.5	880.5	875.5	884.1	885.5	c
3OH	42.0	1136.9	1133.9	1094.9	dry	1102.4	sf
3PS	125.0	1136.9	1032.9	1009.0	1015.4	1016.3	c
3PD	257.0	1136.9	883.6	877.7	884.9	893.0	c
4OH	18.0	889.1	886.1	871.1	dry	878.2	sf
4P	32.7	889.1	860.2	855.6	862.0	864.1	c
6OH	44.0	1093.5	1090.5	1049.5	dry	1080.9	sf
6PS	55.0	1093.5	1045.5	1037.5	1038.2	1039.1	c
6PD	91.0	1093.5	1031.5	1001.5	1008.5	1009.7	f
7P	110.0	1105.5	1085.5	995.5	1011.2	1016.0	f
8P	50.5	1233.5	1224.5	1183.0	1194.9	1205.8	sf
9P	50.5	1317.5	1308.5	1267.0	1272.3	1285.9	sf

* sf–shallow fracture; f–fracture; c–coal

Note: Piezometers 1OH, 1PS, 1PD, and 9P are not included in data interpretation.

GROUND-WATER ZONES

Strata in this study area are in the lower Breathitt Formation. The Magoffin Member is only present in isolated patches on the higher ridges. No water-quality data were available from this investigation; consequently, ground-water



Shallow-fracture zone - 8P

Figure 63. Cross section A–A' (see Figure 61 for location) showing screened intervals and ground-water zones for the Fishtrap Lake site.

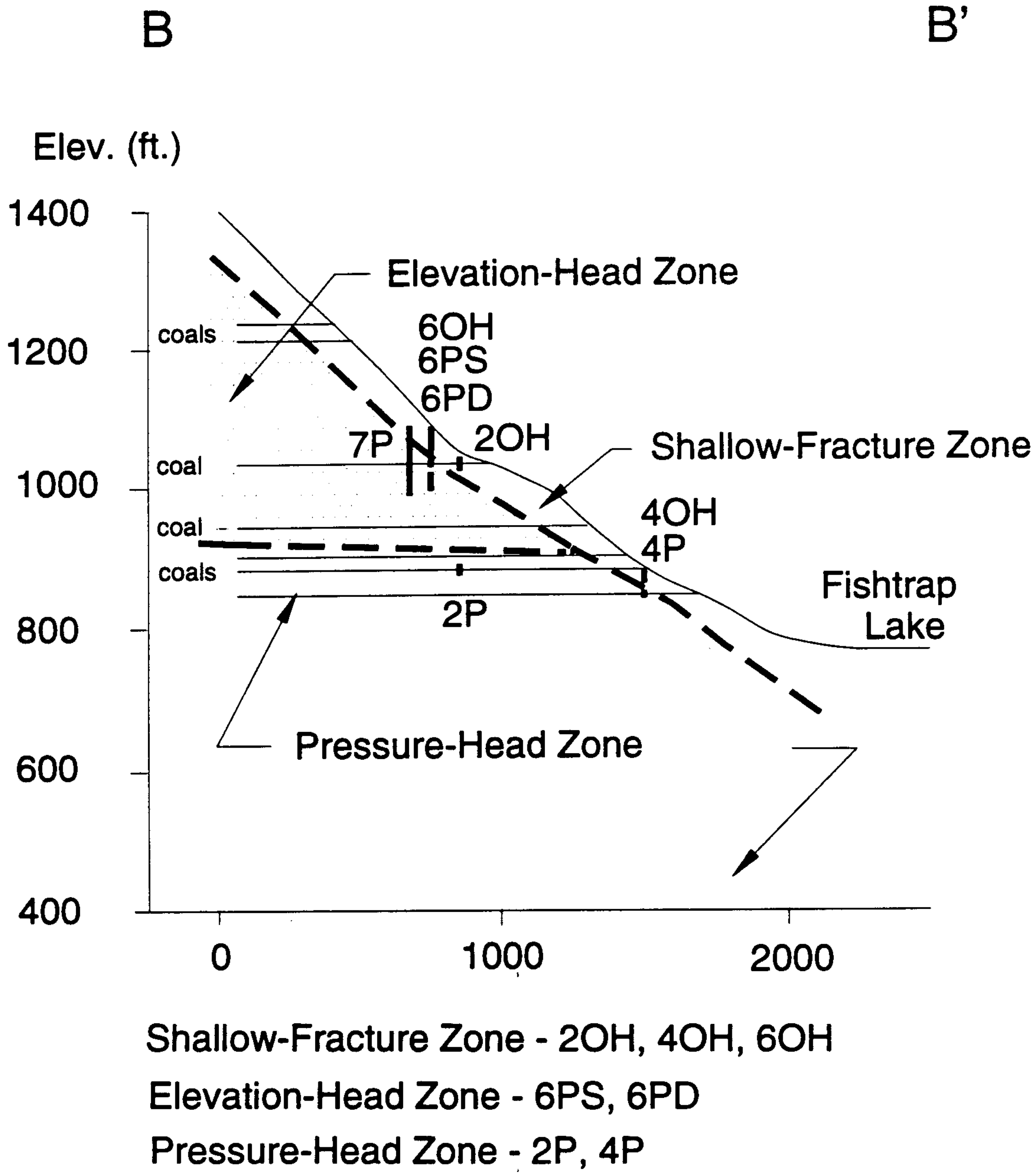


Figure 64. Cross section B–B' (see Figure 61 for location) showing screened interval and ground-water zones for the Fishtrap Lake site.

zones, relating to water types, were not evaluated.

Data from six core logs (2,3,4,6,7,and 8) show that strata on ridge tops and valley sides are commonly fractured to a depth of 40 to 50 feet. Qualitative inspection of core data suggests that fracture frequency is greater in sandstone-dominated strata than in shale. Where shale is underlain by sandstone, the underlying sandstone shows more fractures than the overlying shale unit. Two of the six core holes, located in a V-shaped valley bottom, showed very few fractures.

Five monitoring Points, 20H, 30H, 40H, 60H, and 8P, are in the shallow-fracture zone. Because water levels relative to fracture locations are known, possible effects of fractures on water levels may be evaluated. Figure 66 shows fractured intervals and water levels for the five monitoring points in the shallow-fracture zone. Water levels fluctuate seasonally; water levels are lowest in the dry fall months.

One valley bottom well, 20H, does not contain any fractures in the monitored interval. This well remained dry much of the year, containing water only in late winter.

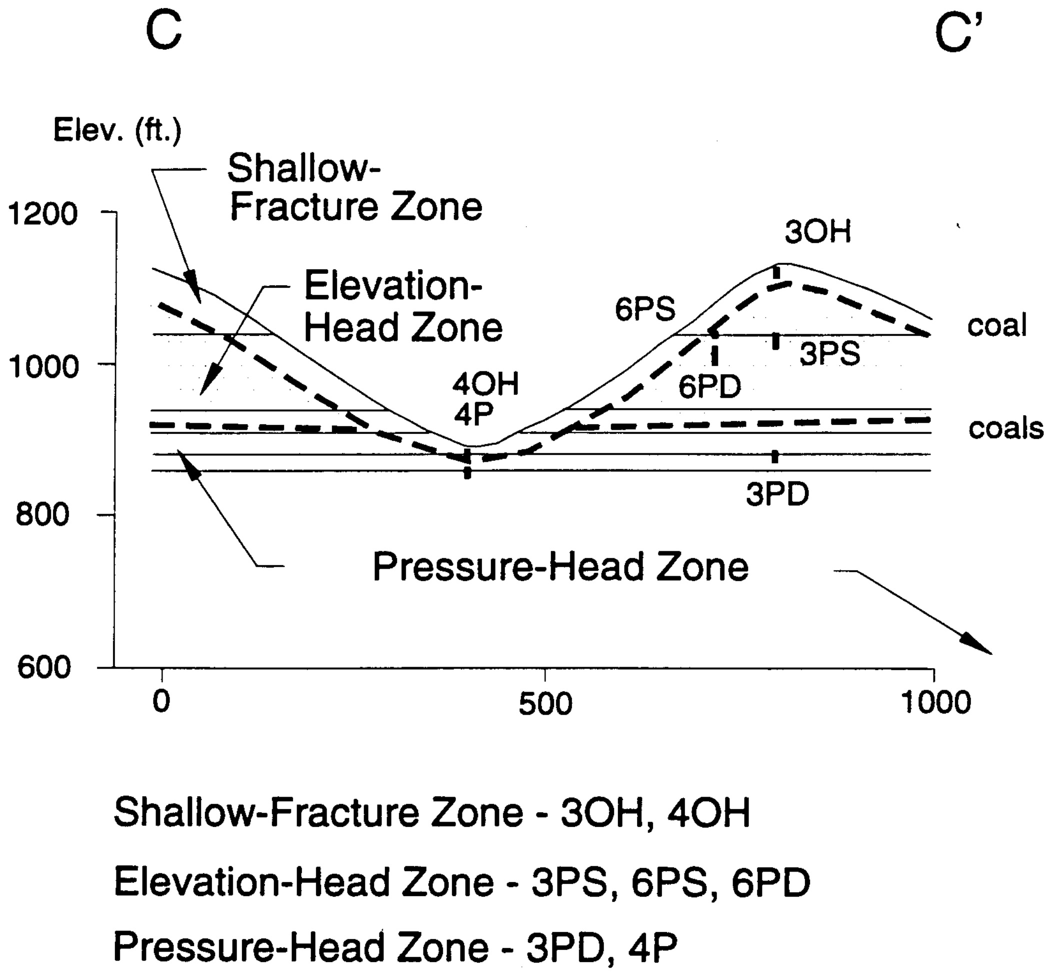


Figure 65. Cross section C–C' (see Figure 61 for location) showing screened intervals and ground-water zones for the Fishtrap Lake site.

The maximum water-level elevation in piezometer 30H may be controlled by the fracture zone between 33 and 35 feet. At minimum water levels, water probably cascades into the well from both overlying fractures. This piezometer, located on the nose of a ridge, has a very small recharge area. Sustained recharge is probably unavailable except during very wet periods.

Piezometer 40H shows wide fluctuations in water level. Water levels are generally above the fracture zone, except in late summer-early fall, when the piezometer goes dry. During periods when the water level is above the fracture, the water level may represent head either in a single fracture or in a system of interconnected fractures. During dry periods, water may drain out of the well. During wet periods, water inflow is sufficient to maintain water in the well, possibly corresponding to an overall rise in the water surface within the shallow-fracture zone.

Well 60H probably has a maximum static water level controlled by a fracture at 12 feet. Head in the interval may represent the head of the fracture at 23 feet during the part of the year where water level is above this fracture. The fracture in this well may or may not be hydraulically connected to surrounding fractures. This well goes dry in the fall and responds to precipitation, indicating that the fractures are variably saturated during the year.

Piezometer 8P illustrates a situation where the spring water level may represent head in a different zone than in the fall. In the fall, only the lowest fracture zone is submerged. In the spring, the water level rises above another fracture zone at 35 feet, indicating that a greater part of the system is saturated. Water-level fluctuation relative to fracture locations indicate that water levels may represent heads in different parts of the system at different times of the year.

Well 7P extends below the shallow-fracture zone, but construction is typical of domestic water supplies. The maximum water level may be controlled by a fracture at 88 feet. Falling water levels indicate that in flow, probably from fractures, declines in response to lower rainfall during

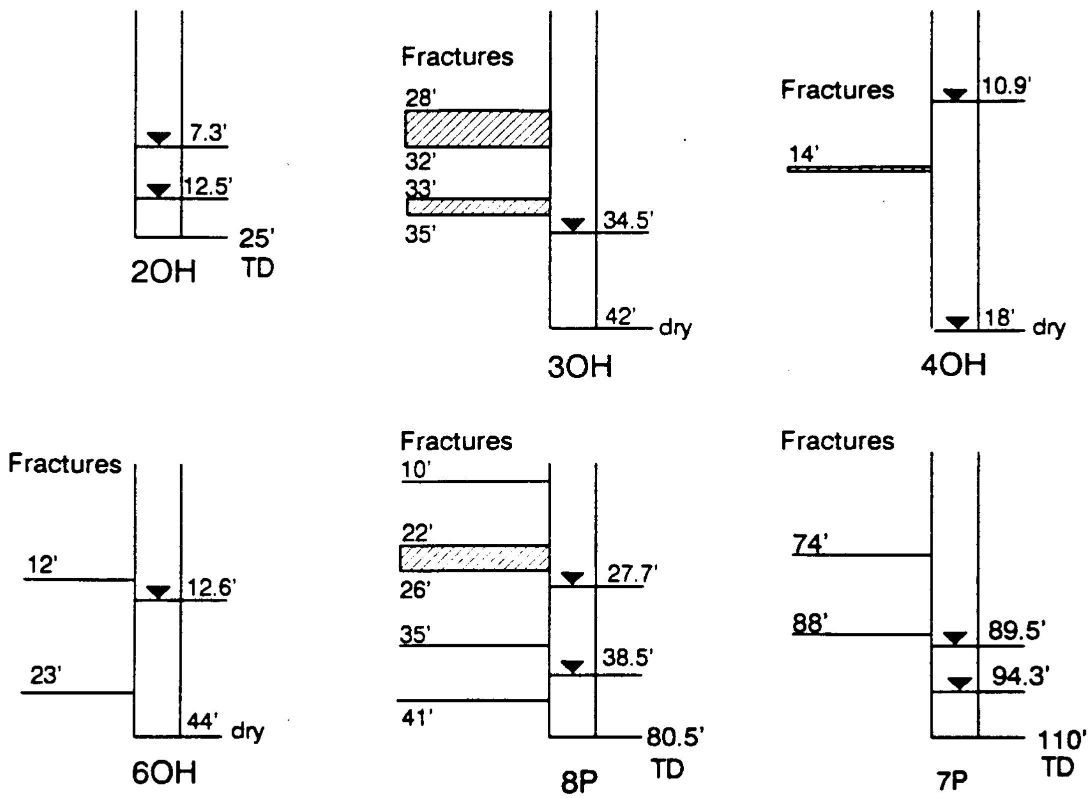


Figure 66. Water levels relative to fracture zones for six wells located in the shallow-fracture zone at the Fishtrap Lake site.

dry periods. Wells that terminate below the shallow fracture zone hold water because water cannot flow out through less conductive strata faster than it can flow in from overlying fractures.

Several coal beds, ranging from one to seven feet in thickness, are present in the ridge above Fishtrap Lake. Pressure-injection-test data show large conductivity differences between coal beds and other strata. This situation, similar to the Edd Fork and Star Fire sites, promotes strong horizontal flow in coal beds and vertical flow in the intervening rock mass. Three piezometers, 3PS, 6PS, and 6PD, illustrated in cross sections B-B' and C-C'(see Figures 64 and 65), maintain water levels within the open interval. These piezometers did not go dry in the fall and exhibited little short-term fluctuation. These responses indicate that they are not part of the shallow-fracture zone. There is a gradient of approximately one-foot per foot downward between piezometers 6PS and 6PD. The above characteristics are similar to those observed in the elevation-head zone at other sites.

Piezometers 2P, 4P, and 3PD, shown in cross sections B-B'and C-C'(see Figures 64 and 65), exhibit water levels that represent artesian conditions. These piezometers are completed in coal beds at elevations between 855 and 875 feet. Piezometer 4P is 32 feet deep; however, the hole shows little fracturing. Because the coal bed is artesian, piezometer 4P was not included in the shallow-fracture zone. Insufficient piezometric data are available at this site to accurately locate the boundary between the elevation-head zone and the pressure-head zone. Piezometers that are believed to be representative of the three zones are identified on cross sections A-A!, B-B'and C-C'(see Figures 63,64, and 65).

CONCEPTUAL MODEL OF LOCAL AND REGIONAL GROUND-WATER FLOW

Objective

The objective of this section is to describe general characteristics of the five ground-water zones identified from site-specific investigations and integrate the ground-water zones into a conceptual model of local and regional flow.

Ground-Water Zones

Above-Magoffin-Member-Zone and Below-and-Including-Magoffin-Member Zone

Three sites, where the Magoffin Member is regionally present, show a marked change in water quality between strata above the Magoffin and strata within or below the Magoffin. Strata located above the Magoffin Member, referred to as the above-Magoffin-Member zone, has ground-water that is predominantly a calcium-magnesium- bicarbonate-sulfate type. Groundwater in the below - and - including - Magoffin - Member zone is predominantly sodium-bicarbonate type or sodium-chloride type. These water types are apparently independent of drainage position and are present where the Magoffin is above or below drainage. As documented by Wunsch (1992), infiltration of water from the surface via fractures creates zones of mixed water types, especially at shallow depths.

Bienkowski (1990) divided the Breathitt Formation into two hydrologic units, distinguishable by chemical differences, on the basis of regional analysis of publicly available well data. Strata from the base of the Magoffin Member to the top of the Lee Formation were included in the Lower Breathitt hydrologic unit. Strata from the base of the Magoffin to the Conemaugh-Breathitt Formation contact were termed the Magoffin hydrologic unit (see Figure 15). Chemical analyses were limited to pH, alkalinity, total iron, total manganese, sulfate, specific conductance, and total dissolved solids. Major and minor ion analyses were not evaluated. Wells in the Magoffin hydrologic unit were higher in manganese and total dissolved solids than water in the Lower Breathitt hydrologic unit throughout the coal field. The Magoffin hydrologic unit above drainage has a lower pH, than the Lower Breathitt hydrologic unit. Where both hydrologic units are below drainage, total iron is higher in the Magoffin hydrologic unit (Bienkowski, 1990). Chemical data from Star Fire (Wunsch, 1992) supports the lower pH values for strata above the Magoffin in above-drainage situations. In Edd Fork, where the Magoffin Member is below the level of Edd Fork, pH values are generally lower in strata above the Magoff in.

Direct comparison of water quality results from studies using discrete sampling intervals and results of the regional study by Bienkowskii (11990), however, is difficult. Most information obtained from Bienkowski's study is obtained from shallow, domestic-type wells with open hole completion and a mean depth of 113 feet. Water quality in shallow wells is influenced by infiltration of recent precipitation, and shallow wells in valley bottoms may represent mixed water types where highly mineralized, older water and younger, less mineralized waters intermingle. On the other hand, discrete sampling intervals at site-specific locations minimize intermixing of ground water from different zones. Another problem is the lack of comparable data. The Star Fire data do not include the same analytes as used in the regional study by Bienkowski (1990).

Recent water-quality data from the Star Fire and Edd Fork investigations indicate that water within the Magoffin Member is more similar to water below the Magoffin than that above it. For this reason, the boundary differentiating above and below Magoffin strata should be placed at the top of the Magoffin Member rather than below it.

Shallow-Fracture Zone

The shallow-fracture zone in eastern Kentucky is a zone of highly fractured strata that parallels the land surface to a depth of 50 or 60 feet. The exact mechanism of fracture development is unknown, however, it is likely a combination of tectonic jointing, overburden unloading, and surficial weathering processes. Possibly, release of stress from overburden unloading occurs along existing joint planes. Surficial weathering may enhance fracture openings. Fractures, both in outcrops and drill holes, have near-vertical orientations. At least one orthogonal set is generally present. Near-horizontal bedding plane fractures are also noted in some core holes. Core holes drilled in V-shaped valleys seem to exhibit fewer fractures than holes drilled in other topographic settings. This observation is supported by stream-valley studies by Hill (1988). The effect of lithology on the distribution of fractures requires more data than are available from this study; however, it is known that fracture spacing differs among lithologies and that fractures may terminate at lithologic boundaries.

High values for hydraulic conductivity in the shallow-fracture zone are directly attributable to fractures general, the equivalent-porous-media-hydraulic-conductivity calculated from pressure- injection tests is approximately 1,000 times greater in fractured rock than in less-fractured strata. Fracture frequency is high in the shallow-fracture zone, as noted in drill logs, increasing the likelihood of intercepting a conductive fracture during hydraulic testing. Intervals in the shallow-fracture zone that do not intercept fractures have hydraulic conductivity values similar to deeper strata, indicating that conductivity is fracture dependent.

Depth to the water table is variable, and is affected by rainfall, topography, fracture location, and previous surface disturbances. Piezometer response to individual precipitation events is rapid and transient, generally lasting less than a day. Saturation conditions are transient as well. Rainy periods cause a rise in the water table throughout the shallow-fracture zone. This is apparent in piezometers in the valley sides and ridges, as well as in valley-bottom piezometers. Fractures that may be unsaturated during dry weather and are above the static-water level become submerged during rainy periods. Abrupt water-level increases in valley bottoms result from increase in head in the shallow-fracture system. Water levels decline as water discharges through fractures to adjacent streams. Seasonal effects are similar, piezometers that contain water during the winter and spring may go dry during extended dry periods, indicating a lower saturated zone.

The position of water levels relative to fracture location illustrates the difficulty of identifying the saturated parts of the shallow-fracture zone. Fracture zones in open intervals may allow water to freely drain out of the piezometer to a zone of lower head. Water from higher, potentially saturated fractures commonly cascades into piezometers or wells if water levels in wells are below the fractures. Flow out of wells may also be greater than incoming flow, resulting in a dry well, or a water level in the well that is below the level of saturated fractures. If fractures are well connected, a continuum may exist, and water levels may represent the head of the continuum or the position of the water table. If individual fractures are poorly connected, a continuum may not exist and water levels may represent very local head. Additionally, the shallow-fracture zone is dynamic, exhibiting transient head conditions that may change daily.

General conclusions about the position of the water table may be drawn from available data. Static-water levels are generally deeper on ridge tops and upper valley slopes than in valley bottoms. The upper surface is probably irregular; being higher where recharge is more direct and lower where less direct infiltration occurs.

Because the shallow-fracture zone receives direct recharge from precipitation, surface disturbances may alter recharge to this zone. Where surface runoff is high, less water may infiltrate. Surface mining removes much or all of the shallow-fracture zone and may clog underlying fractures, resulting in diminished infiltration to deeper zones. Overlying mine spoil may store precipitation and buffer recharge to the shallow-fracture zone.

Flow through the shallow-fracture zone is difficult to quantify. Fracture flow may be non-Darcy flow because, of the potential for turbulent flow and because on a small scale, a continuum in both space and time, may not exist. Because flow is highly fracture dependent, estimates of discharge based on fracture frequency and properties are preferred. However, more information than is presently available on the distribution, spacing and aperture of fractures is required to quantity flow using these methods. It is evident, though, that significant flow passes through shallow fractures. Streams in small basins are commonly flashy; hydrographs show steep rising and falling limbs. It is reported that surface (overland) flow in forested watersheds is virtually nonexistent and that runoff is in the shallow subsurface (Springer and Coltharp, 1978). Runoff studies in an undisturbed, eastern Kentucky watershed by Springer and Coltharp (1978), indicate that 31.5 inches (59 percent of total precipitation) is subsurface storm runoff. Because of shallow soil cover and the rapid response of shallow piezometers to precipitation, it seems reasonable that at least part of subsurface storm runoff is through the shallow fracture zone. Slow release of water from storage in this zone probably sustains flow in first-order streams. During extended dry periods small streams may go dry, when water in the surface-fracture zone is depleted.

Water quality in the shallow-fracture zone is variable. Fracture-zone wells in small, relatively pristine basins are predominantly calcium, magnesium, sulfate, and bicarbonate waters. Iron and manganese are variable. Total dissolved constituents are variable, ranging in this study from less than 50 mg/L to more than 800 mg/L. The magnitude of the values is not necessarily related to mining impacts, but, may be more dependent on proximity to direct recharge, location within the flow system, and lithology. Shallow wells in recharge zones are generally low in total dissolved solids because of rapid influx of rain water (Wunsch, 1992). Wells in close proximity to coal beds may have pH values in the acidic range and contain significant amounts of iron (Wunsch,1992). Shallow wells, close to third-order or higher streams, commonly contain significant amounts of sodium and chloride, the result of mixing of deep water with shallow water.

Elevation-Head Zone

The elevation-head zone, located above drainage, is characterized by a downward head loss over the entire interval of approximately one-foot-per foot. The overall vertical gradient is attributable to hydraulic stratification resulting from highly conductive coal beds that are interbedded with poorly conductive sandstone, shale, and claystone.

Lithologic stratification creates hydraulic stratification where conductivity differences between coal beds and other strata may be four orders of magnitude or more. Such conductivity extremes between coal beds and non-coal strata, creates a situation where flow is near-vertical in the non-coal strata and more nearly horizontal in the coal beds.

The influence that coal seams exert on the flow system can be investigated by calculating horizontal deflection of flow in coal beds and by estimating the potential discharge through coal beds.

Fractures are present in the elevation-head zone although frequency is less than in the shallow-fracture zone. Loss of drilling circulation in this zone and fracture-controlled heads indicate that fractures influence flow locally in this zone, but the net impact of fractures throughout the elevation head zone is unknown.

The effects of stratification on ground-water flow can be investigated using the Tangent Law as it applies to refraction of ground-water flow lines. Flow lines that cross boundaries of different hydraulic conductivity refract (Figure 67a) according to the following relationship (Freeze and Cherry, 1979):

$$\frac{K_{coal}}{K_{rock}} = \frac{\operatorname{Tan}\Theta_{coal}}{\operatorname{Tan}\Theta_{rock}}$$

where:

K_{coal} = Hydraulic conductivity of coal

K_{rock} = Hydraulic conductivity of rock

Tan Θ_{rock} = angle of flow into coal

Tan Θ_{coal} = refracted angle

The horizontal travel of a water particle within a stream tube can be estimated using this relationship. Three factors impact the horizontal distance travelled through a coal bed; the conductivity ratio of the two units, the angle of incoming flow, and the coal-bed thickness. The incoming-flow angle is estimated at 0.1 degree Theta_{rock}. To estimate the impact of conductivity changes, conductivity ratios are varied over four orders of magnitude. Figure 67b shows the effect of flow line refraction per foot of coal thickness. Lateral deflection for a one-foot-thick coal bed ranges from 0.01 foot for a one order of magnitude difference in conductivity to 17.5 feet of lateral deflection where coal is 10,000x more conductive than rock. In a typical hillside, where coal is 1,000x more conductive than rock and totals 10 feet thick, maximum theoretical horizontal flow for a water particle would be 17.5 feet. Because coal is generally thin and flow lines must intersect rock below the coal, some part of the total flow must pass into the underlying strata.

Darcy's Law may be used to calculate the volume of water discharge through a coal bed. The following assumptions are used:

1. Darcy's Law is valid.
2. Incoming flow is vertical and the gradient is one foot per foot.
3. Flow within the coal is horizontal and the gradient is calculated using the coal thickness divided by the length of travel. Gradients in coal beds are low because head is generally located within or near the top of the coal.

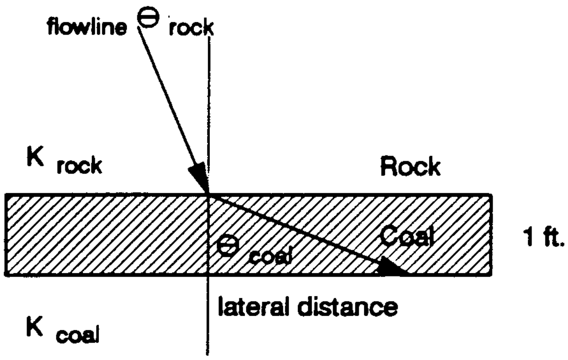
Figure 68a is a schematic of the theoretical conditions. Calculations using a reasonable range of conductivity values for coal and rock produce a wide range of ratios for flow-out versus flow-in. If the lowest conductivity value is used for rock and the highest value is used for coal, then coal can transmit 3,000x as much water as flows in. Conversely, if vertical conductivity of the rock is on the order of $7x10^{-6}$ feet per minute and coal conductivity is low, on the order of $1 x10^{-5}$ feet per minute, then the rock transmits 10,000x more water than the coal. Using mid-range values of $7x10^{-7}$ feet per minute for rock and $1x10^{-4}$ feet per minute for coal; the rock has the potential to transmit 120 times more water than does coal. It is not unreasonable to conclude that incoming flow from rock is greater than outgoing f low from the coal, given the greater cross-sectional area of the rock (400 square feet for rock and 3 square feet for coal).

From this illustration, one can see the importance of conductivity estimates. Vertical conductivity in rock may be dependent on fractures and in-situ vertical conductivity measurements are virtually non-existent. On the basis of observed discharge from coal beds and piezometer water levels that are within coal beds, it is apparent that coal beds discharge considerable flow. That amount, however, may be small compared to the volume of flow that may recharge deeper systems.

Water levels in the elevation-head zone near the ridge interior are generally stable, seldom varying by more than a foot. Water levels in piezometers nearer valley walls fluctuate by several feet, because of their closer proximity to surface fractures.

The base of the elevation-head zone is probably associated with a coal bed that can effectively relieve head in overlying units. However, it is not necessarily the lowest above-drainage coal bed. Confined conditions exist in some above-drainage coal beds. Data from available sites suggests that the base of this zone may also be related to distance above drainage. If coal seams are present within a ridge above drainage ' regardless of stream size, at least 70 percent of the above-drainage strata (below the shallow-fracture zone) will be in the elevation-head zone.

(a)



(b) LATERAL MOVEMENT IN COAL BEDS

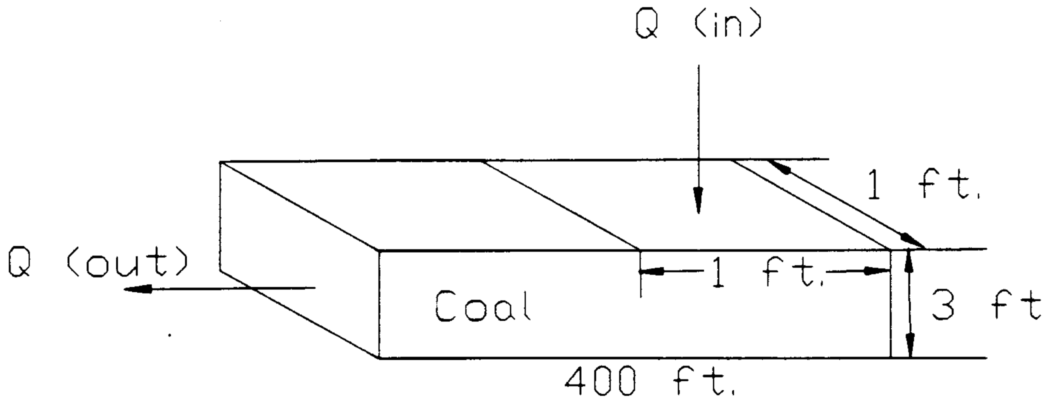
Order of Magnitude	Ratio of K (coal) to K (rock)	Ratio of K (rock) to K (coal)	Theta (rock) (degrees)	Lateral Movement per Foot of Coal Thickness (feet)
1	10	0.1	0.1	0.0175
	20	0.05	0.1	0.03
	50	0.02	0.1	0.09
2	100	0.01	0.1	0.175
	150	0.006	0.1	0.29
	500	0.002	0.1	0.87
3	1,000	0.001	0.1	1.75
4	10,000	0.0001	0.1	17.5

Figure 67. (a) Flowline refraction at rock/coal boundary and (b) lateral movement of water in coal per foot of coal thickness.

Pressure-Head Zone

The pressure-head zone extends from the base of the elevation-head zone (or the shallow-fracture zone near valley bottoms) to the fresh-saline-water interface. Although the ground-water system is confined and saturated below the interface, the fresh-saline-water interface is a convenient boundary because it marks the limits of fresh ground water. Strata above drainage eventually build up head because pressure is no longer relieved laterally. Conductivity differences between coal beds and other lithologic units are smaller than in shallower rocks. Fracture zones, generally associated with stream valleys, are highly conductive and produce use able amounts of water. Rocks that do not contain open fractures or that contain poorly connected fractures are saturated but yield very little water. Lowest calculated horizontal values for this zone are approximately $1x10^{-7}$ feet per minute.

Few piezometers are located in this zone, consequently, head distribution and flow are poorly understood. There is generally a gradient (0.037 foot per foot at Star Fire) from the ridge interior toward major drainage. Vertical-head drops near drainage are an order of magnitude greater than apparent horizontal gradients indicating at least some part of the flow is moving vertically



Darcy's Law: Q = KA dh/dl

where: Q = discharge
K = hydraulic conductivity
A = cross-sectional area
dh/dl = hydraulic gradient

K (ft./min.)	Q (in) (cf./min.)	K (ft./min.)	Q (in) (cf./min.)
7E-06	2.8E-03	1E-03	2.3E-05
7E-07	2.8E-04	1E-04	2.3E-06
7E-08	2.8E-05	1E-05	2.3E-07
7E-09	2.8E-06		

(b)

Figure 68. (a) Schematic of theoretical conditions used for calculating flow into and out of coal and (b) calculation of volume of water transmitted over a range of hydraulic conductivity values in coal.

into a regional flow system. Gradients in this zone depend on location within the flow system.

THE FRESH-SALINE-WATER INTERFACE

The fresh-saline-water interface is the lower boundary of fresh ground-water flow in Kentucky. Its location with respect to major stream valleys is documented by Hopkins (1966) and Wunsch (1992) in Kentucky. Its depth beneath upland areas is not documented; however, drill data indicate that the interface is deeper in these areas than near stream valleys (Wunsch, 1992). The argument that the interface is depressed below ridges may be substantiated from ground-water theory using following equation (Davis and DeWeist, 1966):

$$\text{Sin } \alpha = -\left[\frac{1}{K_f} * \frac{\varrho_f}{\varrho_f - \varrho_s} * V_{f,s} - \frac{1}{K_s} * \frac{\varrho_s}{\varrho_f - \varrho_s} * V_{s,s}\right]$$

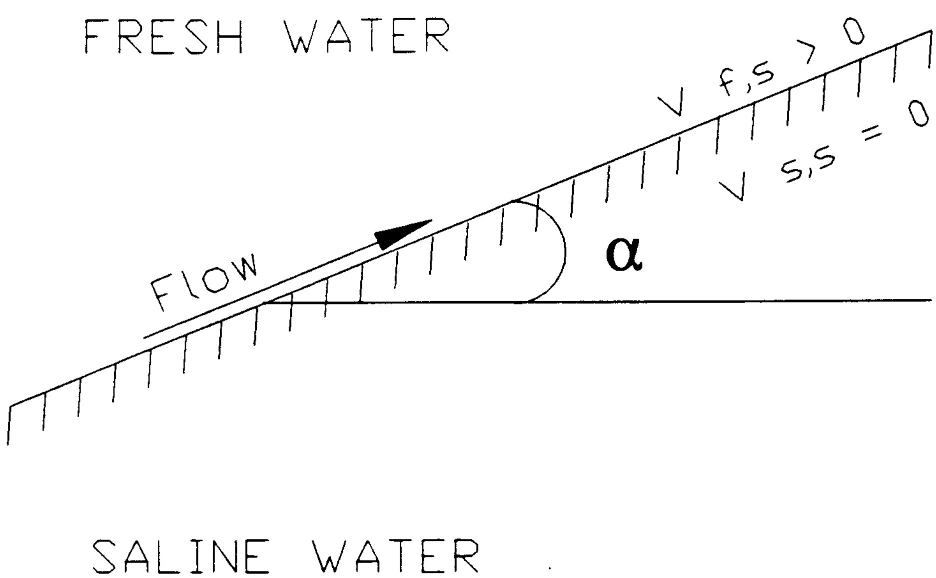
Components are illustrated in Figure 69 and assumptions for the analyses follow.

1 . The fresh-saline-water interface is a discrete boundary and is, therefore, a flow line.
2. Saline water below the interface is stagnant: fresh water flows above it. $V_{f,s}$ and $V_{s,s}$ are components of darcy velocity along the interface, where, $V_{f,s}$ does not equal 0 and $V_{s,s}$ is equal to 0.
3. The density of fresh water is less than saline water and is represented by ρ_f and ρ_s, respectively.
4. Hydraulic conductivity above and below the interface is K_f and K_s, respectively.
5. The slope of the interface is sin (alpha).

Because it is assumed that there is no flow below the boundary, the last terms in the equation are zero and the equation becomes:

$$\text{Sin } \alpha = -\left[\frac{1}{K_f} * \frac{\varrho_f}{\varrho_f - \varrho_s} * V_{f,s} - 0\right]$$

Sin(alpha) increases with increasing values of $V_{f,s}$. Because sin(alpha) is positive, the interface slopes upward in the direction of flow of the overlying fluid. Because ground water flows from the ridge interiors toward the major stream valleys, the interface must be deeper under ridges than under streams. The magnitude of the interface slope is controlled by the flow velocity and hydraulic conductivity of the strata. Because the cross-sectional area of fresh-water flow decreases closer to the discharge zone, flow, conductivity, or both, must increase. If this change in hydraulic properties is a shallow phenomenon, the interface may rise sharply closer to the stream valley. The interface may be flatter under the upland areas where flow is slow and there is a larger cross-sectional area for fresh water to flow.



$$Sin\alpha = -\left[\frac{1}{K_f} * \frac{\rho_f}{\rho_f - \rho_s} * V_{f,s} - \frac{1}{K_s} * \frac{\rho_s}{\rho_f - \rho_s} * V_{s,s}\right]$$

Figure 69. Darcy-velocity components for determining the slope of the fresh-saline-water interface (modified from Hubbert, 1940).

Conceptual-Flow Model

Local and regional flow systems are identifiable in the Eastern Kentucky Coal Field. The shallow-fracture zone comprises the local flow system. Water that does not discharge via shallow fractures becomes part of the regional system. Part of this deeper flow system may discharge as a more intermediate system in intervening valleys, but, in the context of this discussion, intermediate flow is more similar to regional flow systems than local flow systems.

First-Order Stream Basins

Low-order, upland streams are sustained by local ground-water flow in the shallow-fracture zone. There is a loss of head below first-order streams, indicating that deeper strata do not discharge to these streams. Water levels in valleys of first-order streams show that heads only rise above stream level at shallow depths within the shallow-fracture zone.

Third-Order and Larger Stream Basins

Third-order streams derive flow from both local (shallow-fracture zone) flow systems and regional-f low systems. Water in the regional system flows downward from the upland areas toward the fresh-saline-water interface. Because saline water is considered stagnant relative to fresh water, flow must eventually parallel the interface in the direction of major stream valleys. A conceptual model of ground-water flow in the Eastern Kentucky Coal Field is shown in Figure 70.

GROUND-WATER MONITORING STRATEGY

Objective

The fourth objective of this study is to develop a ground-water monitoring strategy that will detect adverse quality and quantity changes to ground-water resources.

Monitoring Strategy

A highly used ground-water resource and one subject to disruption from surface and underground disturbances in the Eastern Kentucky Coal Field is the shallow-fracture zone. According to Bienkowski (1990), most water wells in the coal field are less than 100 feet deep and few are deeper than 225 feet. Shallow, fractured bedrock is obviously an important, and virtually irreplaceable ground-water resource for many domestic users. Because most of the ground-water flow is within 100 feet of the surface, surface activities have the potential to seriously disrupt ground-water supplies, either by removing the shallow-fracture zone or by altering recharge, flow, or water quality. Underground mines also have the potential to affect shallow ground water where they discharge to the surface, intersect the shallow fracture zone, or drain ground water from overlying or adjoining strata.

Baseline Monitoring

In an area like eastern Kentucky that characteristically exhibits temporal or spatial water quality and quantity variations, documentation of seasonal baseline variations is essential. Examples of coal-field variations include documented differences in water quality above and below the Magoffin Member; detrimental constituents that may be linked to particular coal-bearing or coal-associated strata; or water quality variations associated with mixing water types, such as in discharge zones. Baseline conditions need to be defined, considering that much impact to ground water is attributable to mining, an activity that potentially magnifies undesirable ground water characteristics that may exist naturally. For example, shallow ground-water supplies are commonly impacted during periods of drought. Common complaints are diminished supply and inferior water quality, the same adverse impacts that are generally attributed to mining. Wells that may normally contain relatively low dissolved solids during periods of normal precipitation may go dry or exhibit an increase in dissolved constituents if more mineralized water is gradually released from storage. It may be difficult or impossible to distinguish these natural, long-term variations from mining-related impacts. A thorough documentation of seasonal flow and quality fluctuations is needed to establish a "normal" range of values.

Surface Mining

Surface mining impacts ground water in the shallow fracture zone in several ways. The most obvious impact is physical removal of all or part of the zone during the mining process. Other impacts may include changing recharge characteristics or altering water quality. These types of impacts have the potential to affect the usability of the shallow-fracture zone as a domestic water source.

Site-specific effects of surface mining may be monitored using shallow (within the fracture zone) wells located downslope of the proposed disturbance. In small basins, where baseflow is sustained by the shallow fracture zone, wells located near streams may allow more continual monitoring of ground water, especially if surface flow diminishes during dry weather. Shallow,

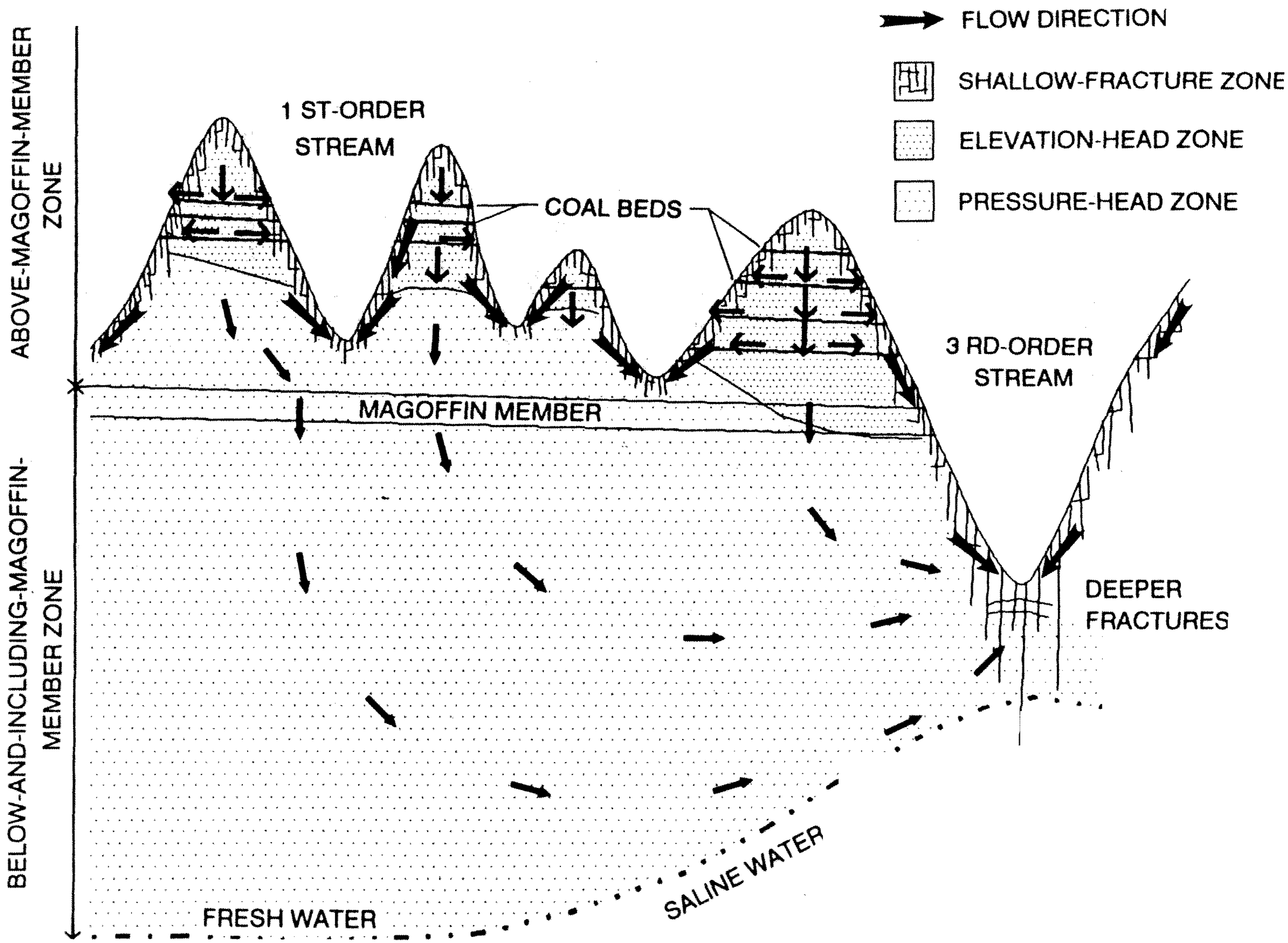


Figure 70. Conceptual model of local and regional ground-water flow showing the five ground-water zones.

subsurface flow commonly continues even though surface flow may cease.

Near larger streams, where the shallow fracture zone may include regional discharge as well as local discharge, monitoring wells should be located high enough on the hillside to avoid zones of mixed water types. For either small or large basins, monitoring wells located on the outer edge of mining benches and completed the entire thickness of the shallow-fracture zone, would detect immediate and localized impacts to the fracture-zone ground water.

Underground Mining

Underground-mining impacts to ground water vary depending on the mining method, the position of the mine relative to the elevation-head zone and the pressure-head zone, and whether or not the mine is above or below drainage.

The effects of room and pillar mining, a mining method that leaves sufficient coal in-place to prevent or minimize failure of overlying strata, may have minimal impact on ground water in overlying rock. Such mines can intercept the shallow4racture zone near the coal outcrop if a sufficient barrier is not left between the mined out areas and the valley wall. Potential drainage from the mine into fractures can affect water quality in the shallow-fracture zone if quality is poor, or cause increased flow through the fracture zone.

Mine works located in the elevation-head zone would not be expected to build up pressure head. Conditions are naturally atmospheric and inflow to the mine is ultimately determined by the conductivity of the overlying strata. The creation of high-conductivity conduits (entryways) would potentially after the nature of discharge from the mine. Rather than diffuse ground-water flow along the outcrop, flow would concentrate in the entryways and create "point-source" discharges. Mine water could preferentially enter the shallow-fracture zone along entryways near valley walls.

Mining in the pressure-head zone is more likely to disrupt the pressure distribution in the ground-water system by creating a low-pressure sink. The increased gradient toward the mine would result in the gradual depressurization of the surrounding strata. Hydraulic conductivity of the surrounding strata and the gradient toward the mine will ultimately control inflow to the mine. Strata in the pressure-head zone generally exhibit poor conductivity and are not generally used for water supplies. The area of importance, with regard to monitoring in this mining situation, is along coal outcrops where there is potential to impact shallow fractures.

Room-and-pillar, above-drainage mines, whether in the elevation-head zone or the pressure-head zone, create similar monitoring problems: (1) mining too close to the outcrop can result in infiltration of water into the shallow fracture zone from the mine works, (2) flow will be concentrated along entryways where flow of water is unrestricted and could increase water flow in the shallow4racture zone, (3) in the case of mines in the pressure-head zone, the mine works will remain a zone of high conductivity compared to the surrounding strata.

Monitoring above-drainage room-and-pillar mines should be concentrated along potential discharge points. Wells should be located in the shallow-fracture zone below adits. An outcrop barrier that is sufficiently wide to prevent interception of the shallow-fracture zone by underground mining would minimize potential impacts to shallow ground-water sources.

Mines in the pressure-head zone that are below drainage are most likely to impact overlying streams that are undermined and also, shallow fractures near the mine adits. These mines are, for the most part, located in the regional flow system and do not directly affect aquifers. Mines have the potential, however, to intercept fractures associated with valleys. Stress-release as a result of mining under V-shaped valleys has been documented to induce fracturing (Hill, 1988). Both situations have the potential to cause dewatering of streams or lowering of water levels in valley bottom wells. Monitoring should include surface monitoring of undermined streams and monitoring of wells in and immediately adjacent to stream valleys that may be adversely affected.

Mining methods, such as longwall or pillar-extraction mining, in which roof support is removed, impact ground-water in strata overlying the mine in addition to creating impacts similar to those associated with room-and-pillar mining. Mining-induced fracturing creates permanent or temporary changes in water quality or quantity. Such effects appear to be variable and are related to topography, geology, mine design, seam thickness, and depth of overburden.

Surface- Water Monitoring

Surface-water monitoring points effectively document changes the ground-water system in addition to assessing changes attributable to surface runoff. Because shallow ground water in small, upland watersheds discharges directly to streams, basin-wide ground-water quality and quantity changes can be effectively evaluated using surface-water monitoring methods. This method of monitoring ground-water changes is most effective during periods of little rainfall when stream water quality is most likely representative of ground-water quality. Monitoring stations upstream and downstream of proposed disturbances would provide much information on discharge variations and water quality in a small watershed. Multiple-basin monitoring points may be required where surface mining crosses drainage divides, such as in mountaintop mining.

Base flow in third-order or larger streams is sustained by regional flow as well as local flow through the shallow-fracture zone. In such situations, stream monitoring methods would not be diagnostic of mining impacts on ground water. Impacts related to surface runoff, however, can be observed.

Monitoring-Well Construction

Effective wells can be constructed with screened intervals open to the fracture zone. A blank section of pipe installed below the screen will capture water that may potentially pass through the well bore. Wells that continually produce water should be purged then immediately sampled. Wells that produce water intermittently can be sampled by allowing water to accumulate in the blank section of pipe. Other viable options for downslope monitoring are existing (or newly emergent) seeps and springs.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Ground-water flow in the Eastern Kentucky Coal Field is controlled by climate, topography, and geology. The humid, temperate climate provides nearly continuous recharge to the ground-water system. Steep topography promotes downward ground-water flow from ridgetops towards valley bottoms. Bedded and fractured strata complicate the flow system by creating heterogeneous and anisotropic conditions. Flow modifications may also result from underground (mining) and surface disturbances.

Researchers throughout the Appalachian coal-bearing region have documented that the majority of bedrock ground water is obtained from fracture zones that are generally within 200 feet of the surface where relatively direct connection to infiltrating ground water exists. Fractures, coal beds, and bedded strata alter flow paths largely by differences in fracture density that may be lithologically dependent. This creates contrasting conductivities among layers. Aquifers in coal-bearing regions are generally poorly defined; they are not widespread, identifiable geologic units, but tend to be related to fracture occurrence. Identification of local and regional flow systems, particularly in the mountainous coal-bearing regions such as eastern Kentucky, have not been previously defined.

The objectives of this study are fourfold.

Objective I

Instrument a first-order watershed (Edd Fork site) and describe the flow system.

A previously mined, first-order watershed, located in Leslie County, Kentucky, was selected for intensive monitoring. Three sites, located along a cross section, were selected for coring and installation of piezometer nests. Three core holes, 344, 500, and 760 feet deep were drilled at the valley bottom, midslope, and ridgetop locations, respectively. A continuous hydraulic conductivity profile was obtained for each core hole. A total of 24, multiple-completion piezometers, ranging in depth from 17 to 680 feet, were installed among three nests. Water-level data were collected for approximately six months to obtain vertical-head distribution from the ridgetop to 260 feet below drainage. One set of water samples was collected.

Average hydraulic conductivity values ranged from 4xl0^{-4} feet per minute in fractures to 4x10^{-7} feet per minute in unfractured shale. Conductivity values for coal beds average 9xl0^{-6} feet per minute above drainage to 8x10^{-7} feet per minute below drainage.

Five ground-water zones were identified on the basis of chemical and hydraulic properties. They are:

1. *Above-Magoffin-Member zone*

   Major ions in this zone are generally calcium, magnesium, sulfate, and bicarbonate.

2. *Below-and-including-Magoffin-Member zone*

   Major ions in this zone are sodium and bicarbonate. Ph values are generally higher in ground water located in the below-and-including-Magoffin Member zone than in the above-Magoffin Member zone.

3. *Shallow-fracture zone*

   This zone is a blanket-like, intensively fracture layer that parallels the ground surface to a depth approximately 60 feet. Characteristics are:
   a. rapid infiltration of water via fractures, b. water levels fluctuate with precipitation, and a often fracture controlled.

4. *Elevation-head zone*

   This zone, located above local drainage, comprises approximately the upper 70 percent of the above-drainage strata. Characteristics are:

a. strata contains conductive coal beds interbedded with low conductivity sandstones and shales,
b. head at a point in the system is equal to elevation head; overall head loss across the zone one-foot per foot downward,
c. flow direction within individual units varies an is controlled by conductivity contrasts between units. Flow in sandstone and shale beds is near vertical; flow within coal beds has a horizontal flow component,
d. coal zones laterally relieve pressure head in the system and function as drains. Water diverted laterally through coal beds may re-infiltrate into the shallow-fracture zone.

5. Pressure-head zone

This zone is located below the elevation-head zone (or shallow-fracture zone in the valley bottom). Characteristics are:

a. Ground water has a pressure-head component,
b. Coals and other strata have conductivities that are approximately the same order of magnitude.

Objective 2

Summarize ground-water data from three other sites and identify ground-water zones.

Star Fire site--(Wunsch, 1992)

The Star Fire site, in Perry County, Kentucky, is located adjacent to a third-order stream. Four piezometer nests, located in different topographic positions, were utilized to collect data for an intensive hydrogeochemical investigation. One core hole, drilled to obtain a continuous hydraulic conductivity profile, showed fractures and coal beds to be the most conductive units. Twelve months of water-level and water-quality data were obtained from fifteen piezometers. A vertical distribution of potentiometric heads shows that ground-water flow in the above-drainage strata is primarily downward. Saline water was found in a piezometer located approximately 100 feet below the elevation of Lick Branch. Geochemical data indicates that Lick Branch is a ground-water discharge zone. The same five ground-water zones as described in the Edd Fork investigation were identified. Two additional sites, Wolfpen Branch and Fishtrap Lake, did not provide the level of detail available from the Edd Fork and Star Fire investigations. Data from the latter two studies were used to substantiate the conclusions drawn from the more detailed investigations.

Wolfpen Branch-(Kipp and Dinger, 1987; Kipp and others, 1983)

The Wolfpen Branch site, located in Knott County, Kentucky, is situated in a first-order basin that flows into Lick Creek, a third-order stream. The Wolfpen Branch site is located approximately one mile upstream from the Star Fire site.

The Magoffin Member is below the level of Wolfpen Branch. Four core holes and thirteen monitoring wells were installed at four sites in the basin. Wells were completed with large open intervals, primarily spanning thick sandstone units between coal beds. Several wells were completed in the shallow-fracture zone. Core-hole data show intensive fracturing to a depth of almost 70 feet, substantiating the presence of the shallow-fracture zone. Chemical data were limited to cation analyses from six wells. Water from one well, located within the Magoffin Member, is a sodium-type water. The remaining wells, located above the Magoffin Member, contained calcium and magnesium-type water. The difference in water quality associated with the Magoffin are consistent with previous results. Wells that terminated in an above-drainage coal bed had water levels within the screen, indicating that coals are functioning as drains; consequently, an elevation-head zone is present. Wells completed below the lowest above-drainage coal are confined. Wells completed below the level of Lick Branch, near the confluence of Wolfpen Branch and Lick Branch, show potentiometric head that is above Lick Branch; thus, Lick Creek is a discharge zone. These results are supported by the Star Fire study.

Fishtrap Lake--(Davis, 1986; 1987)

The Fishtrap Lake site is located in Pike County, Kentucky, adjacent to an impounded third-order stream. This site is stratigraphically below the Magoffin Member. Water quality analyses were not a part of this investigation. Some core hole and water-level data were excluded from this analyses because of potential impact from past underground mining activities.

Six core holes show intensive fracturing to a depth of approximately 50 feet. Pressure-injection tests performed on selected intervals show that fracture conductivity is generally between $1x10^{-2}$ feet per minute and $3xl0^{-4}$ feet per minute. Coal bed conductivities are generally greater than $3xl0^{-5}$ feet per minute. Twelve multiple-completion monitoring wells were installed in the core holes. Water level fluctuations, especially in the shallow-fracture wells, show the relationship of water levels to fracture zones and the seasonal variation in fracture saturation. Wells that are approximately 200 feet above lake level maintain water levels within the well screen. Wells that are in coal beds located approximately 100 feet above lake level are confined. As in the other sites the boundary between the elevation-head and pressure-head zones is above drainage.

Water quality differences associated with the Magoffin Member at the four selected sites were compared to the results of a ground-water chemistry study for the entire Eastern Kentucky Coal Field by Bienkowski (1990). Bienkowski concluded that there was a difference in water quality between strata above and below the Magoffin Member.

Objective 3

Describe, in general, ground-water zones identified from analyses of the site-specific investigations, and integrate these zones into a conceptual model of local and regional ground-water flow.

Two zones are differentiated on the basis of water quality differences; the *above-Magoffin-Member zone* and the *Below-and-including-Magoffin-Member zone.* Major ions in the *Above-Magoffin- Member zone* are calcium, magnesium, sulfate, and bicarbonate; whereas, sodium and bicarbonate are common in the below-and-including-Magoffin-Member zone. Chloride becomes more prevalent in the below-drainage flow system with increasing proximity to the fresh-saline water interface. Ph values are generally higher in ground water located in the *Below-and-including-Magoffin-Member zone* than in the *Above-Magoffin-Mernber zone.* Both zones exhibit variations in water chemistry as a result of in filtration of recent precipitation or mixing of ground water in discharge zones.

Three zones, the shallow-fracture zone, the elevation-head zone, and the pressure-head zone, are delineated on the basis of hydraulic characteristics.

The *shallow-fracture zone is* a blanket-like, intensively fractured layer that parallels the ground surface to a depth of 50 to 70 feet. Characteristics are:

1. a rapid infiltration of water via fractures;

2. water levels that fluctuate rapidly with precipitation, and are fracture controlled;

3. water quality that varies in response to infiltration by precipitation and location within the flow sys tem;

4. depth to water table is affected by rainfall, topography, fracture location and interconnection, and surface disturbances; and

5. static water levels are generally deeper on ridges and hillslopes than in valley bottoms.

The *elevation-head zone,* located above local drainage, comprises approximately the upper 70 percent of the above-drainage strata. Characteristics are:

1 . strata contain conductive coal beds interbedded with low conductivity sandstones and shales;

2. calculated conductivity values from pressure injection tests vary nearly five orders of magnitude ($7x10^{-3}$ to $1x10^{-7}$ feet per minute);

3. flow direction within individual units varies and is controlled by conductivity contrasts between units. Flow in sandstone and shale beds is near-vertical; flow within coal beds has a horizontal flow component;

4. head at a point in the system is equal to elevation head; overall head loss across the zone is 1 foot per foot downward;

5. coal zones laterally relieve pressure head in the system and function as drains. Water diverted laterally through coal beds may re-infiltrate into the shallow-fracture zone;

6. fracture frequency and interconnection are probably less in this zone than in the shallow-fracture zone;

7. water levels in piezometers are generally more stable than in the shallow-fracture zone.

The *pressure-head zone is* located beneath the two previously described zones. The majority of this zone is below drainage. Characteristics are:

1. ground water is confined;

2. hydraulic conductivity values calculated from pressure-injection tests show that differences between coal beds and other strata are less in this zone than in the elevation-head zone;

3. fracture zones, generally associated with some larger stream valleys, are highly conductive;

4. strata that do not contain open fractures are saturated, but, have very low conductivity values;

5. flow in this zone is generally in the regional system, rather than in the local flow system (see Figure 70).

A conceptual model for local and regional groundwater flow was developed for the Eastern Kentucky Coal Field. Local flow systems develop in response to topography; however, the local flow system is contained within the shallow-fracture zone. Flow that does not discharge via the shallow-fracture zone flows downward toward the fresh-saline water interface and becomes part of a more regional flow system. Specific points of the conceptual model are:

1. first-order streams are discharge points only for the local flow system;
2. there is a downward head loss below drainage in strata located below the shallow-fracture zone;
3. the fresh-saline-water interface below upland regions is deeper than below third-order or larger streams;
4. ground-water flow to third-order or larger streams has both a local and regional component;
5. water in the regional system flows from upland regions toward third-order or larger streams.

Objective 4

Develop a ground-water-monitoring strategy that is appropriate for eastern Kentucky.

A monitoring strategy must characterize spatial and seasonal ground-water variations. Impacts to shallow-fracture water supplies can be evaluated by installing wells in the shallow-fracture zone downslope of the disturbance. Ground-water changes in first order basins can be detected by monitoring surface streams above and below disturbances. Common impacts to shallow fractures are:

1. removal of the shallow-fracture zone by surface mining;
2. change in recharge, flow volume, or quality resulting from surface mining,
3. interception of the shallow-fracture zone near the outcrop by underground mines, allowing water from the mine to enter the fracture zone.

Conclusions

1 Five ground-water zones are identified in the Eastern Kentucky Coal Field Region. Two zones, the *above-Magoffin-Merriber zone* and the *below-and- including- Magoffin- Member zone,* differentiated by water quality, are present where the Magoffin Member, an areally extensive, leaky confining unit, is present. Three zones, the *shallow-fracture zone,* the *elevation-head zone,* and the *pressure-head zone* are delineated on the basis of hydraulic characteristics.

2. A conceptual model for local and regional groundwater flow suggests that local flow systems develop in response to topography; however, the local flow system is contained within the shallow-fracture zone. Flow that does not discharge via the shallow-fracture zone flows enters the regional flow system. Regional ground-water flow is primarily downward beneath upland areas toward the fresh-saline-water interface. The interface is generally located at its deepest point beneath uplands regions and slopes upward toward third-order or larger streams. Regional ground-water flow roughly parallels the interface; consequently, third-order or larger streams are discharge zones for regional flow.

3. Calculated conductivity values are consistently higher for fractures and coal beds than for other strata.

4. Piezometers located in sandstone and shale commonly take longer than six months to equilibrate if the formation is not fractured. This situation makes it difficult to obtain both head data and chemical data from the same piezometers.

Recommendations

Recommendations of both a practical and theoretical nature are identified from this study.

Theoretical

1 . Because ground-water flow in the Eastern Kentucky Coal Field is fracture dominated, fracture orientation, spacing relative to lithology, expected depths of open fractures, and mechanism of formation of the shallow-fracture zone need to be better understood.

2. Construct a numerical model based on the conceptual model. Head distribution in the system is much better known now that extensive piezometer networks have been installed in different-order watersheds. Numerical analyses may lead to a better understanding of flow rates and the position of the fresh-saline-water interface.

Practical

3. Multiple two-inch piezometers that are greater than 300 or 400 feet deep are difficult to install. Well development and sampling are even more difficult. Schedule 80 pipe is generally needed to insure adequate strength, but, its smaller inside diameter, makes lowering purging equipment (bailers) more difficult because of the tight fit. In addition, the volume of water that can be removed per bail is generally small. Water levels, especially in recharge zones, are deep; thus, require mechanized bailing procedures. As a result, deep, two inch piezometers are very difficult and time consuming to purge and sample. Deep piezometers that are intended for frequent sampling should be constructed using larger-diameter pipe. Even

though such construction results in a greater volume of water to be removed, there is a wider choice of equipment available with which to remove it.

ACKNOWLEDGEMENTS

I would like to recognize my graduate committee, Dr. James Dinger, Dr. William Thomas, Dr. Sergio Serrano, and Dr. Richard Sweigard, and Gary Felton for their input and review of this dissertation. Special acknowledgements go to my graduate advisor, Dr. Lyle Sendlein for his unending enthusiasm for this dissertation and for motivating me to push onward.

I want to thank Drs. Sendlein and Dinger for giving me the opportunity to be involved with the Deep Mine project which provided financial support for much of my graduate study and also provided data for this research. I would also like to thank Forrest Hamilton of Shamrock Coal Company for his cooperation and assistance.

Much deserved recognition goes to Jim Kipp of KGS for his ideas and thought-provoking questions during the many trips back and forth to Leslie County. I also extend my thanks to the Water Resources Section and the rest of the KGS staff for their help and friendship. I especially want to thank Dave Harmon for driving the 'truck-o-joy" back and forth to Leslie County. Linda Chapman at IMMR deserves special credit for sneaking me appointments with Dr. Sendlein whenever I had that panic-stricken look on my face.

I would also like to thank my friends and family for putting up with me for the last few years; John and Jeanne Zibell for making sure I had at least one meal a month, and especially Don Hutcheson for his friendship and moral support during the high and low periods. I would like to -acknowledge my older brother, Gordon Jr., who sparked my young imagination with his sometimes misguided emulations of "Mr. Wizard" and my father, Gordon Sr., who taught me never to take life for granted. I especially want to thank my mother, Camille, who worked very hard to support my undergraduate education and it is to her that this dissertation is dedicated.

Thanks everybody.

REFERENCES CITED

Aller, L., Petty, R., Lehr, J. H., Nielson, D., Denne, J. A., 1989, Handbook for suggested practices for the design and construction of ground-water monitoring wells: National Water Well Association, 398 p.

Ammerman, M. L., and Keller, G. R., 1979, Delineation of the Rome Trough in eastern Kentucky by gravity and deep drilling data: American Association of Petroleum Geologists Bulletin, v. 63, no. 3, p. 341-353.

Bienkowski, L. S., 1990, Delineation and characterization of the aquifers of the Eastern Kentucky Coal Field: Lexington, University of Kentucky, Ph.D. Dissertation, 319 p.

Booth, J. C., 1984, A numerical model of groundwater associated with an underground coal mine in the Appalachian Plateau, Pennsylvania: Pennsylvania State University, Ph.D. Dissertation, 458 p.

Booth, J. C., 1988, Interpretation of well and field data in a heterogeneous layered aquifer setting, Appalachian Plateau: Ground Water, v. 26, no. 5, p. 596-606.

Booth, J. C., and Saric, J. A., 1987, The effects of abandoned underground mines on ground water, Saline County, Illinois, *in* Proceedings, National Symposium on Mining, Hydrology, Sedimentology, and Reclamation: University of Kentucky, Lexington, Kentucky, December 7-11, 1987, p. 243-248.

Brown, R. L., and Parizek, R. R., 1971, Shallow ground water flow systems beneath strip and deep coal mines at two sites, Clearfield County, Pennsylvania: College Earth and Mineral Sciences, Special Research Report SR-84, Pennsylvania State University, 216 p.

Campbell, M. D., and Forster, K., 1991, Hydrogeology: Workshop at the 8th Congress, International Society for Mine Surveying and the National Symposium on Mining: University of Kentucky, College of Engineering, Lexington, Kentucky, September 24, 1991.

Carswell, L. D., and Bennett, G. D., 1963, Geology and hydrology of the Neshannock Quadrangle, Mercer and Lawrence Counties, Pennsylvania: Pennsylvania Geological Survey, ser. 4, Bulletin W 15, 90 p.

Chesnut, D. R., 1981, Marine zones of the upper Carboniferous of eastern Kentucky, *in* Cobb, J. C., and others, eds., Coal and coal-bearing rocks of eastern Kentucky (Guidebook and roadlog for Coal Division of Geological Society of America Field Trip No. 14): Kentucky Geological Survey, ser. 11, p. 57-66.

Chesnut, D. R., 1988, Stratigraphic analysis of the Carboniferous rocks of the Central Appalachian Basin: Lexington, University of Kentucky, Ph.D. Dissertation, 297 p.

Davis, R. W., 1986, Data from test drilling to trace movement of ground water in coal-bearing rocks near Fishtrap Lake in Pike County, Kentucky: U.S. Geological Survey Open-File Report 86-535, 64 p.

Davis, R. W., 1987, Movement of ground water in coalbearing rocks near Fishtrap Lake in Pike County, Kentucky: U.S. Geological Survey Water Resources Investigations Report 87-4084, 24 p.

Donaldson, A. C., 1974, Pennsylvanian sedimentation of the Central Appalachians, *in* Briggs, Garrett, ad., Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 47-48.

Driscoll, F. G., 1986, Groundwater and wells (2d ad): St. Paul, Minnesota, Johnson Filtration Systems, Inc., 1089 p.

Dyer, K. L., 1983, Effects on water quality of coal mining in the basin of the North Fork, Kentucky River, eastern Kentucky: U.S. Geological Survey Water Resources Investigations Report 81-215, 94 p.

Earl, T. A., 1986, Flow system considerations in understanding Appalachian coal hydrology, in Proceedings, Depositional Environment and Coal Hydrology: Clarion, Pennsylvania, Clarion University, January 23,1986,p.49-67.

Englund, K. J., Henry, T. W., Pfefferkorn, H. W., Gillespie, W. H., MacKenzie, G., Jr., Cecil, C. B., Randall, A. H., III, Stanton, R. W., Dulon, F. T., Rupert, L. F., and Renton, J. J., 1981, Mississippian-Pennsylvanian boundary in the central part of the Appalachian Basin, part 1: Southwestern Virginia-southern West Virginia, in Roberts, T. G., ad., GSA Cincinnati '81 Field Trip Guidebook, v. 1: Stratigraphy, sedimentology: Falls Church, Virginia, American Geological Institute, p. 153-194.

Ettensohn, F. R., and Dever, G. R., Jr., 1979, Carboniferous geology from the Appalachian Basin to the Illinois Basin through eastern Ohio and Kentucky: Field Trip No. 4, Ninth International Congress of Carboniferous Stratigraphy and Geology: Lexington, University of Kentucky, 293 p.

Ferguson, H. F., 1967, Valley stress relief in the Allegheny Plateau, engineering geology: Association of Engineering Geologists Bulletin, v. 4, no. 1, p. 63-68.

Farm, J. C., 1974, Carboniferous environmental models in eastern United States and their significance, *in* Briggs, Garrett, ad., Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 79-95.

Farm, J. C., and Melton, R. A., 1977, A guide to cored rocks in the Pocahontas Basin: University of South Carolina, Department of Geology, Carolina Coal Group, 90 p.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Freeze, R. A., and Witherspoon, P. A., 1967, Theoretical analysis of regional groundwater flow: 2, effect of water table configuration and subsurface permeability variation: Water Resources Research, v. 3, no. 2, p. 623-634.

Haney, D. C., Hester, N. C., and Hoge, H. P., 1975, Evidence for fault-controlled deposition of Pennsylvanian sediments in central eastern Kentucky [abs.]: Geological Society of America Abstracts with Programs, v. 7, p. 495-496.

Harlow, G. E., Jr., and LeCain, G. D., 1991, Hydraulic characteristics of, and ground-water flow in, coal-bearing rocks of southwestern Virginia: U.S. Geological Survey Open-File Report 91-250, 48 p.

Helgeson, J. 0., Larson, S. P., and Razem, A. C., 1982, Model modifications for simulation of flow through stratified rocks in eastern Ohio: U.S. Geological Survey Water Resources Investigation 82-4019,109 p.

Hill, J. J., 111, 1988, The influence of stream valleys on coal mine ground control, *in* Proceedings, 7th International Conference on Ground Control in Mining, August 3-5,1988: U.S. Bureau of Mines, U.S. Mine Safety and Health Administration, and West Virginia University, Morgantown, West Virginia, p. 247-258.

Hobba, W. A., Jr., 1991, Relation of fracture systems to transmissivity of coal and overburden aquifers in Preston County, West Virginia: U.S. Geological Survey Water-Resources Investigations Report 89-4137, 24 p.

Hollyday, E. F., and McKenzie, S. W., 1973, Hydrogeology of the formation and neutralization of acid waters draining from underground coal mines of western Maryland: Maryland Geological Survey Report of Investigations 20, 50 p.

Hopkins, H. T., 1966, Fresh-saline interface map of Kentucky: Kentucky Geological Survey, ser. 10, scale approx. I in.=8 mi.

Home, J. C., and Farm, J. C., 1978, Carboniferous depositional environments, eastern Kentucky and southern West Virginia: Columbia, University of South Carolina, Department of Geology, 151 p.

Hubbert, M. K., 1940, The theory of ground water motion: Journal of Geology, v. 48, no. 8, p. 785-944.

Huddle, J. W., Lyons, E. J., Smith, H. L., and Farm, J. C., 1963, Coal reserves of Kentucky: U.S. Geological Survey Bulletin 1120, 247 p.

Kentucky Water Resources Commission, 1959, Department of Conservation, Division of Flood Control and Water Usage, August 1959.

Kipp, J. A., and Dinger, J. S., 1987, Stress-relief fracture control of groundwater movement in the Appalachian Plateaus: Focus Conference on Eastern Regional Ground-Water Issues, National Water Well Association, July 15,1987, Burlington, Vermont, p. 423-438.

Kipp, J. A., Lawrence, F. W., and Dinger, J. S., 1983, A conceptual model of ground water flow in the Eastern Kentucky Coal Field: Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation, University of Kentucky, Lexington, Kentucky, November 27-December2,1983.

Larson, J. D., and Powell, J. D., 1986, Hydrology and effects of mining in the upper Russell Fork Basin, Buchanan and Dickenson Counties, Virginia: U.S. Geological Survey Water Resources Investigation 85-4238, 63 p.

Leist, D. W., Quinones, F., Mull, D. S., and Young, M., 1982, Hydrology of area 15, Eastern Coal Province, Kentucky and Tennessee: U.S. Geological Survey Water Resources Investigations Open-File Report 81-80, 81 p.

McFarlan, A. C., 1943, Geology of Kentucky: Lexington, University of Kentucky, 521 p.

McGrain, Preston, and Thomas, G. R., 1951, Preliminary report on the natural brines of eastern Kentucky: Kentucky Geological Survey, ser. 9, Report of Investigations 3, 22 p.

McHaffie, P. H., 1982, Linear features map of Kentucky: Kentucky Geological Survey.

Merin, I. S., 1989, Characterization of fractures in Devonian siltstone, northern Appalachian Plateau: Implications for groundwater flow: Proceedings of the Third National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, presented by the Association of Ground Water Scientists and Engineers, Division of National Water Well Association, Orange County Convention Center, Orlando, Florida, May 22-25, 1989,p.921-934.

Moebs, N. N., 1989, Appalachian roof instability: Coal, v. 26, no. 3, p. 43-45.

Musser, J. J., 1963, Description of physical environment and of strip-mining operations in parts of Beaver Creek Basin, Kentucky: U.S. Geological Survey Professional Paper 427-A, 25 p.

Nickelson, R. P., and Hough, V. D., 1967, Jointing in the Appalachian Plateau of Pennsylvania: Geological Society of America Bulletin, v. 78, p. 609-630.

Owili-Eger, A. S. C., 1987, Dynamic fractured flow simulation model: Society of Mining Engineers Annual Meeting, Denver, Colorado, February 24-27, 1987, Preprint 87-3.

Press, F., and Siever, R., 1974, Earth: San Francisco, W. H. Freeman and Co., 945 p.

Price, W. E., 1956, Geology and groundwater resources of the Prestonsburg (7.5-minute quadrangle) Kentucky (parts of Floyd and Johnson Counties): U.S. Geological Survey Water-Supply Paper 1359,140 p.

Price, W. E., Jr., Mull, D. S., and Kilburt, C., 1962, Reconnaissance of groundwater resources in the Eastem Coal Field region, Kentucky: U.S. Geological Survey Water-Supply Paper 1607, 56 p.

Quinones, F., Mull, D. S., York, K., and Kendall, V., 1981, Hydrology of area 14, Eastern Coal Province, Kentucky: U.S. Geological Survey Water Resources Investigations 81-137, 82 p.

Rice, C. L., Sable, E. G., Dever, G. R., Jr., and Kehn, T. M., 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States--Kentucky: U.S. Geological Survey Professional Paper 1110-F, 32 p.

Rice, C. L., and Smith, J. H., 1980, Correlation of coal beds, coal zones, and key stratigraphic units in the Pennsylvanian rocks of eastern Kentucky: U.S. Geological Survey Map MF-11 188.

Rice, D. D., 1975, Geologic map of the Helton Quadrangle, southeastern Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-1 227.

Rulon, J. J., Rodway, R., and Freeze, R. A., 1985, The development of multiple seepage faces on layered slopes: Water Resources Research, v. 21, no. 11, p. 1625-1636.

Sable, E. G., and Dever, G. R., Jr., 1990, Mississippian rocks in eastern Kentucky: U.S. Geological Survey Professional Paper 1503, 125 p.

Saines, M., 1981, Errors in interpretation of ground-water level data: Ground Water Monitoring Review, Spring 1991.

Schubert, J. R, 1980, Fracture flow of groundwater in coal-bearing strata: Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation, University of Kentucky, Lexington, Kentucky December 1-5,1980, p. 61-73.

Sendlein, L. V. A., and Dinger, J. S., 1990, Hydrologic impact of below-drainage, underground mining in

Kentucky: Kentucky Geological Survey-University of Kentucky Institute for Mining and Minerals Research Proposal.

Sergeant, R. E., and Haney, D. C., 1980, Stratigraphic evidence for late Paleozoic reactivation of subsurface tectonic elements in northeastern Kentucky [abs.]: Geological Society of America Abstracts with Programs, v. 12, p. 208.

Songer, N. L., and Ewers, R. 0., 1987, Seepage velocities in stress-relief fractures in the Eastern Kentucky Coal Field: Kentucky Division of Water, Ground Water Section, MOA 006131.

Springer, E. P., and Coltharp, G. B., 1978, Some hydrologic characteristics of small forested watersheds in eastern Kentucky: Kentucky Academy of Science Transactions, v. 39, nos. 1-2, p. 31-38.

Stone, R., and Snoeberger, D. F., 1977, Cleat orientation and areal hydraulic anisotropy of a Wyoming coal aquifer. Ground Water, v. 15, no. 6, p. 434-438.

Stoner, J. D., 1983, Probable hydrologic effects of subsurface mining: Ground Water Monitoring Review, Winter 1983, p. 128-137.

Tankard, A. J., 1986, Depositional response to foreland basin deformation in the Carboniferous of eastern Kentucky: American Association of Petroleum Geologists Bulletin, v. 70, no. 7, p. 853-868.

Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 68, no. 16, p. 4795-4811.

Trainer, F. W., 1983, Some perspectives on near-surface fractured rock aquifers: Proceedings of the 14th Biennial Conference on Ground Water, September 19-20,1983, Sacramento, California, p. 104-122.

U.S. Bureau of Reclamation, 1974, The design of small dams: Technical Publication.

U.S. Geological Survey, 1990, Project proposal: Hydrologic investigation of stress-relief fractures of a ,steep-sloped valley in the coal areas of eastern Kentucky: March 1990, 10 p.

Weiss, J. S., and Razem, A. C., 1984, Simulation of ground-water flow in a mined watershed in eastern Ohio: Ground Water, v. 22, no. 5, p. 540-560.

Woodward, H. P., 1961, Preliminary subsurface study Of southeastern Appalachian Interior Plateau: American Association of Petroleum Geologists Bulletin 45, no. 10, p. 1634-1655.

Wright, W. G., 1987, Hydrologic factors affecting flow in the groundwater systems of the coal fields of southwestern Virginia: Proceedings, 1987 National Symposium on Mining, Hydrology, Sedimentology, and Reclamation, University of Kentucky, Lexington, Kentucky; December 7-11, 1987.

Wunsch, D. R., 1992, Ground water geochemistry and its relationship to the flow system at an unmined site in the Eastern Kentucky Coal Field: Lexington, University of Kentucky, Ph.D. Dissertation, 239 p.

Wyrick, G. G., and Borchers, J. W., 1981, Hydrologic effects of stress-relief fracturing in an Appalachian valley: U.S. Geological Survey Water Supply Paper 2177, 51 p.

Zehner, H. H., 1983, Hydrologic investigation of the Maxey Flats radioactive waste burial site, Fleming County, Kentucky: U.S. Geological Survey Open File Report 83-133,148 p.

APPENDIX A:
Core Logs

Core Hole A

County: Leslie
U.S.G.S. Quadrangle: Helton, KY
Location: Edd Fork of Trace Branch (valley-side)
Surface Elevation: 1756.2 feet (ground)
Date Started: 12/4/91
Date Completed: 12/12/91
Drilled By: CBC Drilling
Total Depth: 500.5 feet
Core size: NXE Wireline

From (feet)	To (feet)	Description
0	14.0	Casing - 4" steel pipe
14	14.1	Dark gray fire clay (127)
14.1	14.8	Gray sandy fire clay, weathered, broken (327)
14.8	14.9	Gray sandstone with coal streaks, weathered (749)
14.9	22.0	Gray sandstone with shale streaks (543), rooted; weathered bedding fractures at 14.9 ft., 15.3 ft., 15.8 ft.,18.6 ft., and 19.4 ft.
22.0	41.3	Massive gray sandstone (544) with iron stains; high-angle weathered fractures at 22.3 ft.,23.7 ft., 25.5 ft., and 26.4 ft.; lost circulation in high-angle fracture at 30 to 31 ft.
41.3	44.7	Dark gray shale with sandstone streaks (323)
44.7	51.55	Dark gray shale (124); weathered bedding plane at base
51.55	51.9	Dark gray burrowed sandy shale (328)
51.9	52.15	Dark gray shale (124)
52.15	53.8	Rooted gray sandstone (547); weathered zones with weathered fracture at base
53.8	62.7	Gray sandstone with shale streaks, rippled (543);coal spars; weathered bedding fracture at 59.8 ft.; weathered vertical fracture at 61 ft.; Base is broken, weathered
62.7	74.0	Dark gray massive sandy shale (324)
74.0	76.1	Dark gray shale (124)
76.1	76.4	Coal (020); Hazard Coal zone
76.4	76.7	Dark gray fire clay (127)
76.7	77.1	Coal (020); Hazard Coal zone
77.1	80.9	Dark gray shale (124)
80.9	81.6	Dark gray fire clay (127)
81.6	82.2	Gray sandy fire clay (327)
82.2	83.1	Broken coal and bone (020); Hazard Coal zone
83.1	83.6	Dark gray fire clay (127)
83.6	84.0	Coal (020); Hazard Coal zone
84.0	84.1	Bone

84.1	90.7	Gray sandstone with shale streaks (543); rooted in upper half
90.7	90.9	Dark gray shale (124)
90.9	91.3	Coal (020); Hazard Coal zone
91.3	95.0	Dark gray sandy fire clay (327)
95.0	100.0	Dark gray massive sandy shale (324)
100.0	103.8	Massive gray sandstone (544)
103.8	106.9	Gray sandstone with shale streaks, flat (543)
106.9	108.0	Massive gray sandstone (544)
108.0	109.15	Gray sandstone with shale streaks, flat (543)
109.15	113.5	Cross bedded gray sandstone (541)
113.5	118.9	Gray sandstone with shale streaks, flat (543); some coal streaks
118.9	123.5	Gray sandstone with shale streaks ad coal spars, rippled (543); fracture from 121.7 ft. to 122.9 ft., upper part of fracture is iron stained, fracture is calcite-filled
123.5	123.7	Gray shale pebble conglomerate (742)
123.7	124.0	Coal (020)
124.0	124.5	Gray sandstone with coal spars (749)
124.5	128.0	Massive gray sandstone (544)
128.0	130.7	Gray sandstone with shale streaks, rippled (543)
130.7	131.8	Dark gray sandy fire clay (327)
131.8	131.9	Dark gray fire clay (127)
131.9	132.3	Coal (020)
132.3	134.75	Dark gray sandy fire clay (327)
134.75	134.8	Coal (020)
134.8	136.65	Dark gray sandy fire clay (327)
136.65	137.4	Dark gray interbedded sandstone and shale, rippled and streaked (322); some roots
137.4	140.3	Dark gray massive sandy shale (324)
140.3	147.4	Dark gray shale with sandstone streaks (323)
147.4	152.8	Dark gray massive sandy shale (324)
152.8	153.8	Gray sandstone with coal bands (748)
153.8	155.9	Dark gray massive sandy shale (324)
155.9	156.3	Black shale (114)
156.3	157.6	Coal (020); Haddix Coal zone
157.6	161.6	Dark gray sandy fire clay (327)
161.6	164.6	Dark gray churned sandy shale (325)
164.6	165.7	Gray sandstone with shale streaks, rippled (543)
165.7	167.0	Dark gray massive sandy shale (324)

167.0	167.9	Sandy shale mudflow (018)
167.9	187.0	Gray sandstone with shale streaks, rippled (543)
187.0	187.4	Gray shale pebble conglomerate (742)
187.4	187.6	Dark gray interbedded sandstone and shale, rippled (322)
187.6	194.4	Gray sandstone with coal bands (748)
194.4	203.1	Dark gray churned sandy shale (325);, with bands of gray-green shale (134)
203.1	207.1	Gray shale pebble conglomerate (742), has gray-green shale pebbles
207.1	209.0	Massive gray sandstone (544)
209.0	209.3	Gray sandstone with coal spars (749)
209.3	212.4	Massive gray sandstone (544)
212.4	222.0	Gray sandstone with shale streaks, rippled (543); coal bands from 207.45 ft. to 207.6 ft.
222.0	223.6	Gray sandstone with coal spars (749)
223.6	224.0	Ironstone pebble conglomerate (743)
224.0	235.0	Gray sandstone with coal spars (749)
235.0	255.0	Gray sandstone with shale streaks, rippled (543)
255.0	260.75	Gray sandstone with coal spars (749)
260.75	262.7	Gray sandstone with shale streaks, rippled (543)
262.7	264.0	Gray sandstone with coal spars (749)
264.0	264.25	Ironstone pebble conglomerate (743)
264.25	266.5	Massive gray sandstone (544)
266.5	268.5	Gray sandstone with coal spars (749)
268.5	271.6	Gray sandstone with shale streaks (323)
271.6	272.8	Gray sandstone with coal spars (749)
272.8	275.2	Dark gray interbedded sandstone and shale, rippled (322)
275.2	281.3	Gray sandstone with shale streaks, flat (543)
281.3	300.0	Dark gray shale with sandstone streaks (323); Magoffin Member
300.0	309.2	Dark gray massive sandy shale (324); Magoffin Member
309.2	337.7	Dark gray shale with fossil shells (129); fossil hash zones at 329.8 ft. and from 335.5 ft. to 336.4 ft.; Magoffin Member
337.7	338.6	Coal (020); Copland Coal zone
338.6	339.9	Dark gray sandy fire clay (327)
339.9	344.6	Dark gray churned sandy shale (325)
344.6	349.9	Gray sandstone with shale streaks, rippled (543)
349.9	354.25	Dark gray shale (124) with occasional coal streaks
354.25	354.3	Dark gray fire clay (127)
354.3	355.6	Coal (020); Copland Coal zone

355.6	356.1	Dark gray fire clay (127)
356.1	356.8	Dark gray sandy fire clay (327)
356.8	359.95	Dark gray massive sandy shale (324)
359.95	360.4	Dark gray shale with sandstone streaks, rippled (323)
360.4	380.0	Gray sandstone with shale streaks, rippled (543)
380.0	382.0	Gray sandstone with coal spars (749)
382.0	389.0	Massive gray sandstone (544)
389.0	392.1	Gray sandstone with coal bands (748)
392.1	393.9	Gray sandstone with coal spars (749)
393.9	394.0	Gray ironstone pebble conglomerate (743)
394.0	395.1	Dark gray interbedded sandstone and shale, rippled (322)
395.1	395.7	Dark gray churned sandy shale (325)
395.7	404.35	Dark gray massive sandy shale (324)
404.35	404.7	Coal (020); Hamlin Coal zone
404.7	406.95	Dark gray sandy fire clay (327)
406.95	407.05	Coal (020); Hamlin Coal zone
407.05	407.3	Dark gray sandy fire clay (327)
407.3	410.1	Dark gray massive sandy shale (324)
410.1	410.65	Dark gray sandy fire clay (327)
410.65	410.7	Coal (020); Hamlin Coal zone
410.7	411.1	Dark gray sandy fire clay (327)
411.1	412.4	Coal (020); Hamlin Coal zone
412.4	413.9	Dark gray sandy fire clay (327)
413.9	415.0	Dark gray churned sandy shale (325)
415.0	416.3	Rooted gray sandstone (547)
416.3	417.25	Dark gray massive sandy shale (324)
417.25	417.9	Rooted gray sandstone (547)
417.9	420.25	Gray sandstone with shale streaks, rippled (543)
420.25	420.65	Coal (020); Hamlin Coal zone
420.65	421.4	Dark gray sandy fire clay (327)
421.4	443.1	Dark gray burrowed sandy shale (328)
443.1	464.0	Dark gray massive sandy shale (324); calcite-filled fractures from 458.5 ft. to 459.4 ft.
464.0	467.6	Dark gray shale (124)
467.6	467.8	Dark gray fire clay (127)
467.8	470.6	Dark gray churned sandy shale (325)

470.6	475.4	Dark gray interbedded sandstone and shale, rippled (322)
475.4	478.0	Dark gray shale with sandstone streaks, rippled (323)
478.0	478.1	Dark gray shale (124)
478.1	478.4	Coal (020); Fire Clay Rider Coal zone
478.4	478.6	Dark gray shale (124)
478.6	479.1	Coal (020) ; Fire Clay Rider Coal zone
479.1	479.6	Dark gray fire clay (127)
479.6	480.0	Coal (020); Fire Clay Rider Coal zone
480.0	480.9	Dark gray fire clay (127)
480.9	491.15	Dark gray interbedded sandstone and shale, rippled (322)
491.15	494.3	Gray sandstone with shale streak, rippled (323)
494.3	496.0	Dark gray interbedded sandstone and shale, rippled (322)
496.0	497.7	Dark gray sandy fire clay (327)
497.7	499.8	Dark gray shale (124)
499.8	500.5	Dark gray interbedded sandstone and shale, rippled (322)

Core Hole B

County: Leslie
U.S.G.S. Quadrangle: Helton, KY
Location: Edd Fork of Trace Branch (hilltop)
Surface Elevation: 2020.2 feet (ground)
Date Started: 12/4/91
Date Completed: 12/12/91
Drilled By: CBC Drilling
Total Depth: 764.6 feet
Core size: NXE Wireline

From (feet)	To (feet)	Description
0	39.0	Casing -4" steel pipe
39.0	44.2	Gray sandstone with shale streaks, rippled (543); miceaous; carbonaceous fragments in shale streaks
44.2	51.6	Dark gray shale with sandstone streaks (323)
51.6	53.2	Dark gray massive sandy shale (324)
53.2	56.7	Gray sandstone with shale streaks (543); rippled; iron-stained bedding planes; 55.2 to 56.7 is shale with silt laminae; sharp lower contact
56.7	69.4	Massive gray sandstone (544); iron-stained; weathered bedding planes; some cross bedding
69.4	78.0	Gray sandstone with shale streaks (544); iron-stained from 75.9 ft. to 76.3 ft.; low angle cross beds with drapes on low angle forsets
78.0	85.3	Massive gray sandstone (544)
85.3	93.6	Gray sandstone with shale streaks (543); low angle cross beds
93.6	102.0	Massive gray sandstone (544)
102.0	106.2	Gray sandstone with coal spars (749)
106.2	111.9	Gray sandstone with shale streaks (543); from 111.6 ft. to 111.9 ft. is deformed gray siltstone; low angle cross beds
111.9	113.1	Gray sandstone with coal spars (749); contains some shale and siderite pebbles
113.1	114.2	Burrowed gray sandstone (548); Burrowed at top of cross bed cosets; from 13.8 ft. to 114.2 ft.is gray shale with sandstone laminae on foresets
114.2	132.0	Massive gray sandstone (544); minor shale streaks; shale streaks are foreset drapes
132.0	139.4	Gray shale pebble conglomerate (742); ironstone pebble conglomerate (743) from 132 ft. to 133 ft.; gray sandstone with shale streaks from 135.4 ft. to 138 ft.; some coal spars
139.4	150.2	Massive gray sandstone (544); minor shale streaks; some crossbeds; gray shale pebble conlomerate (742) from 149.2 ft. to 150.2 ft.
150.2	161.9	Dark gray shale (124); black shale (114) from 152.1 ft. to 152.4 ft.; gray sandstone from 153.6 ft. to 154.2 ft.; shale with sandstone streaks (543) from 154.2ft. to 154.7 ft.; burrowed (328) from 157.6 ft. to 158 ft.; deformed sandstone from 161.5 ft.to 161.9 ft.

161.9	165.7	Dark gray interbedded sandstone and shale (322); 161.9 ft. to 162.6 ft. is deformed sandstone; from 162.6 ft. to 163 ft. is gray shale with siderite nodules; from 165.2 ft. to 165.6 ft. is deformed sandstone
165.7	171.2	Dark gray shale (124)
171.2	172.9	Coal (020); Hazard # 8 Rider; coal 0.6 ft.; shale 0.7 ft.; coal 0.4 ft.
172.9	186.0	Dark gray massive sandy shale (324); some churned sandy shale (325)
186.0	186.7	Coal (020); Hazard # 8 Rider; Coal 0.7 ft.
186.7	187.6	Dark gray sandy fire clay (327)
187.6	194.0	Dark gray massive sandy shale (324); some ironstone nodules; some churned sandy shale (325) zones
194.0	196.6	Dark gray sandy fire clay (327); small slickensides; plant debris, probably rooted
196.6	220.8	Dark gray massive sandy shale (324); sandstone with shale streaks (543) from 201 ft. to 202.8 ft., from 211.8 ft. to 212.8 ft., from 213.3 ft. to 214.1 ft., and from 214.7 ft. to 216.4 ft.
220.8	221.0	Black shale (114)
221.0	224.3	Coal (021); Hazard # 8; coal 3.3 ft.
224.3	230.0	Dark gray sandy fire clay (327); large slickensides
230.0	239.9	Dark gray massive sandy shale (324); ironstone bands and nodules; several rooted zones; upper half is churned (325)
239.9	243.3	Gray sandstone with shale streaks, (543); rippled
243.3	255.55	Dark gray massive sandy shale (324); ironstone bands; black shale streak (114) from 251.2 ft. to 251.35 ft.; some rooted zones
255.55	258.1	Dark gray interbedded sandstone and shale (322); rippled
258.1	262.15	Dark gray shale with sandstone streaks (323)
262.15	262.7	Gray sandstone with shale streaks (543); rippled
262.7	263.7	Dark gray massive sandy shale (324)
263.7	264.7	Dark gray shale (124)
264.7	267.2	Coal (020); Hazard #7 Upper Split; coal 2.5 ft. with bone parting
267.2	267.6	Dark gray sandy fire clay
267.6	278.7	Dark gray massive sandy shale (324); ironstone bands
278.7	279.05	Dark gray shale (124)
279.05	281.5	Coal (020); Hazard # 7 Lower Split; coal 0.2 ft.; fire clay 0.35 ft.; coal 1.9 ft.; fire clay 0.25 ft.
281.5	283.8	Massive gray sandstone (544); 8 to 10 inches of root-penetrated quartzose sandstone (557)
283.8	288.1	Burrowed gray sandstone (548); possibly deformed bedding; deformed interbedded sandstone and shale from 285.6 ft. to 288 ft.
288.1	290.75	Dark gray interbedded sandstone and shale (322); rippled;
290.75	299.6	Sandstone with shale streaks (543); weathered buff; iron-stained vertical fractures at 292 ft. and 295.2 ft.; lost circulation at 295 ft.
299.6	302.5	Dark gray interbedded sandstone and shale (322); rippled

302.5	316.95	Dark gray massive sandy shale (324); Cow Creek Shale Member (informal); ironstone bands; invertebrate fossils from 314.85 ft. to 316.95 ft.; contains the pelecypod Astartella and the articulate brachipods spiriferid, productoid, and compositid; interval also contains plant debris
316.95	322.0	Rooted gray sandstone (547)
322.0	328.95	Gray sandstone with shale streaks (543); rippled
328.95	341.9	Dark gray massive sandy shale (324); ironstone bands
341.9	342.85	Dark gray shale (124); some coal streaks
342.85	352.1	Coal (020); Hazard Coal Zone; coal 0.15 ft.; fire clay 0.25 ft.; coal 0.3 ft.; shale 0.20 ft.; coal 0.3 ft.; fire clay 0.25 ft.; coal 0.3 ft.; fire clay 5.6 ft.; coal 1.2 ft.; fire clay 0.5 ft.; coal 0.5 ft.
352.1	356.35	Dark gray massive sandy shale (324); churned (325) in upper 0.6 ft.
356.35	357.1	Coal (020); Hazard Coal Zone; coal 0.75 ft.
357.1	360.65	Dark gray fire clay (127); sandy fire clay (327) in lower 0.35 ft.
360.65	363.85	Burrowed gray sandstone (548); contains sand-injected fracture
363.85	364.4	Sandy shale mudflow (018)
364.4	382.0	Gray sandstone with shale streaks (543); rippled; gray shale pebble conglomerate (742) from 374.7 ft. to 375.4 ft.
382.0	397.6	Gray sandstone with coal spars (749)
397.6	401.3	Gray shale pebble conglomerate (743);
401.3	414.15	Gray sandstone with shale streaks (543); rippled, streaked
414.15	416.6	Gray ironstone pebble conglomerate (743); sharp lower contact with coal
416.6	417.5	Coal (020); Haddix; coal 0.9 ft.
417.5	419.4	Dark gray sandy fire clay (327)
419.4	421.3	Dark gray churned sandy shale (325)
421.3	423.55	Dark gray shale with sandstone streaks (323); rippled;
423.55	425.4	Dark gray interbedded sandstone and shale (322); rippled
425.4	442.7	Gray sandstone with shale streaks (543); low-angle cross beds; rippled
442.7	443.3	Gray ironstone pebble conglomerate (743)
443.3	455.7	Gray sandstone with coal spars (749)
455.7	502.0	Gray sandstone with shale streaks (543); low-angle cross beds; rippled; gray ironstone pebble conglomerate (743) from 475.7 ft. to 475.95 ft.; sandstone with coal spars (749) from 475.95 ft. to 476.4 ft.
502.0	511.6	Gray sandstone with coal bands (748); occaisional shale bands; large gray shale clast approximately 15 inches long
511.6	512.1	Gray ironstone pebble conglomerate (743)
512.1	524.9	Gray shale with sandstone streaks (543); low-angle cross beds; rippled; shale pebble conglomerate (742) from 518.5 ft. to 519.7 ft.
524.9	527.3	Dark gray churned sandy shale (325); scattered ironstone pebbles

527.3	530.3	Gray sandstone with shale streaks (543); rippled; streaked; gray ironstone pebble conglomerate (743) from 527.3 ft. to 527.45 ft.; coal spars from 530.0 ft. to 530.3 ft.
530.3	538.3	Dark gray shale with sandstone streaks (323); Magoffin Member
538.3	542.75	Dark gray massive sandy shale (324)
542.75	543.9	Sandstone mudflow (019); Magoffin Member
543.9	553.2	Dark gray massive sandy shale (324); Magoffin Member
553.2	557.55	Dark gray shale with sandstone streaks (323); gray sandstone with shale streaks (543) flat from 553.2 ft. to 553.45 ft.; Magoffin Member
557.55	576.0	Dark gray massive sandy shale (324); Magoffin Member
576.0	577.85	Dark gray shale (124); Magoffin Member
577.85	593.75	Dark gray massive sandy shale (324) invertebrate fossils; fossil hash from 589.8 ft. to 591.1 ft.; ironstone bands; carbonate concretion at 582 ft.; contains the gastropod Trepospira and the brachiopod chonitid; also pelecypods; Magoffin Member
593.75	596.25	Dark gray shale with fossil shells (129); base of the Magoffin Shale
596.25	596.9	Coal (020); Copland Zone; coal 0.45 ft.; shale 0.15 ft.; coal 0.05 ft.
596.9	597.9	Dark gray sandy fire clay (327); root traces are pyrite filled; pyritized sandy shale mudflow (018) in upper 0.3 ft.
597.9	602.4	Dark gray churned sandy shale (325); dark gray shale (124) from 599.65 ft. to 600.35 ft.
602.4	613.45	Dark gray interbedded sandstone and shale (322); rippled; streaked; occasional roots and burrows
613.45	614.0	Dark gray churned sandy shale (325)
614.0	615.1	Dark gray shale (124)
615.1	616.75	Coal (020); Copland Zone; coal 0.5 ft.; sandy shale 0.35 ft.; coal 0.35 ft.; shale 0.2 ft.; coal 0.25 ft.
616.75	620.1	Rooted gray sandstone (547)
620.1	628.6	Massive gray sandstone (544)
628.6	632.5	Gray sandstone with coal spars (749)
632.5	640.4	Gray sandstone with shale streaks (543); rippled; streaked; coal pebbles from 638.2 ft. 638.4 ft.
640.4	651.5	Gray sandstone with coal spars (749); sandstone with shale streaks (543) from 646.1 ft. to 647.5 ft.
651.5	653.1	Gray sandstone with shale streaks (543); rippled; streaked
653.1	659.9	Gray sandstone with coal spars (749); ironstone pebble conglomerate (743) from 656.6 ft. to 658.3 ft.
659.9	663.25	Massive gray sandstone (544)
663.25	665.0	Gray sandstone with shale streaks (543); rippled
665.0	673.85	Gray sandstone with coal spars (749); ironstone pebble conglomerate (743) from 670.6 ft. to 670.9 ft. and from 673.15 ft. to 673.85 ft.
673.85	675.05	Dark gray churned sandy shale (325)

675.05	676.6	Coal (020); Hamlin; coal 1.55 ft.
676.6	678.4	Dark gray sandy fire clay (327); gray fire clay (127) from 676.6 ft. to 677 ft.
678.4	679.4	Dark gray churned sandy shale (325); ironstone bands
679.4	680.1	Dark gray shale (124); coal from 679.6 ft. to 679.75 ft.
680.1	705.6	Dark gray burrowed sandy shale (328); bioturbated with vertical and horizontal burrows from 688 ft. to 694 ft.; wavy-bedded, flaser-bedded, interbeds of sandstone and shale, probably tidal with largely horizontal burrows from 694 ft. to 705.6 ft.
705.6	709.8	Dark gray massive sandy shale (324); coal streaks
709.8	741.1	Dark gray massive sandy shale (324); ironstone bands; contains the fresh-to-brackish water pelecypod Anthraconaia from 721 ft. to 722 ft.
741.1	741.6	Coal (020) Fireclay Rider; coal 0.5 ft.
741.6	744.4	Dark gray churned sandy shale (325)
744.4	749.3	Coal (020); Fireclay Rider; coal 0.15 ft.; shale 0.15 ft.; coal 0.4 ft.; shale 0.8 ft.; coal 0.45 ft.; shale with soft clay 1.65 ft.; coal 1.3 ft.
749.3	750.9	Dark gray sandy fire clay (327); fire clay (127) from 749.3 ft. to 749.8 ft.
750.9	758.2	Dark gray massive sandy shale (324); churned (325) from 750.9 ft. to 751.9 ft.
758.2	764.6	Gray sandstone with coal bands (748)

Core Hole C

County: Leslie
U.S.G.S. Quadrangle: Helton, KY
Location: Edd Fork of Trace Branch (valley-bottom)
Surface Elevation: 1592.9 feet (ground)
Date Started: 12/4/91
Date Completed: 12/12/91
Drilled By: CBC Drilling
Total Depth: 344.0 ft.
Core size: NXE Wireline

From (feet)	To (feet)	Description
0	30.0	Casing - 4" steel pipe
30.0	32.9	Gray sandstone with coal spars (749); ironstained from 32.3 ft. to 32.6 ft.
32.9	50.65	Gray sandstone with shale streaks, flat (543); coal spars from 39.35 ft. to 39.5 ft.; large shale pebbles from 50.3 ft. to 50.65 ft.
50.65	50.9	Sandy shale mudflow (018)
50.9	52.9	Dark gray shale pebble conglomerate (742)
52.9	53.3	Dark gray shale with sandstone streaks (323)
53.3	54.25	Sandy shale mudflow (018)
54.25	58.3	Dark gray shale pebble conglomerate (742)
58.3	60.65	Massive gray sandstone (544); fractures from 59.45 ft. to 60.0 ft.
60.65	62.05	Dark gray shale with siderite nodules (124)
62.05	64.4	Gray sandstone with coal spars (749). occasional siderite nodules
64.4	66.7	Dark gray churned sandy shale (325)
66.7	67.3	Dark gray shale with ironstone pebbles (124)
67.3	67.85	Sandy shale mudflow (018)
67.85	68.2	Dark gray shale (124)
68.2	70.1	Gray sandstone with shale streaks, rippled and streaked (543)
70.1	71.2	Gray sandstone with shale streaks, flat (543)
71.2	80.8	Gray sandstone with shale streaks, rippled and streaked (543)
80.8	83.75	Massive gray sandstone (544)
83.75	85.55	Dark gray sandstone with shale streaks, rippled and streaked (543)
85.55	89.4	Gray sandstone with coal spars (749)
89.4	92.4	Gray sandstone with shale streaks, rippled and streaked (543)
92.4	94.7	Gray sandstone with shale streaks, flat (543)
94.7	95.65	Gray sandstone with shale streaks, rippled (543)
95.65	96.75	Dark gray interbedded sandstone and shale, rippled (322)
96.75	98.6	Gray sandstone with shale streaks, rippled and streaked (543)

98.6	99.2	Gray sandstone with coal bands (748)
99.2	100.0	Gray sandstone with shale streaks, rippled and streaked (543)
100.0	100.8	Gray sandstone with coal bands (748)
100.8	103.45	Gray sandstone with shale streaks, rippled (543)
103.45	103.65	Gray sandstone with coal spars (749)
103.65	104.0	Gray sandstone with shale streaks, rippled (543)
104.0	104.25	Gray ironstone pebble conglomerate (743)
104.25	109.7	Gray sandstone with coal bands (748)
109.7	112.0	Massive gray sandstone (544)
112.0	114.0	Gray sandstone with coal spars (749)
114.0	115.2	Sandy shale mudflow (018)
115.2	115.7	Dark gray churned sandy shale (325)
115.7	116.6	Dark gray shale (124) with gray-green shale pebbles
116.6	118.0	Sandy shale mudflow (018)
118.0	118.3	Gray ironstone pebble conglomerate (743)
118.3	119.0	Dark gray shale with sandstone streaks, rippled (323)
119.0	119.15	Gray sandstone with coal spars (749)
119.15	122.2	Gray sandstone with shale streaks, streaked (543)
122.2	124.5	Gray sandstone with coal spars (749)
124.5	124.95	Gray ironstone pebble conglomerate (743)
124.95	125.8	Gray sandstone with coal spars (749)
125.8	126.0	Dark gray massive sandy shale (324); Magoffin Member
126.0	126.9	Sandy shale mudflow (018); Magoffin Member
126.9	128.7	Dark gray massive sandy shale (324); Magoffin Member
128.7	129.4	Sandy shale mudflow (018); Magoffin Member
129.4	135.8	Burrowed sandy shale (328); Magoffin Member
135.8	142.3	Dark gray shale with sandstone streaks, rippled (543); occasional burrow; Magoffin Member
142.3	160.3	Dark gray massive sandy shale (324) with siderite nodules; Magoffin Member
160.3	173.6	Dark gray massive sandy shale with fossil shells (129); calcite-filled bedding plane at 163.1 ft.; vertical calcite-filled fracture from 163.6 ft. to 163.95 ft.; Magoffin Member
173.6	173.8	Massive fine-grained limestone with fossils (054); Magoffin Member
173.8	180.9	Dark gray massive sandy shale (324); calcite-filled bedding plane at 180.4 ft. and 180.85 ft.; Magoffin Member
180.9	183.0	Massive fine-grained limestone with fossils (054); Magoffin Member
183.0	183.65	Coal (020); Copland Coal zone

183.65	186.45	Dark gray sandy fire clay (327)
186.45	193.15	Dark gray interbedded sandstone and shale, rippled and streaked (322); some burrows
193.15	193.65	Sandstone mudflow (019)
193.65	195.4	Gray sandstone with shale streaks, rippled and streaked (543)
195.4	198.0	Dark gray massive sandy shale (324)
198.0	199.15	Dark gray shale (124)
199.15	199.65	Coal (020); Copland Coal zone
199.65	199.75	Dark gray shale (124)
199.75	200.55	Coal (020); Copland Coal zone
200.55	201.5	Dark gray fire clay (127)
201.5	202.15	Dark gray sandy fire clay (327)
202.15	221.9	Gray sandstone with shale streaks, rippled and streaked (543)
221.9	223.6	Gray sandstone with coal spars (749)
223.6	224.9	Gray sandstone with shale streaks, rippled and streaked (543)
224.9	229.2	Gray sandstone with shale streaks, flat (543)
229.2	233.1	Massive gray sandstone (544)
233.1	236.3	Gray sandstone with coal spars (749)
236.3	239.45	Dark gray burrowed sandy shale (328)
239.45	245.55	Dark gray interbedded sandstone and shale, rippled, streaked (322); some slump features
245.55	246.9	Dark gray massive sandy shale (324)
246.9	247.25	Coal (020); Hamlin Coal zone
247.25	249.7	Dark gray fire clay (127)
249.7	249.85	Coal (020); Hamlin Coal zone
249.85	250.5	Black shale (114)
250.5	252.4	Coal (020); Hamlin Coal zone
252.4	254.0	Dark gray sandy fire clay (327)
254.0	255.9	Rooted gray sandstone (547)
255.9	260.0	Churned sandy shale (325)
260.0	260.35	Dark gray shale (124) with coal streaks
260.35	260.4	Coal (020)
260.4	261.75	Dark gray fire clay (127)
261.75	283.1	Dark gray burrowed sandy shale (328)
283.1	292.4	Black shale (114) with coal streaks in lower 4.8 ft.; pyrite nodule from 291.1 ft. to 291.3 ft.
292.4	297.0	Dark gray shale with sandstone streaks (323)

297.0	306.0	Dark gray massive sandy shale (324) with siderite nodules
306.0	310.4	Dark gray shale (124)
310.4	310.75	Coal (020)
310.75	311.7	Dark gray fire clay (127)
311.7	312.4	Dark gray sandy fire clay (327)
312.4	314.65	Dark gray churned sandy shale (325)
314.65	321.6	Gray sandstone with shale streaks, rippled and streaked (543)
321.6	322.25	Dark gray massive sandy shale (324)
322.25	322.35	Dark gray shale (124)
322.35	322.5	Coal (020); Fire Clay Rider Coal zone
322.5	322.65	Dark gray shale (124)
322.65	323.05	Coal (020); Fire Clay Rider Coal zone
323.05	323.9	Dark gray shale with soft clay layers (124)
323.9	324.8	Coal with bone (020); Fire Clay Rider Coal zone
324.8	326.9	Dark gray churned sandy shale (325)
326.9	329.3	Dark gray shale with soft clay layers (124)
329.3	331.85	Dark gray massive sandy shale (324)
331.85	344.0	Dark gray interbedded sandstone and shale (322)

APPENDIX B:
Pressure-Injection Test Data

The following procedure was used for pressure-injection testing in core holes:

1. The packer assembly was lowered on BX drill rods to the deepest interval to be tested.
2. Packers were inflated to a pressure greater than the minimum pressure required to ensure an adequate seal. Minimum inflation pressures were calculated using the following formula supplied by the packer manufacturer, Aardvark Corporation:

G = [Dp x PSI per foot of injected fluid + Sp +Pp] x 1.1

where:

G = Inflation pressure at the gage (p.s.i.)
Dp = depth to top of packer (ft)
Dw = depth to static water level (ft)
Sp = unconfined packer pressure rating for the bore hole size (p.s.i.)
Pp = Injection pump pressure (p.s.i.)
1.1 = safety factor

The unconfined packer pressure rating supplied by the manufacturer for a 3-inch diameter hole using Model 34B packers is 30 p.s.i. The maximum confined pressure (maximum inflation pressure at depth) for the Model 34B packer is 700 p.s.i.

3. Water was pumped through the drill rods into the test interval.
4. Injection pressure and flow rate within the interval were allowed to stabilize for several minutes.
5. Injection pressure and flow-rate readings were recorded at one-minute intervals for 3 to 7 minutes, depending on the stability of the readings.
6. After completion of the test, packers were deflated and the packer assembly was raised to the next test interval. Selected interval depths were adjusted to ensure that coal seams were located entirely within a test interval.

Estimates of the equivalent-porous-media hydraulic conductivity for each interval were calculated using the following formula (U.S. Bureau of Reclamation, 1974):

K = Q/2piLH ln l/r, where L >10r

where:

K = hydraulic conductivity
Q = constant rate of flow into the hole (average injection rate over test period)
L = length of test interval
H = differential head of water (includes gravity head and applied pressure head
r = radius of hole

Figure B-1 illustrates two methods to calculate the gravity head {h(g)} component of total head (H). Because of the loss of head with depth throughout the study area, the static water level is closer to the interval midpoint than to the static-water level in the core hole. H(g) is calculated using the method in figure B-1(a), even though the strata is saturated.

Results from the two methods diverge the deeper the hole. If the test interval from 730 to 740 feet in core hole B is calculated using the two methods, the results are as follows:

<u>H(g) calculated using Figure B-1(a)</u>

K = 8.4×10^{-7} ft./min.

<u>H(g) calculated using Figure B-1(b)</u>

K = 2.1×10^{-6} ft./min.

The method shown in Figure B-1(b) produces results that are 2.5 times higher than the method shown in Figure B-1(a). Packer test data and calculations are included in this Appendix.

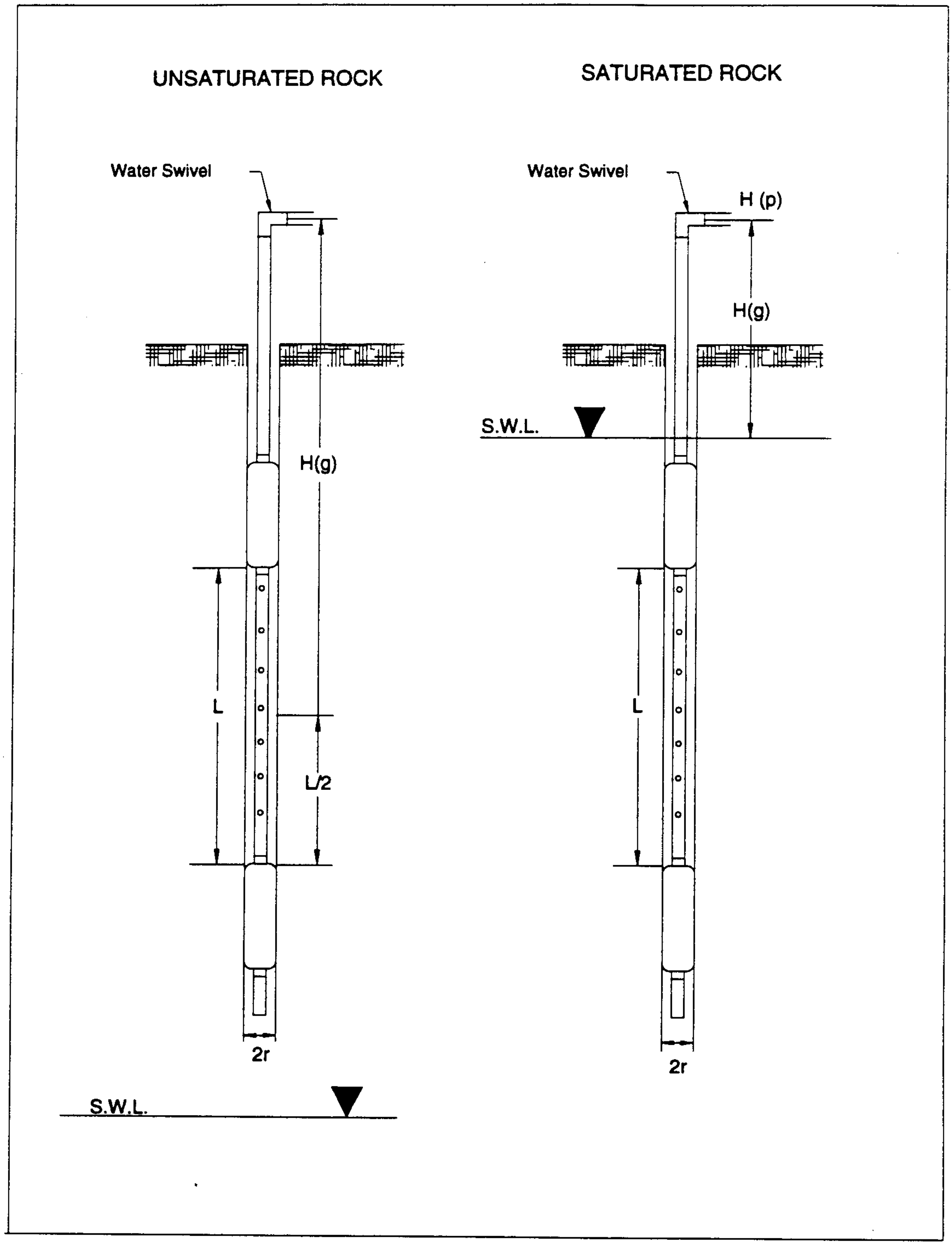


Figure B-1. Methods used to calculate gravity head component of total head for (a) unsaturated rock and (b) saturated rock.

HYDRAULIC CONDUCTIVITY - CORE HOLE A

Test Interval (ft.)	Interval Length L (ft.)	Hole Radius r (ft.)	Avg. Injection Rate Q (gal./min.)	Avg. Applied Pressure (p.s.i.)	Pressure Head H(p)* (ft.)	Gravity Head H(g) ** (ft.)	Total Head H(t)*** (ft.)	Hydraulic Conductivity K **** (ft./min.)
17-27	10	0.125	20.9	11	25.4	30.1	55.5	3.5E-03
27-37	10	0.125	22.2	10	23.1	40.1	63.2	3.3E-03
37-47	10	0.125	0.2	14	32.3	50.1	82.4	2.3E-05
47-57	10	0.125	9.1	12	27.7	60.1	87.8	9.7E-04
57-67	10	0.125	25.3	11	25.4	70.1	95.5	2.5E-03
67-77	10	0.125	0.09	20	46.2	80.1	126.3	6.6E-06
77-87	10	0.125	0.62	23	53.1	90.1	143.2	4.0E-05
87-97	10	0.125	0.03	20	46.2	100.1	146.3	1.9E-06
97-107	10	0.125	0.02	20	46.2	110.1	156.3	1.2E-06
107-117	10	0.125	0.11	24	55.4	112	167.4	6.1E-06
117-127	10	0.125	23.7	26	60.1	122	182.1	1.2E-03
127-137	10	0.125	11.9	20	46.2	132	178.2	6.2E-04
137-147	10	0.125	0.01	25	57.8	142	199.8	4.7E-07
147-157	10	0.125	0.03	26	60.1	152	212.1	1.3E-06
157-167	10	0.125	0.02	26	60.1	162	222.1	8.4E-07
167-177	10	0.125	0.01	26	60.1	172	232.1	4.0E-07
177-187	10	0.125	0.02	26	60.1	182	242.1	7.7E-07
187-197	10	0.125	0.06	26	60.1	192	252.1	2.2E-06
197-207	10	0.125	0.06	25	57.8	202	259.8	2.2E-06
207-217	10	0.125	0.01	30	69.3	212	281.3	3.3E-07
217-227	10	0.125	1.0	30	69.3	222	291.3	3.2E-05
237-247	10	0.125	0.08	34	78.5	242	320.5	2.3E-06
247-257	10	0.125	0.01	31	71.6	252	323.6	2.9E-07
257-267	10	0.125	0.04	31	71.6	262	333.6	1.1E-06
267-277	10	0.125	0.04	32	73.9	272	345.9	1.1E-06
277-287	10	0.125	0.04	36	83.2	282	365.2	1.0E-06
297-307	10	0.125	0.02	31	71.6	302	373.6	5.0E-07
307-317	10	0.125	0.03	32	73.9	312	385.9	7.2E-07
317-327	10	0.125	0.04	32	73.9	322	395.9	9.4E-07
327-337	10	0.125	0.01	32	73.9	332	405.9	2.3E-07
337-347	10	0.125	0.36	30	69.3	342	411.3	8.2E-06
347-357	10	0.125	0.07	29	67.0	352	419.0	1.6E-06
357-367	10	0.125	0.02	31	71.6	362	433.6	4.3E-07
367-377	10	0.125	0.03	31	71.6	372	443.6	6.3E-07
377-387	10	0.125	0.03	31	71.6	382	453.6	6.2E-07
387-397	10	0.125	0.14	30	69.3	392	461.3	2.8E-06
397-407	10	0.125	0.02	31	71.6	402	473.6	3.9E-07
407-417	10	0.125	0.24	33	76.2	412	488.2	4.6E-06
417-427	10	0.125	0.07	31	71.6	422	493.6	1.3E-06
437-447	10	0.125	0.01	32	73.9	442	515.9	1.8E-07
457-467	10	0.125	0.07	31	71.6	462	533.6	1.2E-06
467-477	10	0.125	0.03	32	73.9	472	545.9	5.1E-07
477-487	10	0.125	0.22	42	97.0	482	579.0	3.5E-06
487-497	10	0.125	0.07	33	76.2	492	568.2	1.1E-06

* Applied pressure in units of feet of water.
** H(g) is calculated from interval midpoint
*** H(t) = H(p) + H(g)
**** K = Q / [2 x pi x L x H(t)] x ln [l \ r] x 0.134 cubic feet/gallon.

Lithology of Intervals - Core Hole A

Interval Depth	SS	Sh/ssh	Coal	Interbdd	Fracture	Log
22					-2.45	0.01
32					-2.48	1E-07
42					-4.65	
52					-3.01	
62					-2.61	
72			-5.18			
82			-4.39			
92				-5.72		
102	-5.92					
112	-5.21					
122					-2.92	
132				-3.21		
142				-6.33		
152			-5.88			
162		-6.08				
172	-6.40					
182	-6.11					
192	-5.65					
202	-5.67					
212	-6.48					
222	-4.49					
242	-5.63					
252	-6.54					
262	-5.95					
272	-5.97					
282		-5.99				
302		-6.30				
312		-6.14				
322		-6.03				
332		-6.64				
342			-5.09			
352			-5.81			
362				-6.37		
372	-6.20					
382	-6.21					
392				-5.55		
402			-6.40			
412			-5.34			
422				-5.88		
442		-6.74				
462		-5.91				
472				-6.29		
482			-5.45			
492				-5.94		

HYDRAULIC CONDUCTIVITY - CORE HOLE B

Test Interval (ft.)	Interval Length L (ft.)	Hole Radius r (ft.)	Avg. Injection Rate Q (gal./min.)	Avg. Applied Pressure (p.s.i.)	Pressure Head H(p)* (ft.)	Gravity Head H(g) ** (ft.)	Total Head H(t)*** (ft.)	Hydraulic Conductivity K **** (ft./min.)
42.7-52.7	10	0.125	0.01	17	39.3	49.7	89.0	1.0E-06
50.2-60.2	10	0.125	1.03	17	39.3	60.5	99.8	9.6E-05
60.2-70.2	10	0.125	0.02	17	39.3	70.5	109.8	1.7E-06
70.2-80.2	10	0.125	0.0	24	55.4	80.5	135.9	6.9E-07
80.2-90.2	10	0.125	0.01	18	41.6	90.5	132.1	7.1E-07
90.2-100.2	10	0.125	0.02	19	43.9	100.5	144.4	1.3E-06
100.2-110.2	10	0.125	0.06	20	46.2	110.5	156.7	3.6E-06
110.2-120.2	10	0.125	0.03	18	41.6	120.5	162.1	1.7E-06
120.2-130.2	10	0.125	0.05	19	43.9	130.5	174.4	2.7E-06
130.2-140.2	10	0.125	0.03	19	43.9	140.5	184.4	1.5E-06
140.2-150.2	10	0.125	0.09	18	41.6	150.5	192.1	4.4E-06
150.2-160.2	10	0.125	0.07	18	41.6	160.5	202.1	3.2E-06
160.2-170.2	10	0.125	0.05	17	39.3	170.5	209.8	2.2E-06
170.2-180.2	10	0.125	0.08	17	39.3	180.5	219.8	3.4E-06
180.2-190.2	10	0.125	0.01	18	41.6	190.5	232.1	4.0E-07
190.2-200.2	10	0.125	0.01	18	41.6	200.5	242.1	3.9E-07
200.2-210.2	10	0.125	0.01	18	41.6	210.5	252.1	3.7E-07
210.2-220.2	10	0.125	0.05	18	41.6	220.5	262.1	1.8E-06
220.2-230.2	10	0.125	0.77	19	43.9	230.5	274.4	2.6E-05
230.2-240.2	10	0.125	0.01	19	43.9	240.5	284.4	3.3E-07
240.2-250.2	10	0.125	0.01	19	43.9	250.5	294.4	3.2E-07
250.2-260.2	10	0.125	0.1	19	43.9	260.5	304.4	3.1E-06
260.2-270.2	10	0.125	2.7	17	39.3	270.5	309.8	8.1E-05
278.2-288.2	10	0.125	4.1	18	41.6	285.2	326.8	1.2E-04
290.2-300.2	10	0.125	15.7	22	50.8	300.5	351.3	4.2E-04
300.2-310.2	10	0.125	0.0	18	41.6	310.5	352.1	2.6E-07
310.2-320.2	10	0.125	0.09	18	41.6	320.5	362.1	2.3E-06
320.2-330.2	10	0.125	0.01	18	41.6	330.5	372.1	2.5E-07
330.2-340.2	10	0.125	0.01	18	41.6	335	376.6	2.5E-07
338.2-348.2	10	0.125	0.04	18	41.6	343	384.6	9.7E-07
348.2-358.2	10	0.125	0.37	18	41.6	353	394.6	8.7E-06
360.2-370.2	10	0.125	0.1	18	41.6	365	406.6	2.3E-06
370.2-380.2	10	0.125	0.02	18	41.6	375	416.6	4.5E-07
390.2-400.2	10	0.125	0.01	19	43.9	395	438.9	2.1E-07
400.2-410.2	10	0.125	0.03	19	43.9	405	448.9	6.2E-07
410.2-420.2	10	0.125	2	21	48.5	415	463.5	4.0E-05
420.2-430.2	10	0.125	0.03	19	43.9	425	468.9	6.0E-07
440.2-450.2	10	0.125	0.01	19	43.9	445	488.9	1.9E-07
460.2-470.2	10	0.125	0.04	19	43.9	465	508.9	7.3E-07
480.2-490.2	10	0.125	0.18	20	46.2	485	531.2	3.2E-06
500.2-510.2	10	0.125	0.03	19	43.9	505	548.9	5.1E-07
510.2-520.2	10	0.125	0.01	18	41.6	515	556.6	1.7E-07
520.2-530.2	10	0.125	0.01	21	48.5	525	573.5	1.6E-07
530.2-540.2	10	0.125	0.01	17	39.3	535	574.3	1.6E-07

HYDRAULIC CONDUCTIVITY - CORE HOLE B

Test Interval (ft.)	Interval Length L (ft.)	Hole Radius r (ft.)	Avg. Injection Rate Q (gal./min.)	Avg. Applied Pressure (p.s.i.)	Pressure Head H(p)* (ft.)	Gravity Head H(g) ** (ft.)	Total Head H(t)*** (ft.)	Hydraulic Conductivity K **** (ft./min.)
540.2-550.2	10	0.125	0.01	18	41.6	545	586.6	1.6E-07
550.2-560.2	10	0.125	0.01	18	41.6	555	596.6	1.6E-07
560.2-570.2	10	0.125	0.01	17	39.3	565	604.3	1.5E-07
570.2-580.2	10	0.125	0.01	18	41.6	575	616.6	1.5E-07
580.2-590.2	10	0.125	0.01	19	43.9	585	628.9	1.5E-07
590.2-600.2	10	0.125	0.01	18	41.6	595	636.6	1.5E-07
600.2-610.2	10	0.125	0.06	20	46.2	605	651.2	8.6E-07
610.2-620.2	10	0.125	0.04	18	41.6	615	656.6	5.7E-07
620.2-630.2	10	0.125	0.03	18	41.6	625	666.6	4.2E-07
630.2-640.2	10	0.125	0.03	19	43.9	635	678.9	4.1E-07
640.2-650.2	10	0.125	0.03	18	41.6	645	686.6	4.1E-07
650.2-660.2	10	0.125	0.04	18	41.6	655	696.6	5.4E-07
660.2-670.2	10	0.125	0.04	18	41.6	665	706.6	5.3E-07
670.2-680.2	10	0.125	0.05	15	34.7	675	709.7	6.6E-07
680.2-690.2	10	0.125	0.02	16	37.0	685	722.0	2.6E-07
690.2-700.2	10	0.125	0.04	17	39.3	695	734.3	5.1E-07
700.2-710.2	10	0.125	0.08	18	41.6	705	746.6	1.0E-06
710.2-720.2	10	0.125	0.02	20	46.2	715	761.2	2.4E-07
730.2-740.2	10	0.125	0.07	18	41.6	735	776.6	8.4E-07
740.2-750.2	10	0.125	0.14	16	37.0	745	782.0	1.7E-06
750.2-760.2	10	0.125	0.11	16	37.0	755	792.0	1.3E-06

* Applied pressure in units of feet of water.
** Packer Injection Test Data - H(g) is calculated from interval midpoint
*** H(t) = H(p) + H(g)
**** K = Q / [2 x pi x L x H(t)] x ln [l \ r] x 0.134 cubic feet/gallon.

Lithology of Intervals - Core Hole B

Interval Depth	SS	Sh/Ssh	Coal	Interbdd	Fracture
47		-5.98			
55					-4.02
65	-5.77				
75	-6.16				
85	-6.15				
95	-5.89				
105	-5.45				
115	-5.76				
125	-5.57				
135	-5.82				
145	-5.36				
155		-5.49			
165				-5.65	
175			-5.47		
185			-6.40		
195		-6.41			
205		-6.43			
215		-5.75			
225			-4.58		
235		-6.48			
245		-6.50			
255				-5.51	
265			-4.09		
283			-3.93		
295					-3.38
305		-6.58			
315				-5.63	
325				-6.60	
335		-6.61			
343			-6.01		
353			-5.06		
365	-5.64				
375	-6.35				
395	-6.67				
405	-6.21				
415			-4.40		
425				-6.22	
445	-6.72				
465	-6.13				
485	-5.50				
505	-6.29				
515		-6.78			
525		-6.79			
535		-6.79			

Lithology of Intervals - Core Hole B

Interval Depth	SS	Sh/Ssh	Coal	Interbdd	Fracture
545		-6.80			
555		-6.81			
565		-6.81			
575		-6.82			
585		-6.83			
595			-6.83		
605				-6.07	
615			-6.25		
625	-6.38				
635	-6.39				
645	-6.39				
655	-6.27				
665	-6.28				
675			-6.18		
685		-6.59			
695		-6.29			
705		-6.00			
715		-6.61			
735		-6.08			
745			-5.78		
755		-5.89			

HYDRAULIC CONDUCTIVITY - CORE HOLE C

Test Interval (ft.)	Interval Length L (ft.)	Hole Radius r (ft.)	Avg. Injection Rate Q (gal./min.)	Avg. Applied Pressure (p.s.i.)	Pressure Head H(p)* (ft.)	Gravity Head H(g) ** (ft.)	Total Head H(t)*** (ft.)	Hydraulic Conductivity K **** (ft./min.)
33.7-43.7	10	0.125	0.14	18	41.6	38.7	80.3	1.6E-05
40.4-50.4	10	0.125	0.01	20	46.2	45.4	91.6	1.0E-06
50.4-60.4	10	0.125	9.6	21	48.5	55.4	103.9	8.6E-04
60.4-70.4	10	0.125	2.6	21	48.5	65.4	113.9	2.2E-04
70.4-80.4	10	0.125	0.01	22	50.8	75.4	126.2	7.4E-07
80.4-90.4	10	0.125	0.01	21	48.5	85.4	133.9	7.0E-07
90.4-100.4	10	0.125	0.01	21	48.5	95.4	143.9	6.5E-07
100.4-110.4	10	0.125	0.01	21	48.5	105.4	153.9	6.1E-07
110.4-120.4	10	0.125	0.08	21	48.5	115.4	163.9	4.6E-06
120.4-130.4	10	0.125	0.16	20	46.2	125.4	171.6	8.7E-06
130.4-140.4	10	0.125	0.01	20	46.2	135.4	181.6	5.1E-07
140.4-150.4	10	0.125	0.01	20	46.2	145.4	191.6	4.9E-07
150.4-160.4	10	0.125	0.01	20	46.2	155.4	201.6	4.6E-07
160.4-170.4	10	0.125	0.01	20	46.2	165.4	211.6	4.4E-07
170.4-180.4	10	0.125	0.01	20	46.2	175.4	221.6	4.2E-07
180.4-190.4	10	0.125	0.01	21	48.5	185.4	233.9	4.0E-07
190.4-200.4	10	0.125	0.01	20	46.2	195.4	241.6	3.9E-07
198.4-208.4	10	0.125	0.01	20	46.2	203.4	249.6	3.7E-07
210.4-220.4	10	0.125	0.01	20	46.2	215.4	261.6	3.6E-07
220.4-230.4	10	0.125	0.01	20	46.2	225.4	271.6	3.4E-07
230.4-240.4	10	0.125	0.02	20	46.2	235.4	281.6	6.6E-07
240.4-250.4	10	0.125	0.01	20	46.2	245.4	291.6	3.2E-07
250.4-260.4	10	0.125	0.01	20	46.2	255.4	301.6	3.1E-07
260.4-270.4	10	0.125	0.02	20	46.2	265.4	311.6	6.0E-07
270.4-280.4	10	0.125	0.01	20	46.2	275.4	321.6	2.9E-07
280.4-290.4	10	0.125	0.01	20	46.2	285.4	331.6	2.8E-07
290.4-300.4	10	0.125	0.01	20	46.2	295.4	341.6	2.7E-07
300.4-310.4	10	0.125	0.01	20	46.2	305.4	351.6	2.7E-07
309.4-319.4	10	0.125	0.03	19	43.9	314.4	358.3	7.8E-07
320.4-330.4	10	0.125	0.01	18	41.6	325.4	367.0	2.5E-07
330.4-340.4	10	0.125	0.03	24	55.4	335.4	390.8	7.2E-07

* Applied pressure in units of feet of water.
** H(g) = Distance in feet to the test interval midpoint.
*** H(t) = H(p) + H(g)
**** K = Q / [2 x pi x L x H(t)] x ln [l \ r] x 0.134 cubic feet/gallon.

HYDRAULIC CONDUCTIVITY - CORE HOLE C

Lithology of Interval

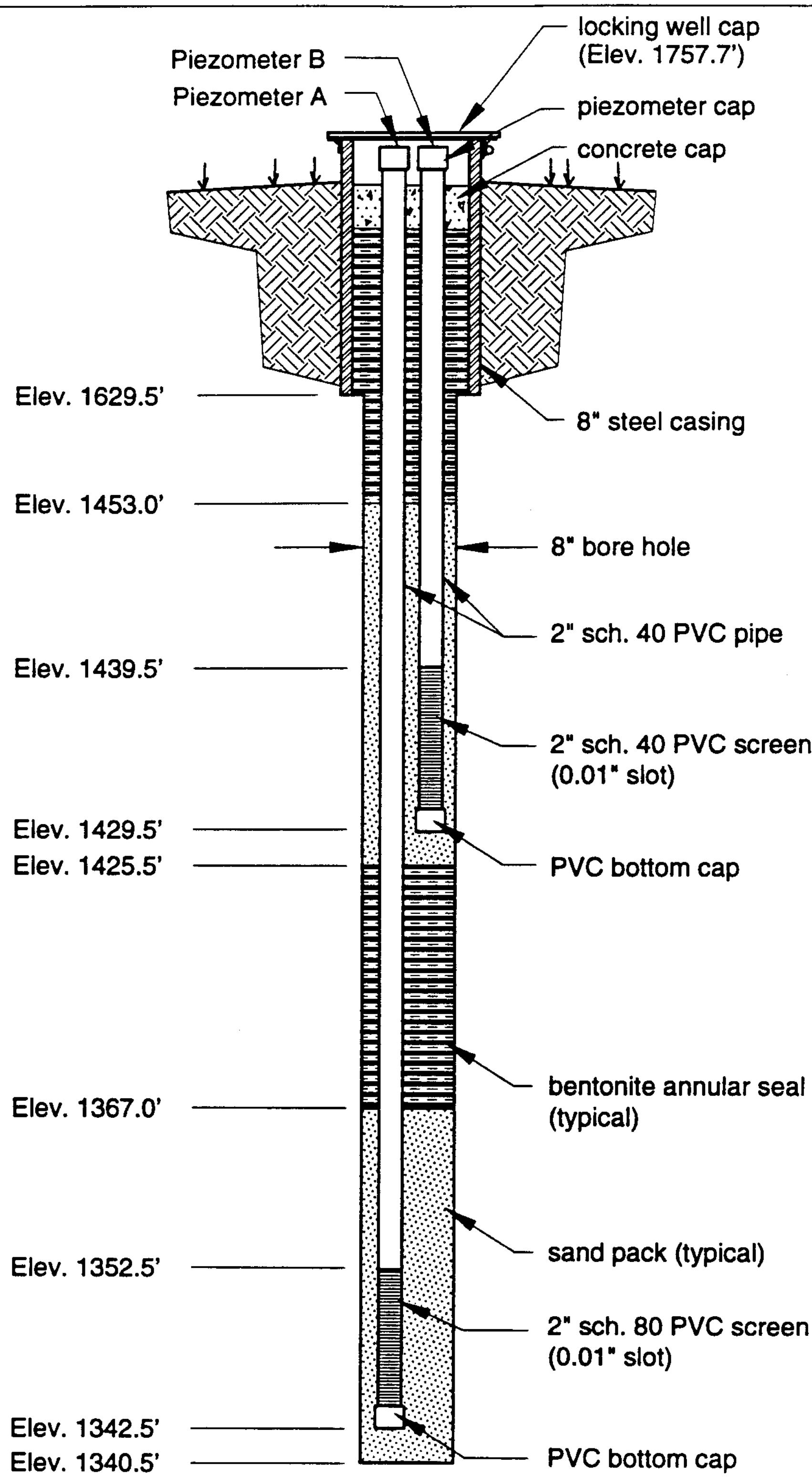
Interval Midpoint	SS	Sh/ssh	Coal	Interbed	Fracture
38.7	-4.79				
45.4	-5.99				
55.4					-3.06
65.4					-3.67
75.4	-6.13				
85.4	-6.15				
95.4	-6.19				
105.4	-6.22				
115.4				-5.34	
125.4				-5.06	
135.4		-6.29			
145.4		-6.31			
155.4		-6.33			
165.4		-6.36			
175.4		-6.38			
185.4			-6.4		
195.4				-6.41	
203.4			-6.43		
215.4	-6.45				
225.4	-6.46				
235.4	-6.18				
245.4		-6.5			
255.4			-6.51		
265.4		-6.22			
275.4		-6.54			
285.4		-6.55			
295.4		-6.56			
305.4		-6.58			
314.4		-6.11			
325.4			-6.6		
335.4				-6.15	

APPENDIX C:
Daily Precipitation Data

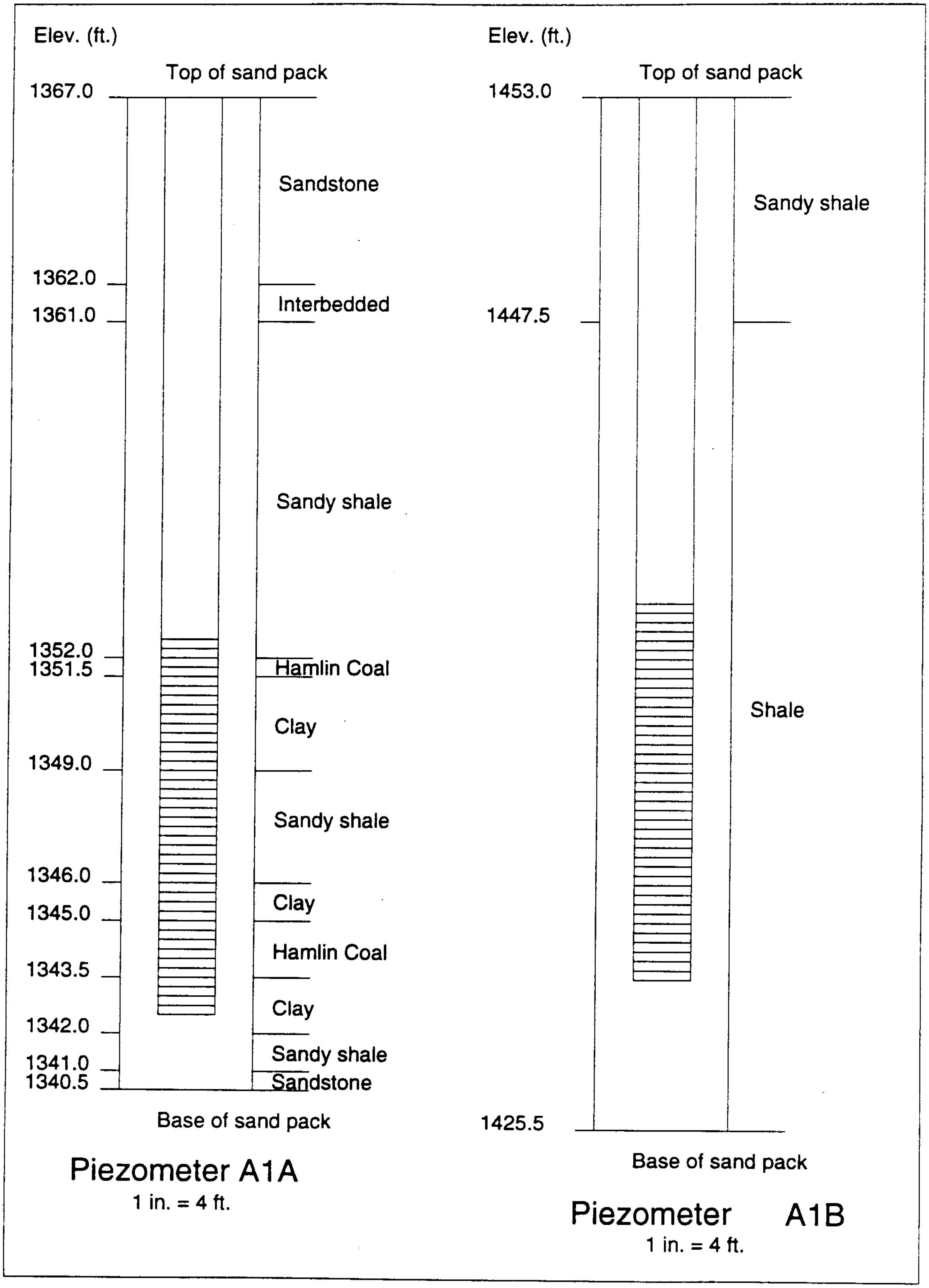
Precipitation Data for Edd Fork
(Inches of Rain)

Day	June 1992	July 1992	Aug 1992	Sept. 1992	Oct. 1992	Nov. 1992	Dec. 1992	Jan. 1993	Feb. 1993
1		1.27	0.00	0.00	0.00	0.03	0.09	0.02	0
2		0.00	0.00	0.00	0.00	0.20	0.14	0.00	0
3		0.30	0.00	0.00	0.00	0.00	0.04	0.00	0
4		0.00	0.06	0.72	0.71	0.43	0.21	0.29	0
5		0.78	0.00	0.01	0.56	0.31	0.01	0.15	0
6		0.13	0.00	0.00	0.00	0.02	0.00	0.01	0
7		0.00	0.00	0.63	0.00	0.04	0.03	0.1	0
8		0.00	0.17	0.01	0.09	0.00	0.00	0.31	0
9		0.00	0.46	0.00	0.42	0.00	0.03	0.02	0
10		0.00	0.04	0.69	0.00	0.00	0.64	0.00	0
11		0.00	0.00	0.00	0.00	0.02	0.00	0.27	0.58
12	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.16	0.11
13	0.18	0.00	0.98	0.00	0.00	0.00	0.22	0.09	0.05
14	0.76	0.80	0.00	0.00	0.00	0.00	0.06	0.00	0
15	0.37	0.36	0.39	0.00	0.00	0.07	0.00	0.00	0.05
16	0.54	0.00	0.00	0.00	0.03	0.00	0.62	0.00	0.76
17	0.04	0.68	0.02	0.00	0.00	0.00	0.93	0.00	0.01
18	1.19	0.01	0.00	1.21	0.00	0.00	0.00	0.00	0
19	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.01	0
20	0.00	0.00	0.00	0.00	0.00	0.00	0.76	0.01	0.08
21	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.18	1.84
22	0.00	0.04	0.16	0.14	0.00	0.50	0.21	0.00	0
23	0.00	0.29	0.01	0.03	0.00	0.00	0.95	0.00	0
24	0.38	0.02	0.00	0.00	0.00	0.28	0.01	0.58	0
25	0.18	1.33	0.00	0.00	0.00	0.01	0.00	0.00	0.01
26	0.44	0.04	1.97	0.16	0.00	0.00	0.03	0.00	0.45
27	0.00	0.51	0.01	0.32	0.11	0.01	0.36	0.00	0
28	0.00	0.00	2.53	0.00	0.00	0.01	0.09	0.00	0.06
29	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
30	0.04	0.06	0.00	0.00	0.36	0.01	0.00	0.00	
31		0.42	0.00		0.2		0.06	0.00	
Monthly Total	4.23	7.04	6.80	4.04	2.48	2.57	5.49	2.20	4.00

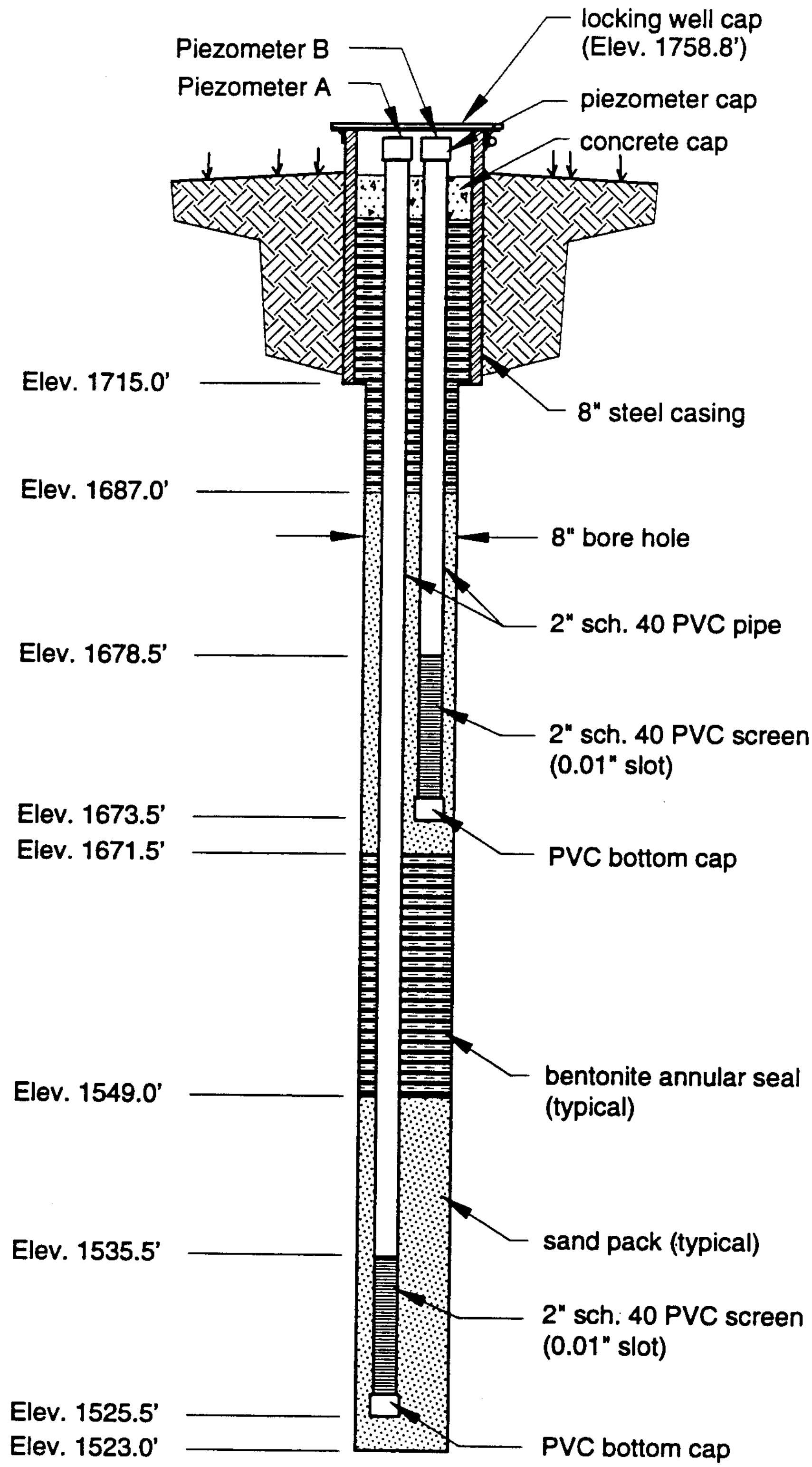
APPENDIX D:
Piezometer Construction Details



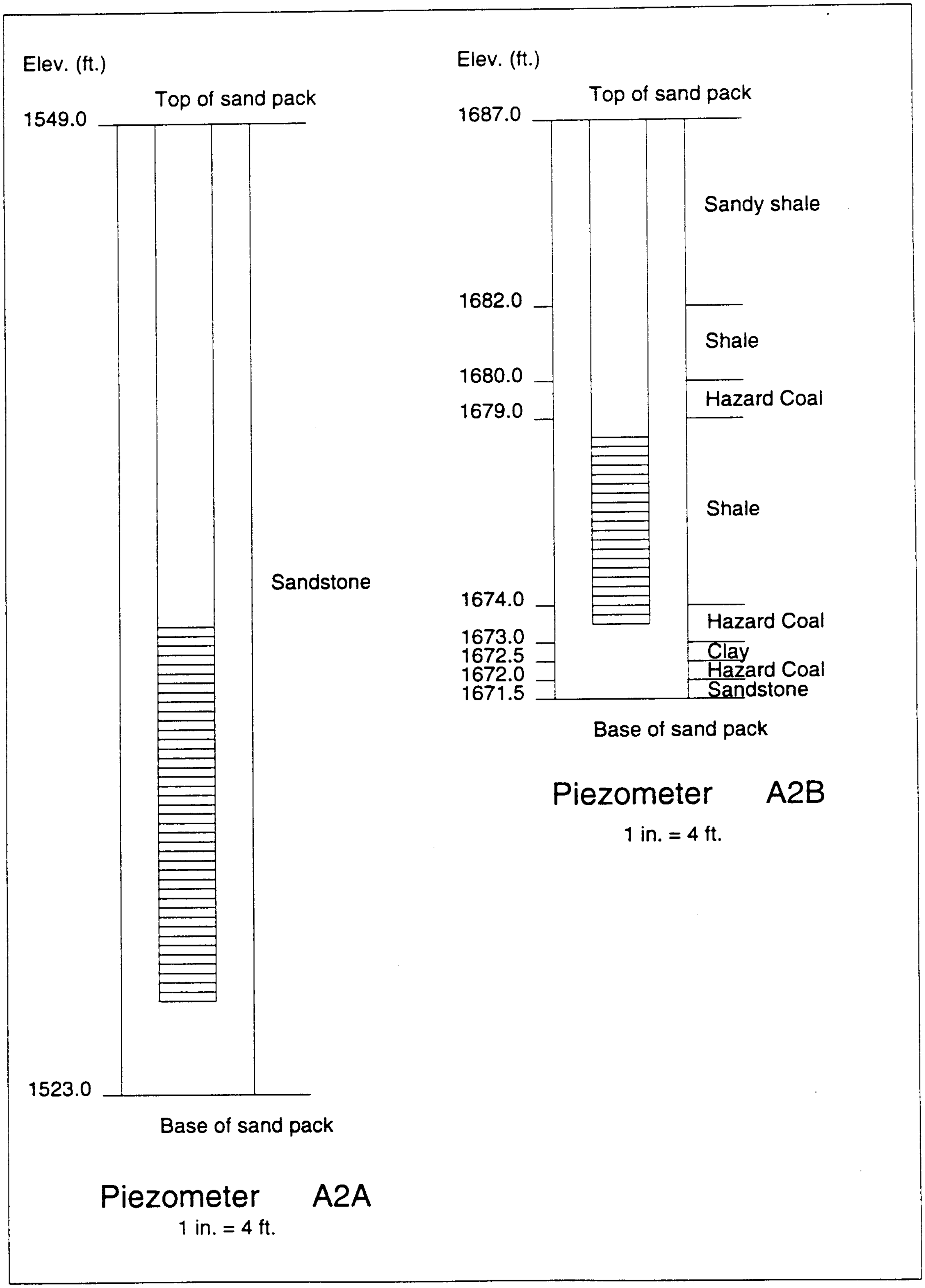
Piezometers A1A and A1B

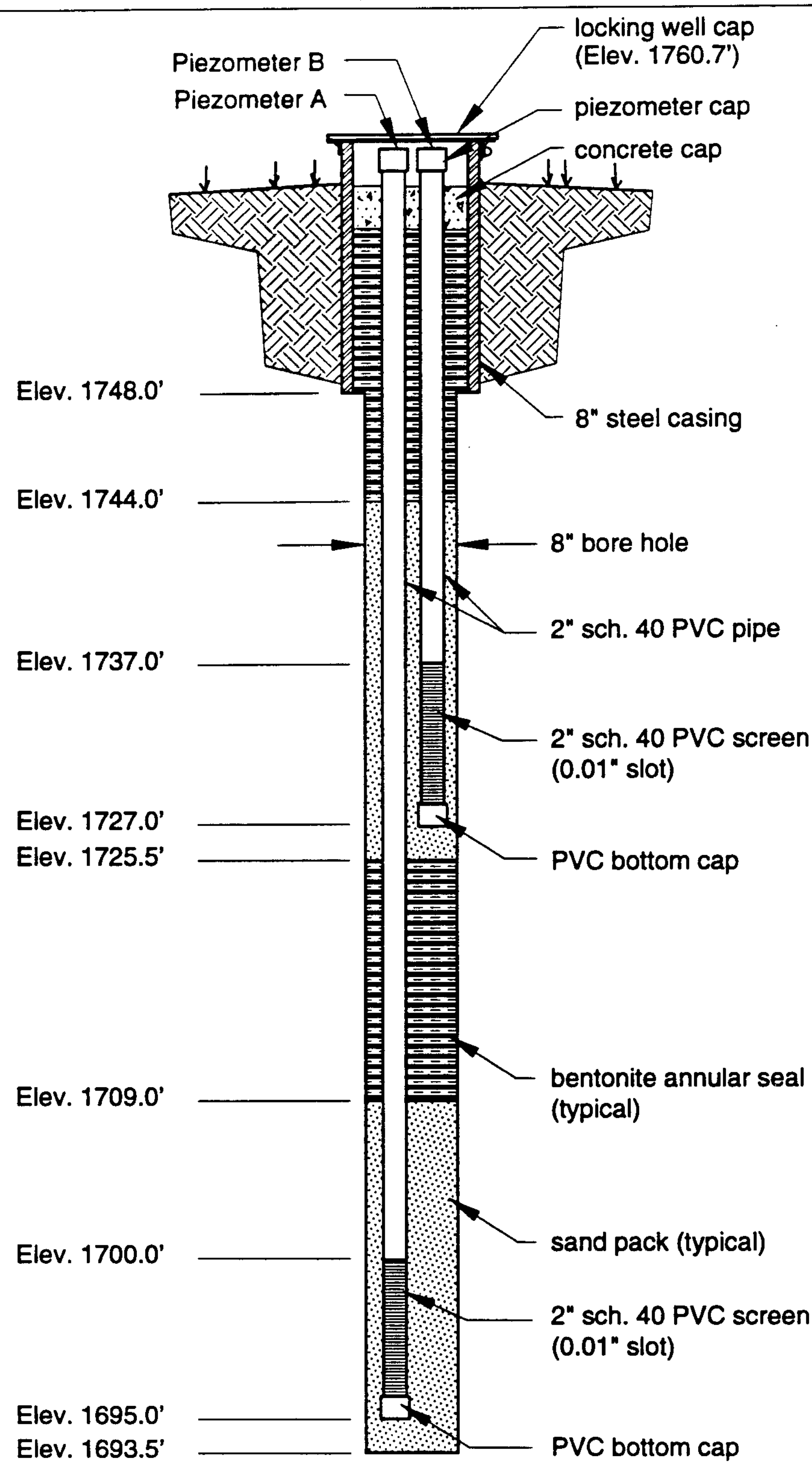


Elev. (ft.)
Top of sand pack
1367.0
Sandstone
1362.0
Interbedded
1361.0
Sandy shale
1352.0
1351.5
Hamlin Coal
Clay
1349.0
Sandy shale
1346.0
Clay
1345.0
Hamlin Coal
1343.5
Clay
1342.0
Sandy shale
1341.0
1340.5
Sandstone
Base of sand pack
Piezometer A1A
1 in. = 4 ft.
Elev. (ft.)
Top of sand pack
1453.0
Sandy shale
1447.5
Shale
1425.5
Base of sand pack
Piezometer A1B
1 in. = 4 ft.

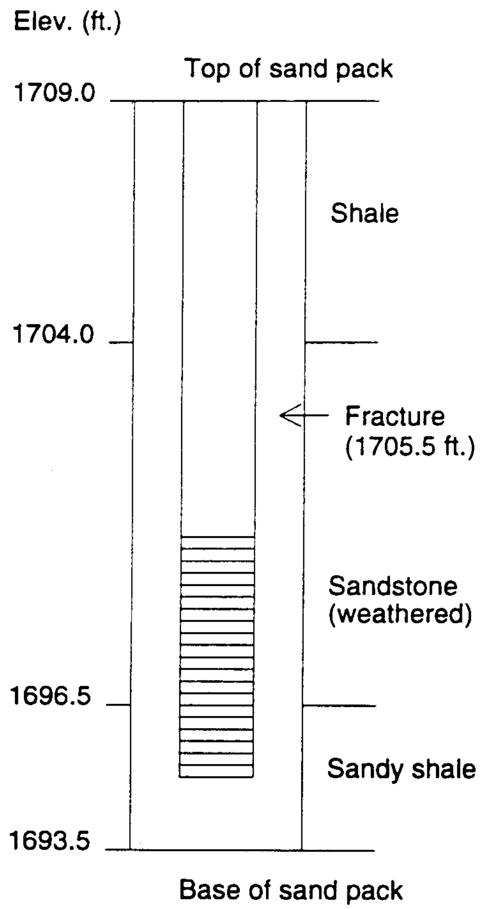


Piezometers A2A and A2B

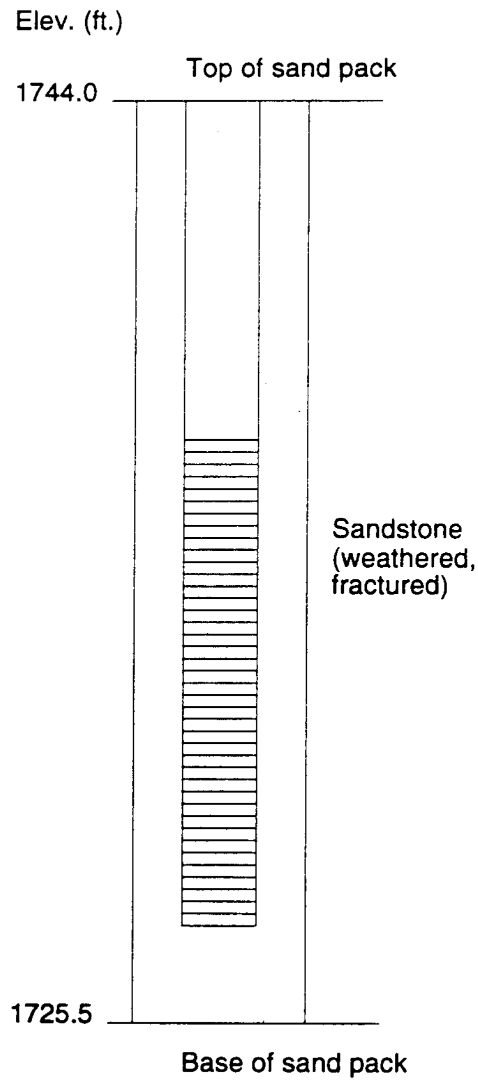

Elev. (ft.)
Top of sand pack
1549.0
Sandstone
1523.0
Base of sand pack
Piezometer A2A
1 in. = 4 ft.
Elev. (ft.)
Top of sand pack
1687.0
Sandy shale
1682.0
Shale
1680.0
Hazard Coal
1679.0
Shale
1674.0
Hazard Coal
1673.0
Clay
1672.5
Hazard Coal
1672.0
Sandstone
1671.5
Base of sand pack
Piezometer A2B
1 in. = 4 ft.



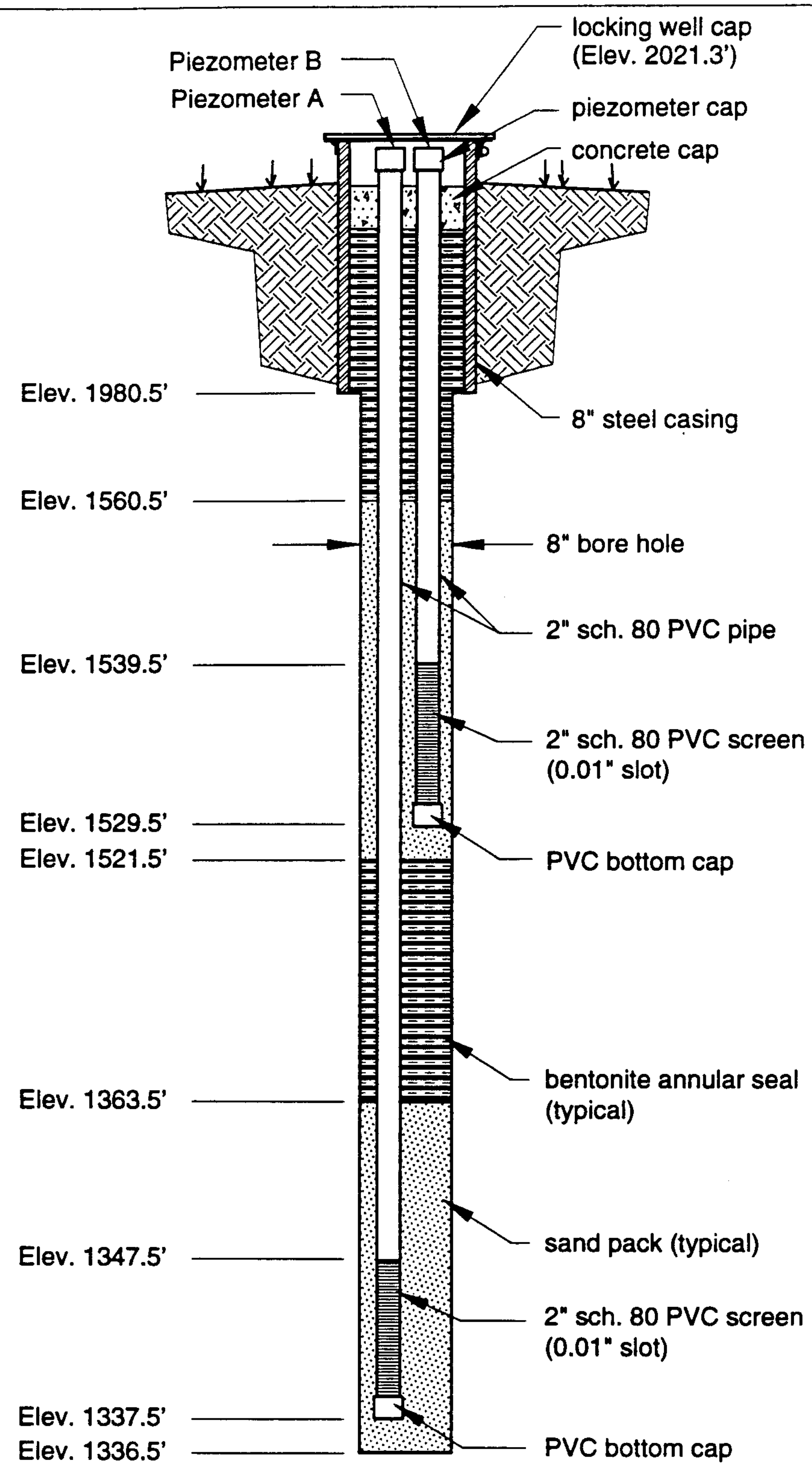
Piezometers A3A and A3B



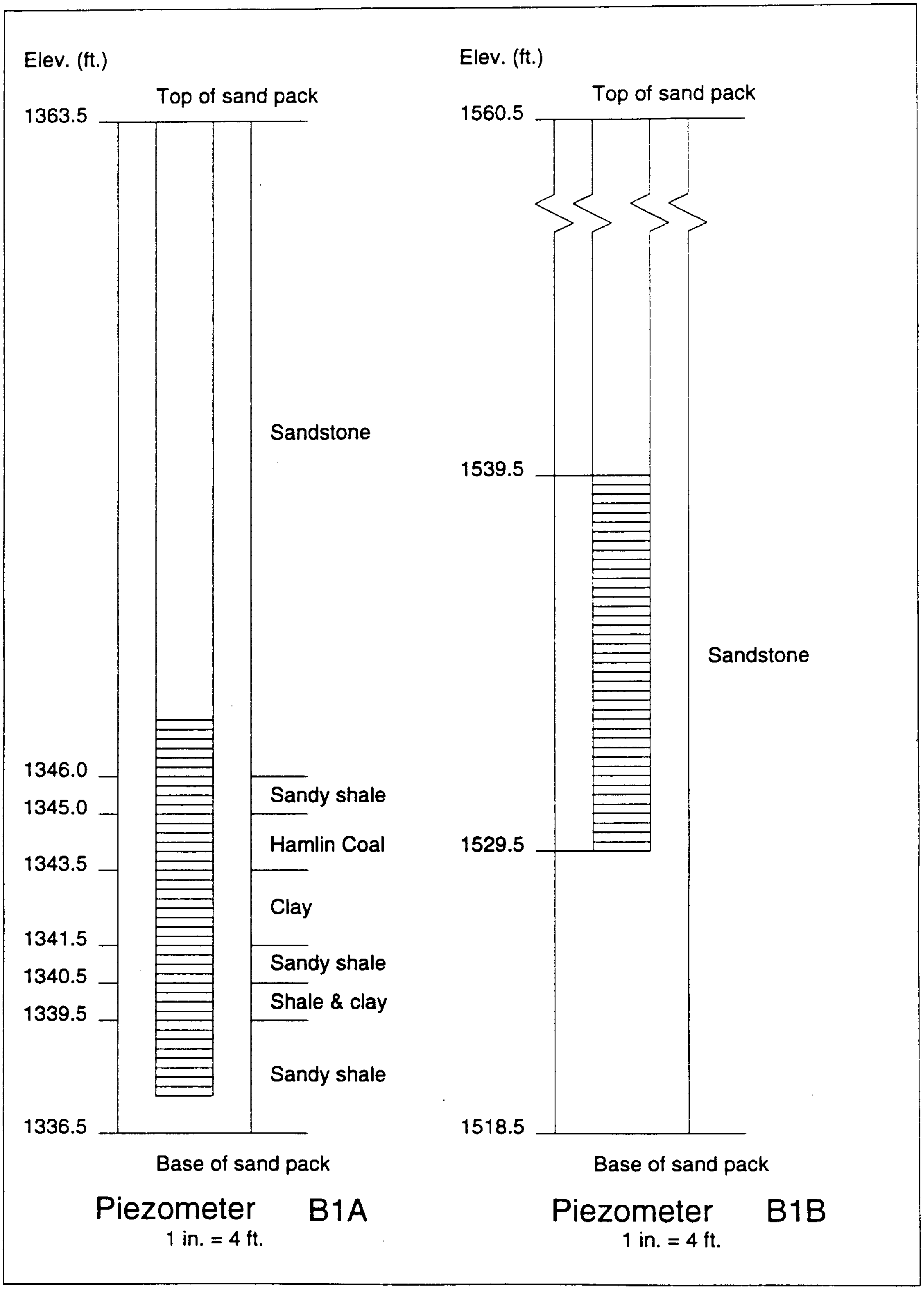
Piezometer A3A
1 in. = 4 ft.

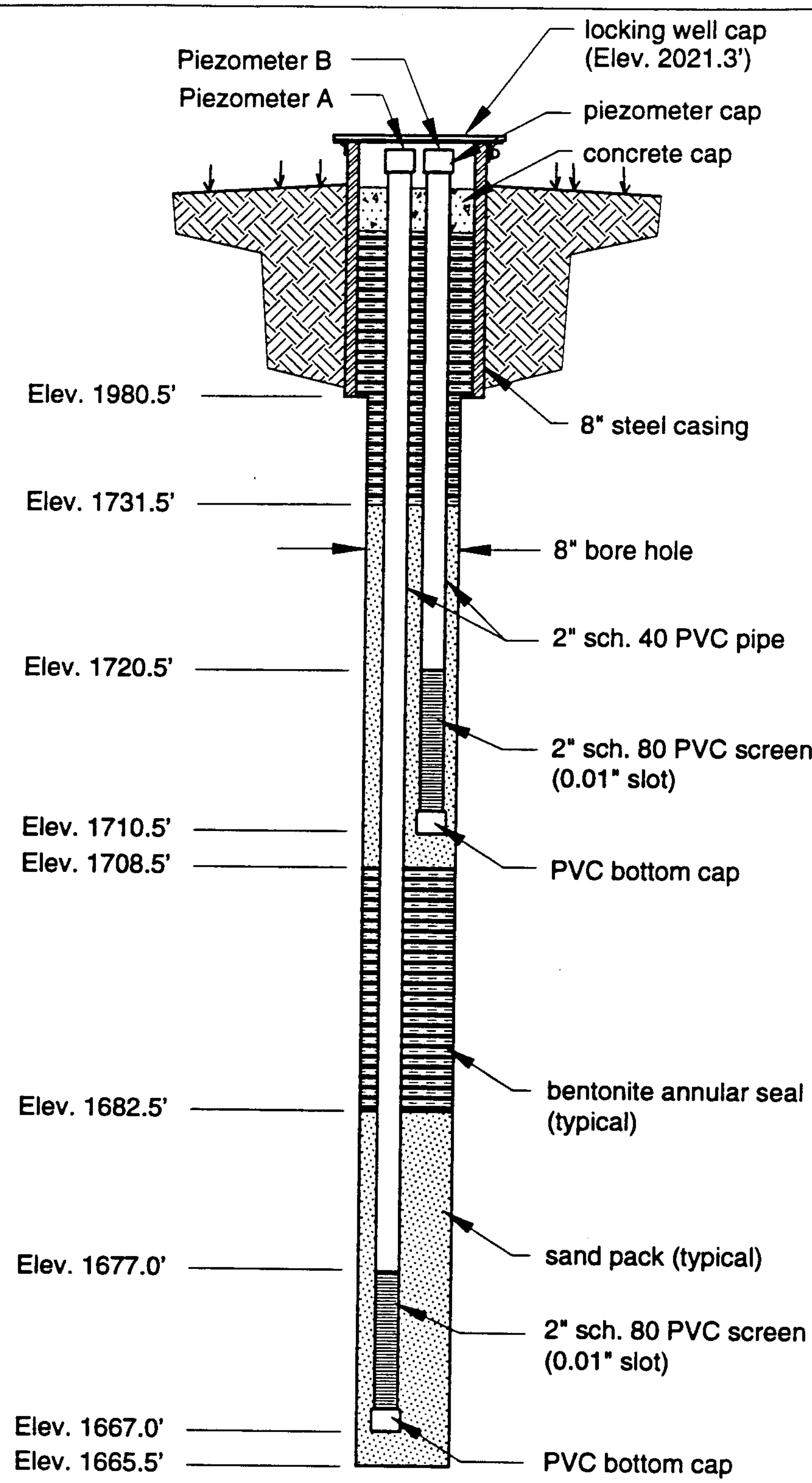


Piezometer A3B
1 in. = 4 ft.

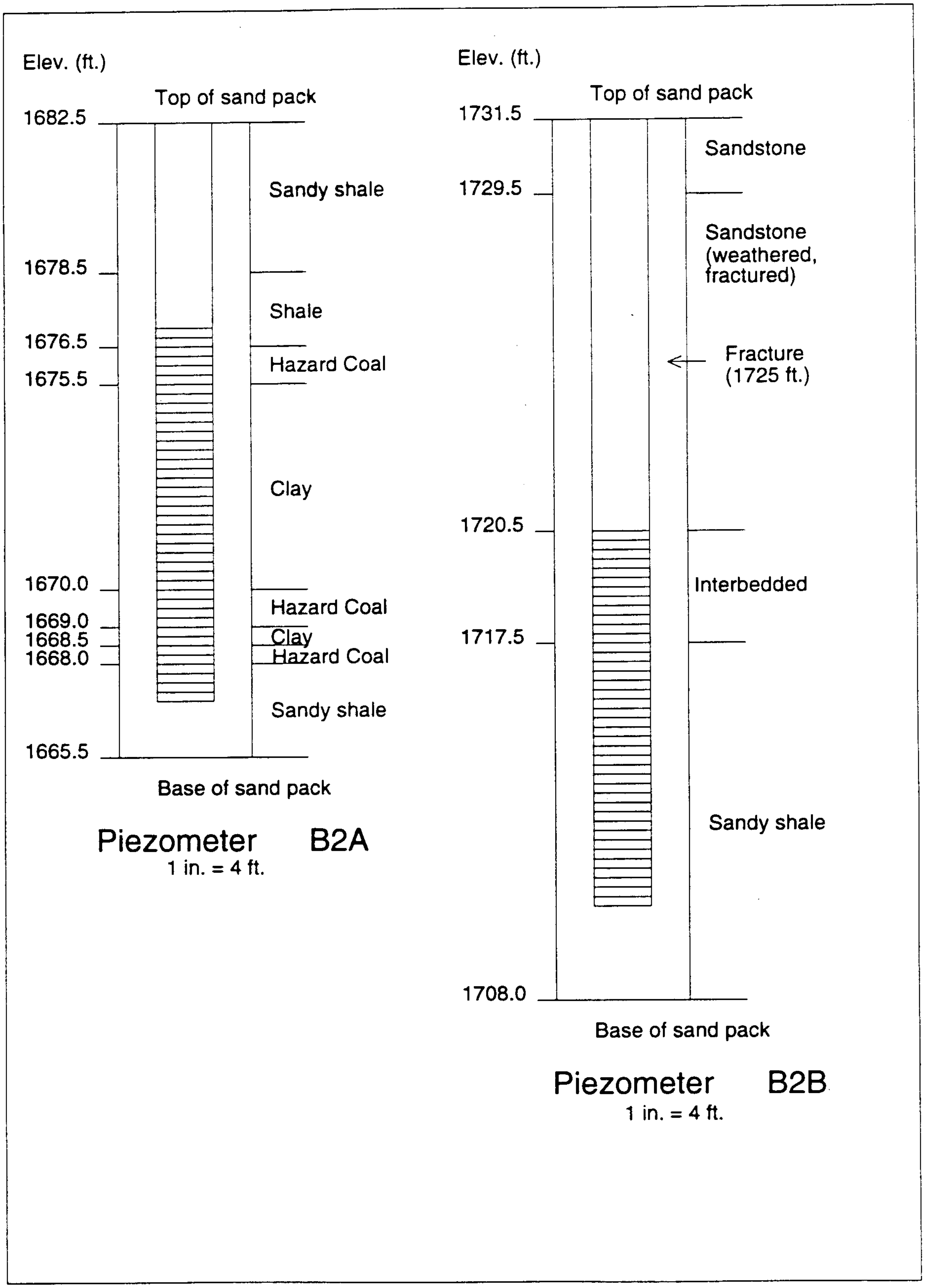


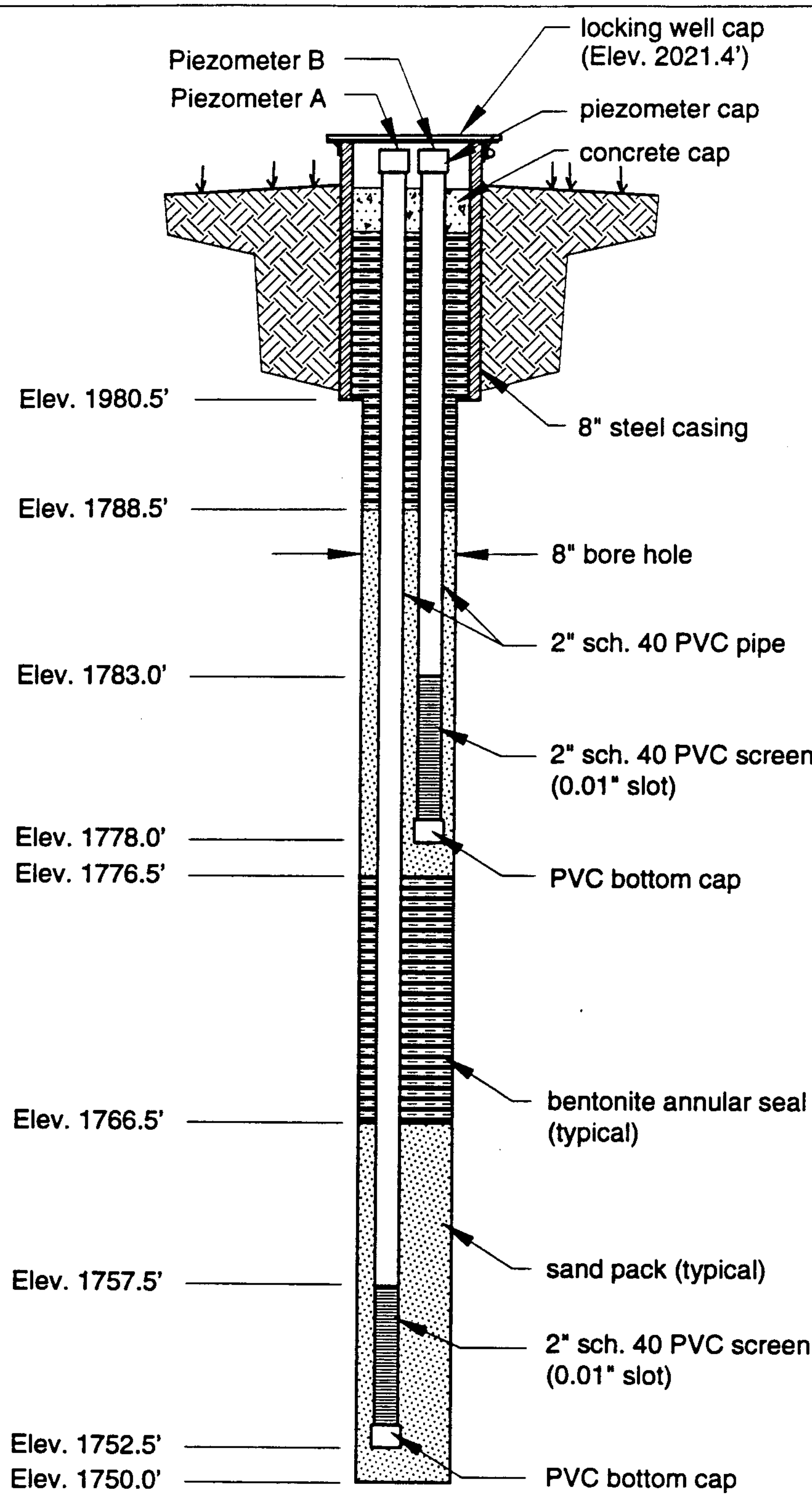
Piezometers B1A and B1B


Elev. (ft.)
Top of sand pack
1363.5
Sandstone
1346.0
Sandy shale
1345.0
Hamlin Coal
1343.5
Clay
1341.5
Sandy shale
1340.5
Shale & clay
1339.5
Sandy shale
1336.5
Base of sand pack
Piezometer B1A
1 in. = 4 ft.
Elev. (ft.)
Top of sand pack
1560.5
1539.5
Sandstone
1529.5
1518.5
Base of sand pack
Piezometer B1B
1 in. = 4 ft.

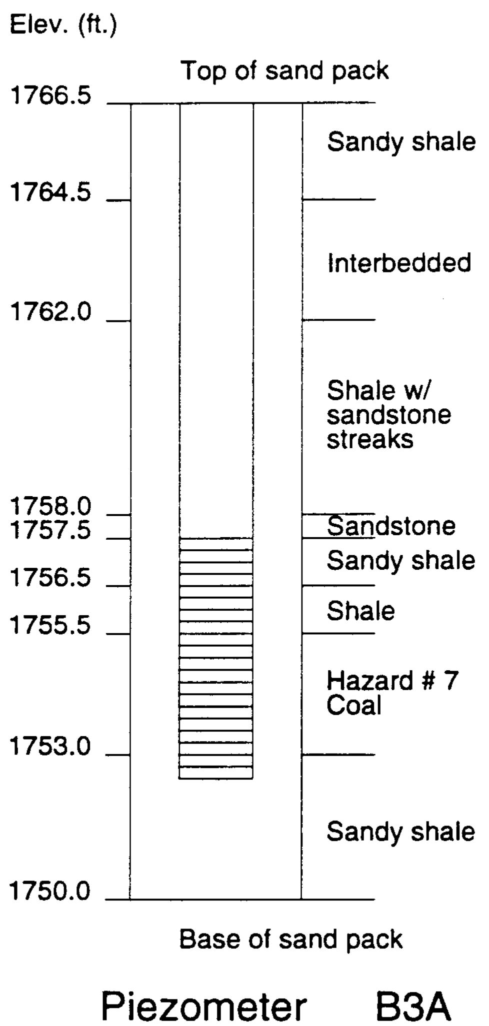


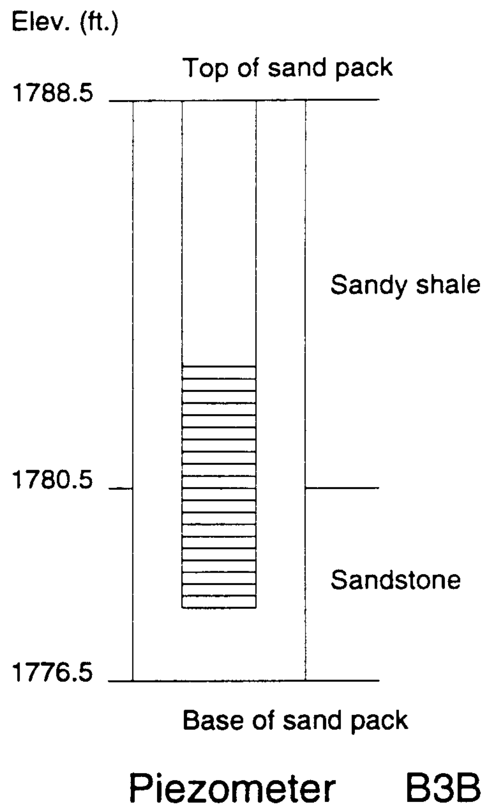
Piezometers B2A and B2B

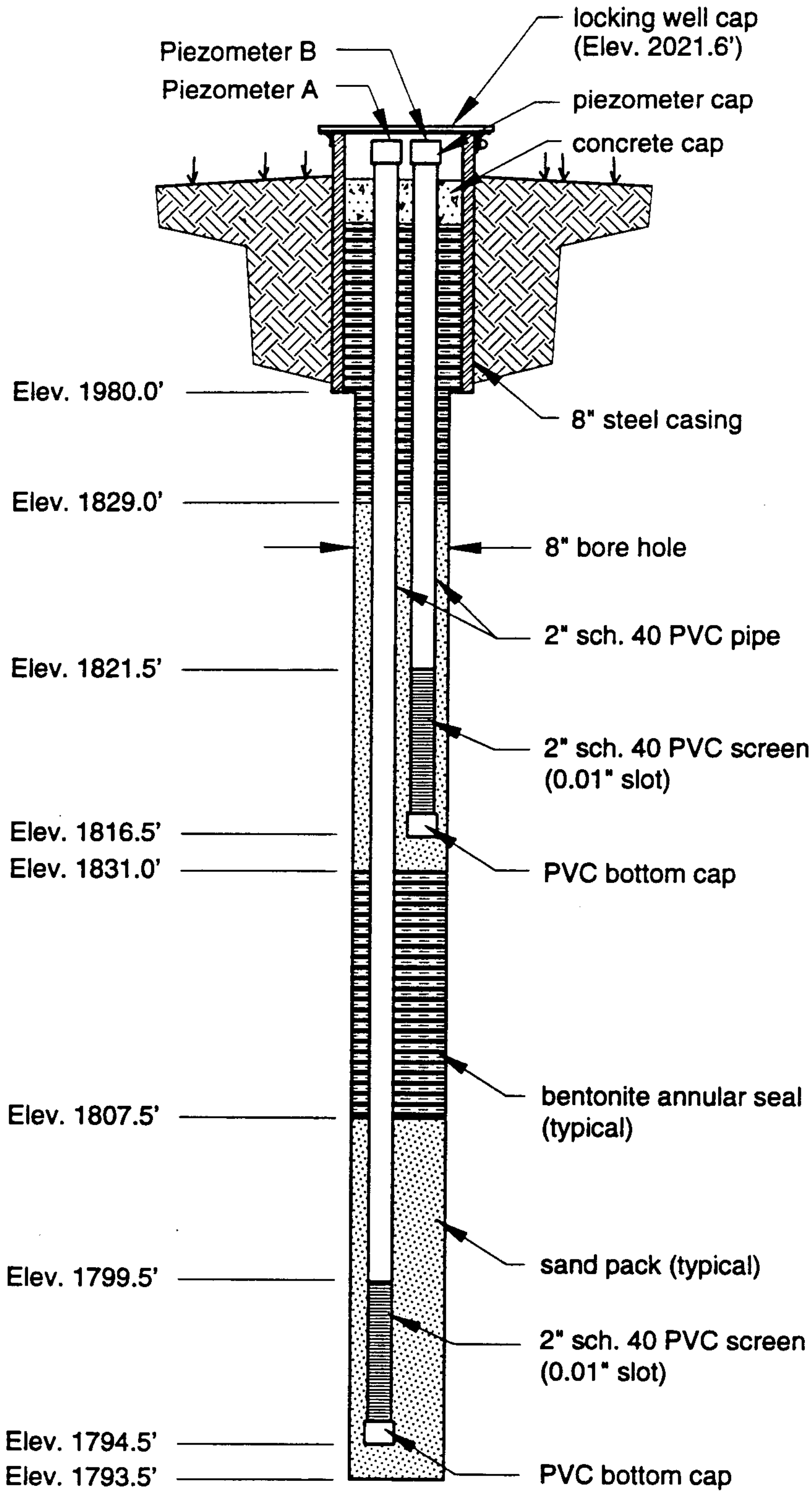

Elev. (ft.)
Top of sand pack
1682.5
Sandy shale
1678.5
Shale
1676.5
Hazard Coal
1675.5
Clay
1670.0
Hazard Coal
1669.0
1668.5
Clay
1668.0
Hazard Coal
Sandy shale
1665.5
Base of sand pack
Piezometer B2A
1 in. = 4 ft.
Elev. (ft.)
Top of sand pack
1731.5
Sandstone
1729.5
Sandstone (weathered, fractured)
Fracture (1725 ft.)
1720.5
Interbedded
1717.5
Sandy shale
1708.0
Base of sand pack
Piezometer B2B
1 in. = 4 ft.



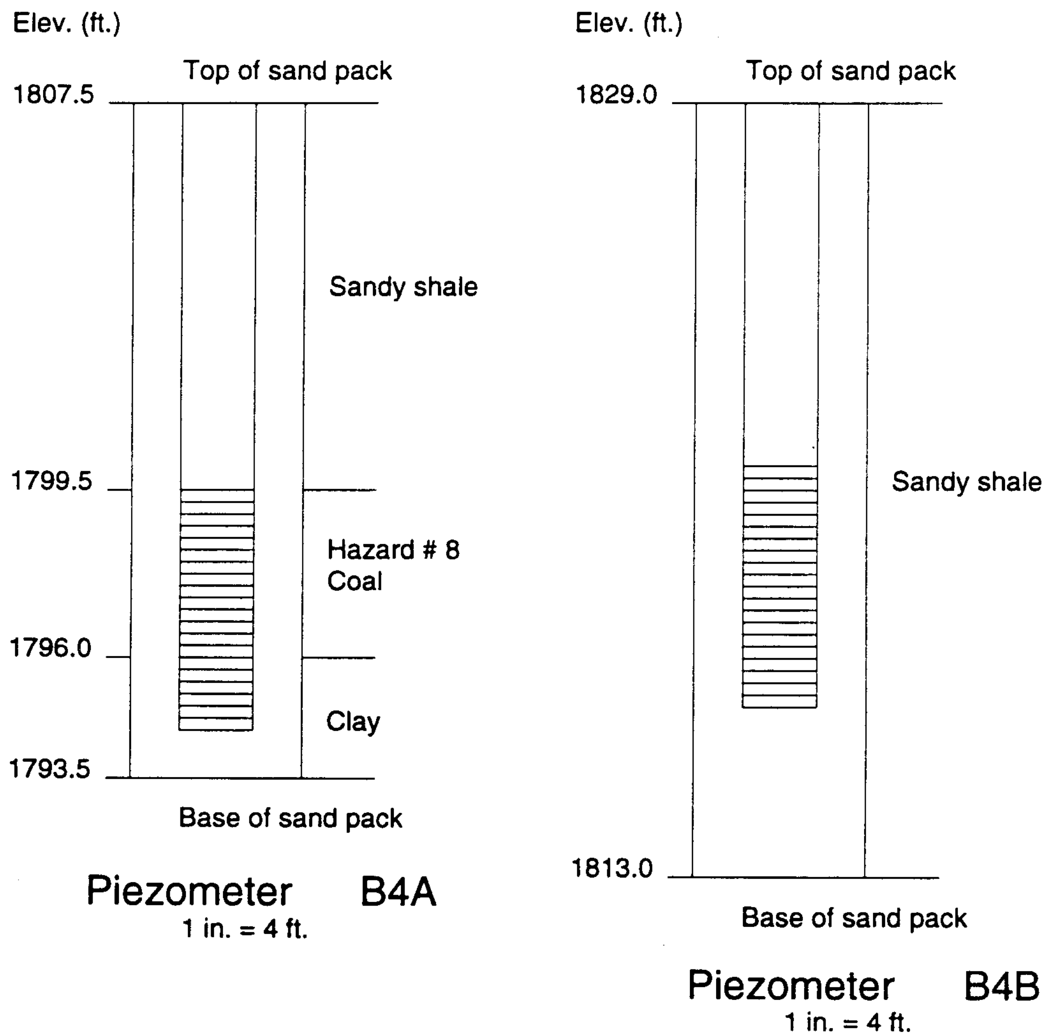
Piezometers B3A and B3B

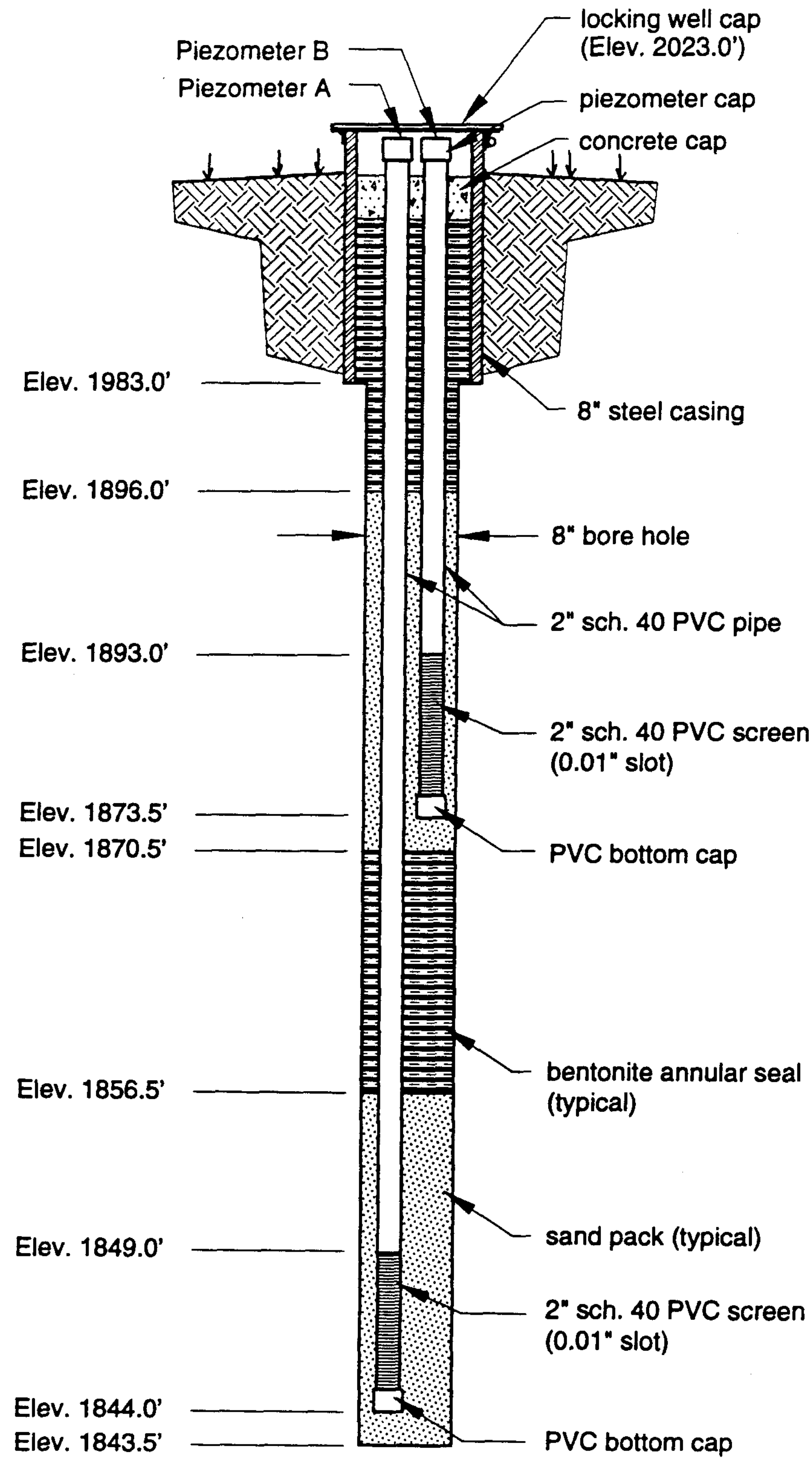

Elev. (ft.)
Top of sand pack
1766.5
Sandy shale
1764.5
Interbedded
1762.0
Shale w/ sandstone streaks
1758.0
1757.5
Sandstone
Sandy shale
1756.5
Shale
1755.5
Hazard # 7 Coal
1753.0
Sandy shale
1750.0
Base of sand pack
Piezometer B3A


Elev. (ft.)
Top of sand pack
1788.5
Sandy shale
1780.5
Sandstone
1776.5
Base of sand pack
Piezometer B3B

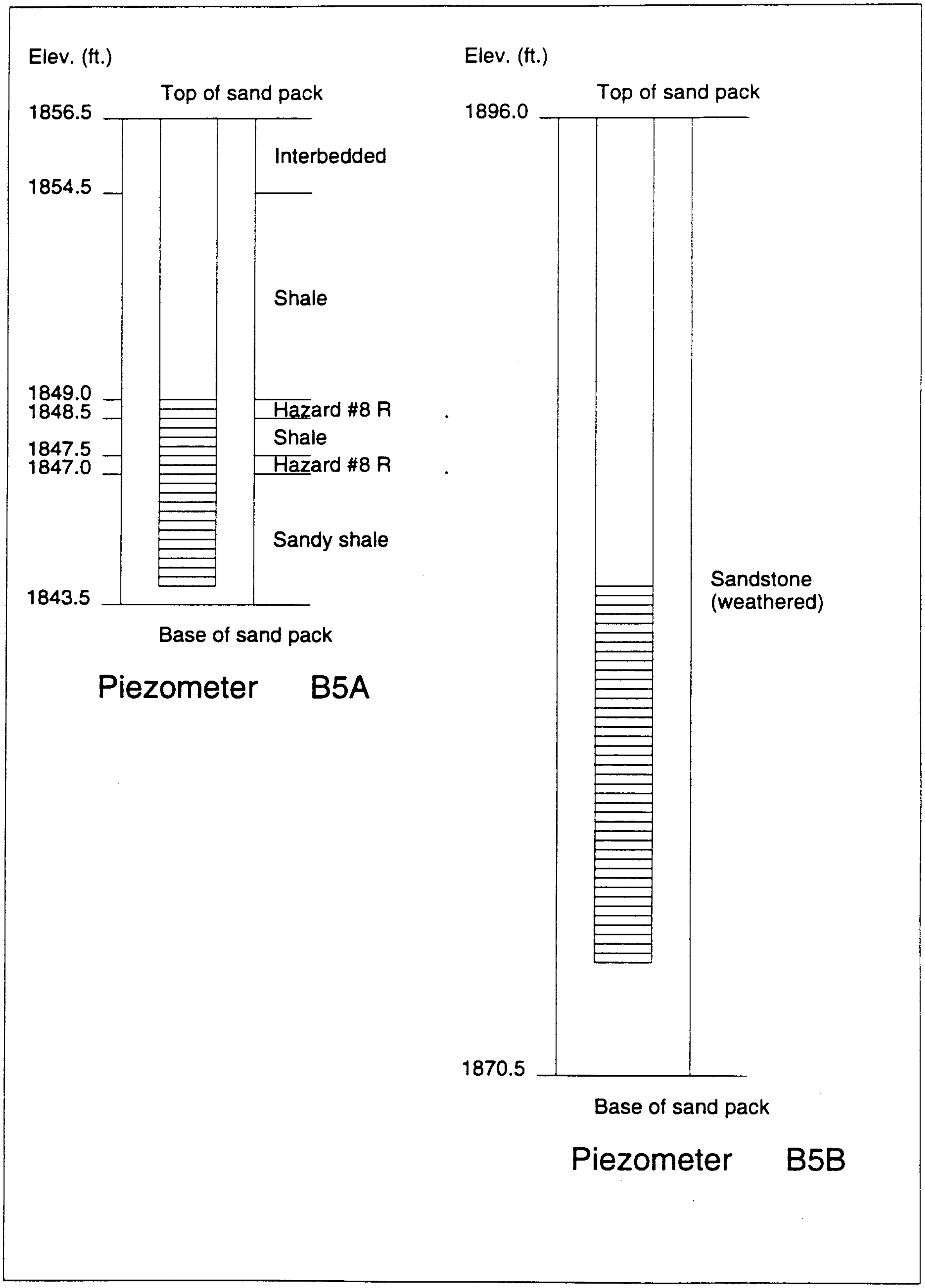


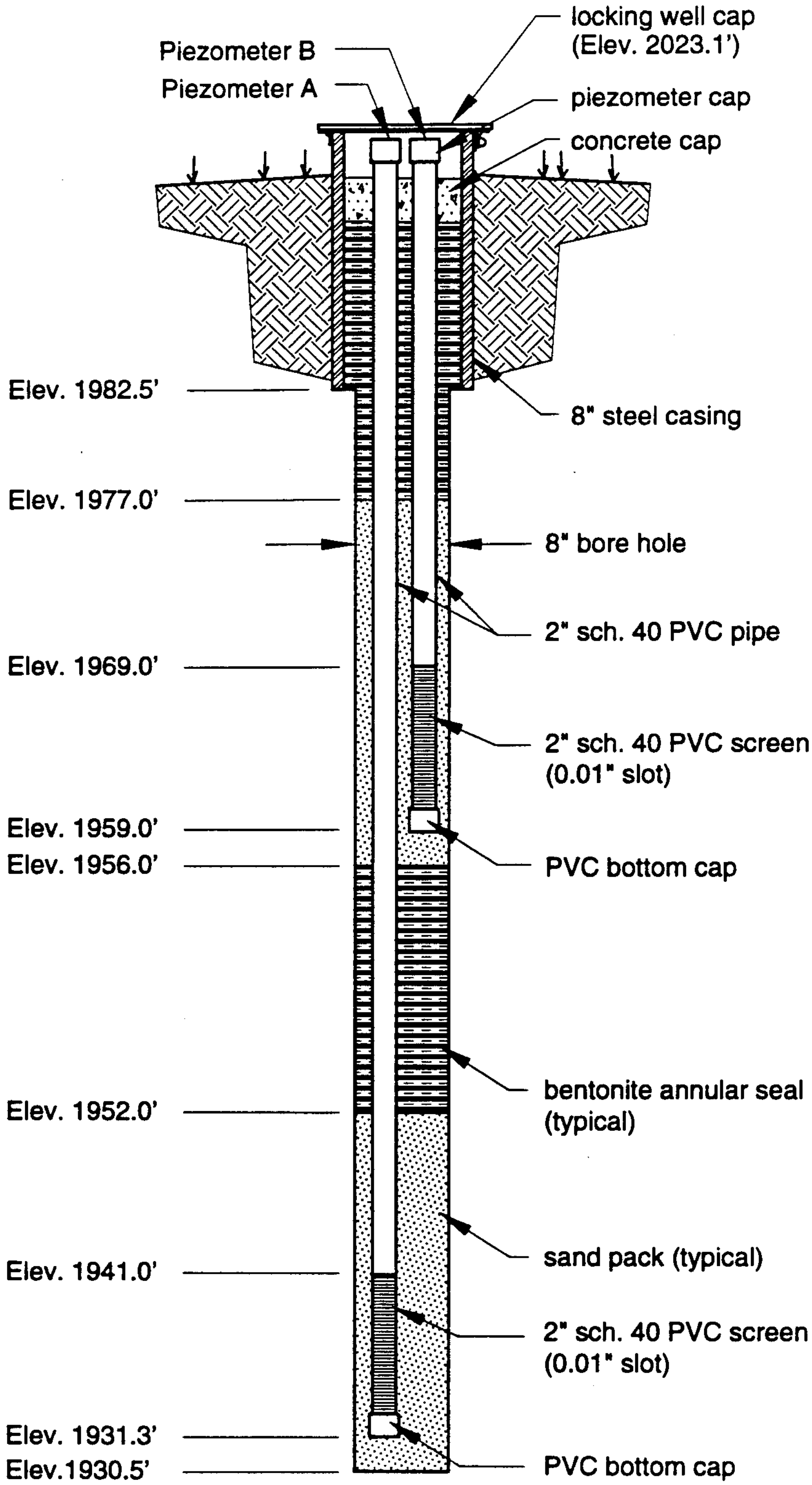
Piezometers B4A and B4B


Elev. (ft.)
Top of sand pack
1807.5
Sandy shale
1799.5
Hazard # 8
Coal
1796.0
Clay
1793.5
Base of sand pack
Piezometer B4A
1 in. = 4 ft.
Elev. (ft.)
Top of sand pack
1829.0
Sandy shale
1813.0
Base of sand pack
Piezometer B4B
1 in. = 4 ft.

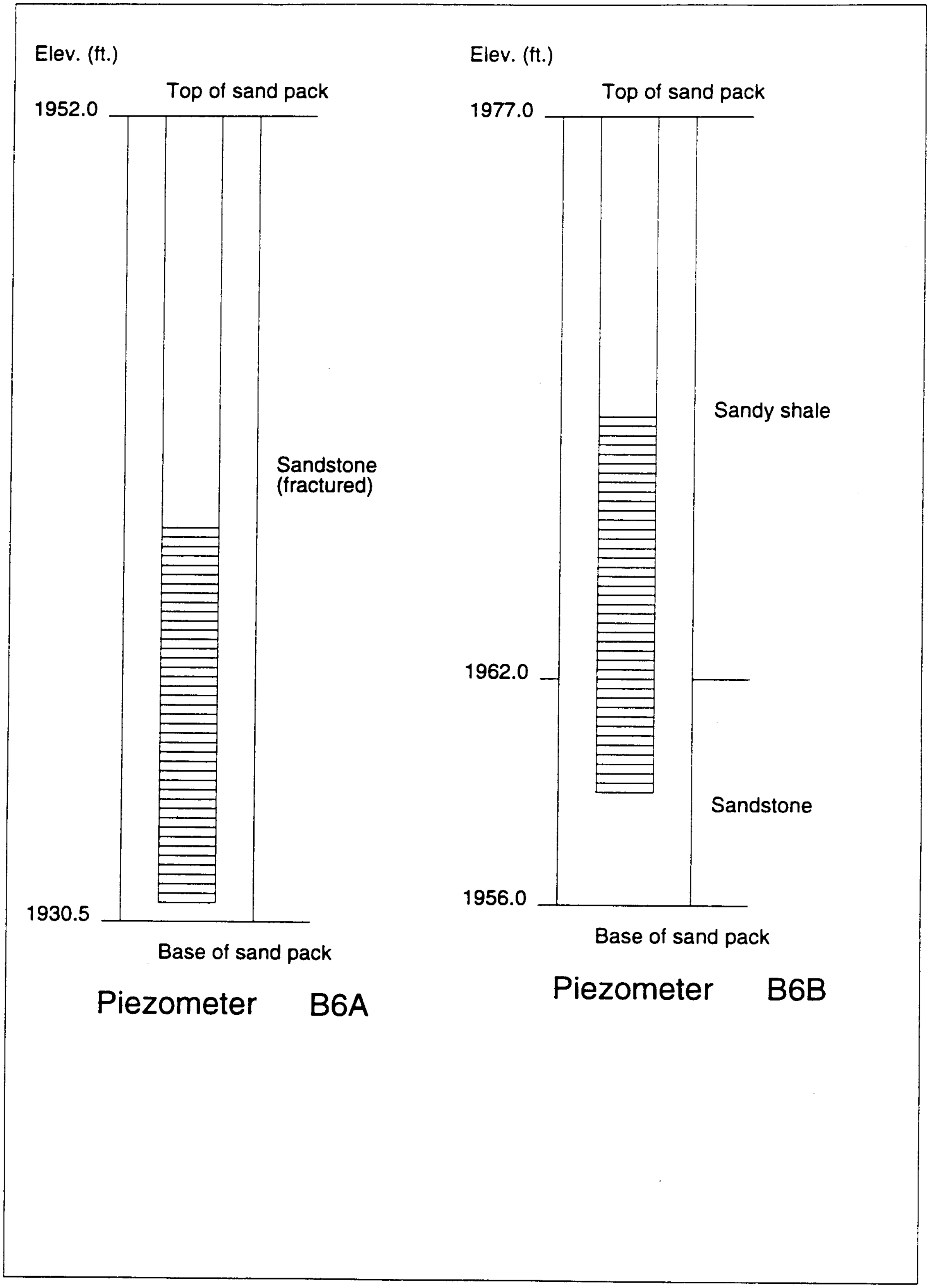


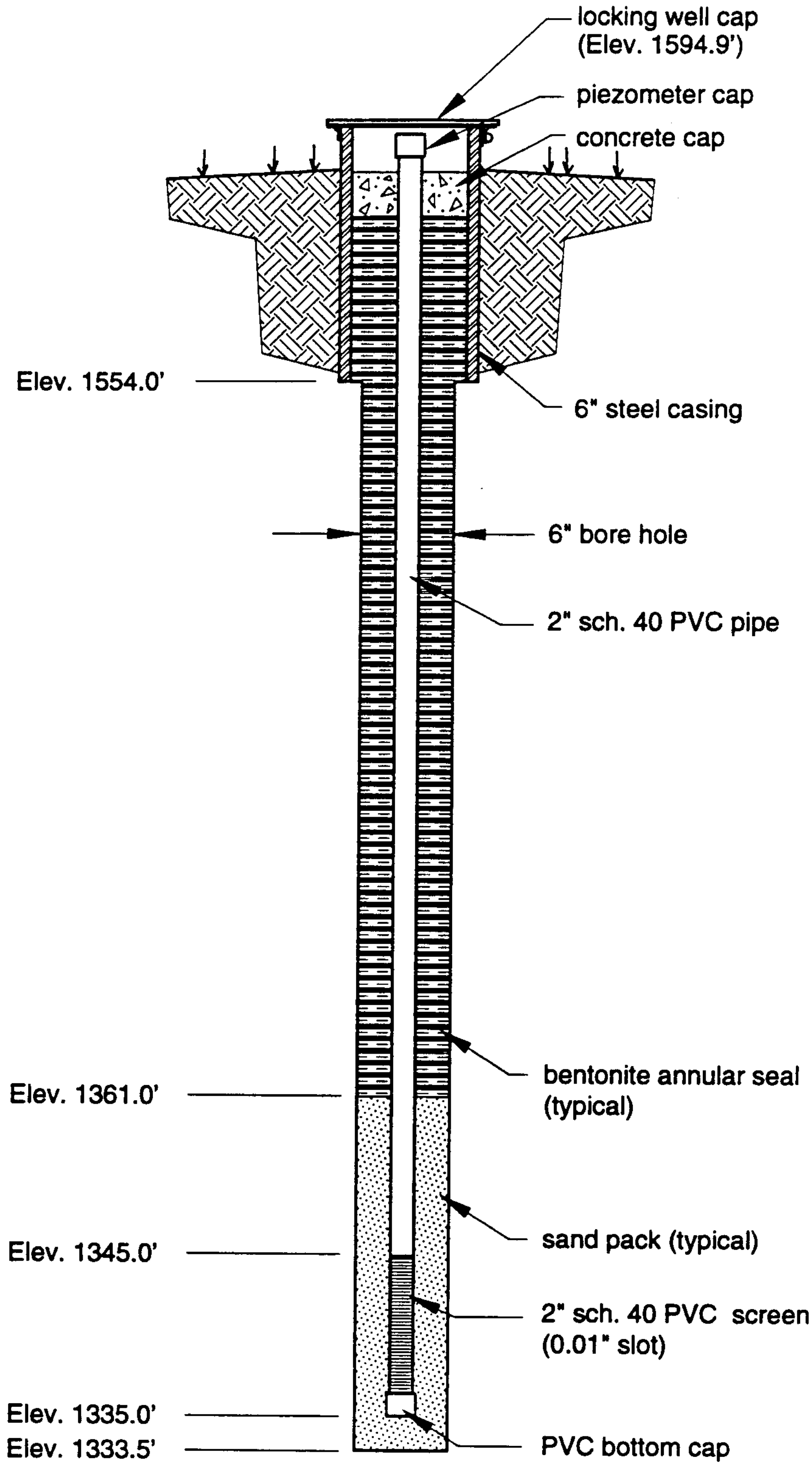
Piezometers B5A and B5B


Elev. (ft.)
Top of sand pack
1856.5
Interbedded
1854.5
Shale
1849.0
1848.5
Hazard #8 R
Shale
1847.5
1847.0
Hazard #8 R
Sandy shale
1843.5
Base of sand pack
Piezometer B5A
Elev. (ft.)
Top of sand pack
1896.0
Sandstone
(weathered)
1870.5
Base of sand pack
Piezometer B5B

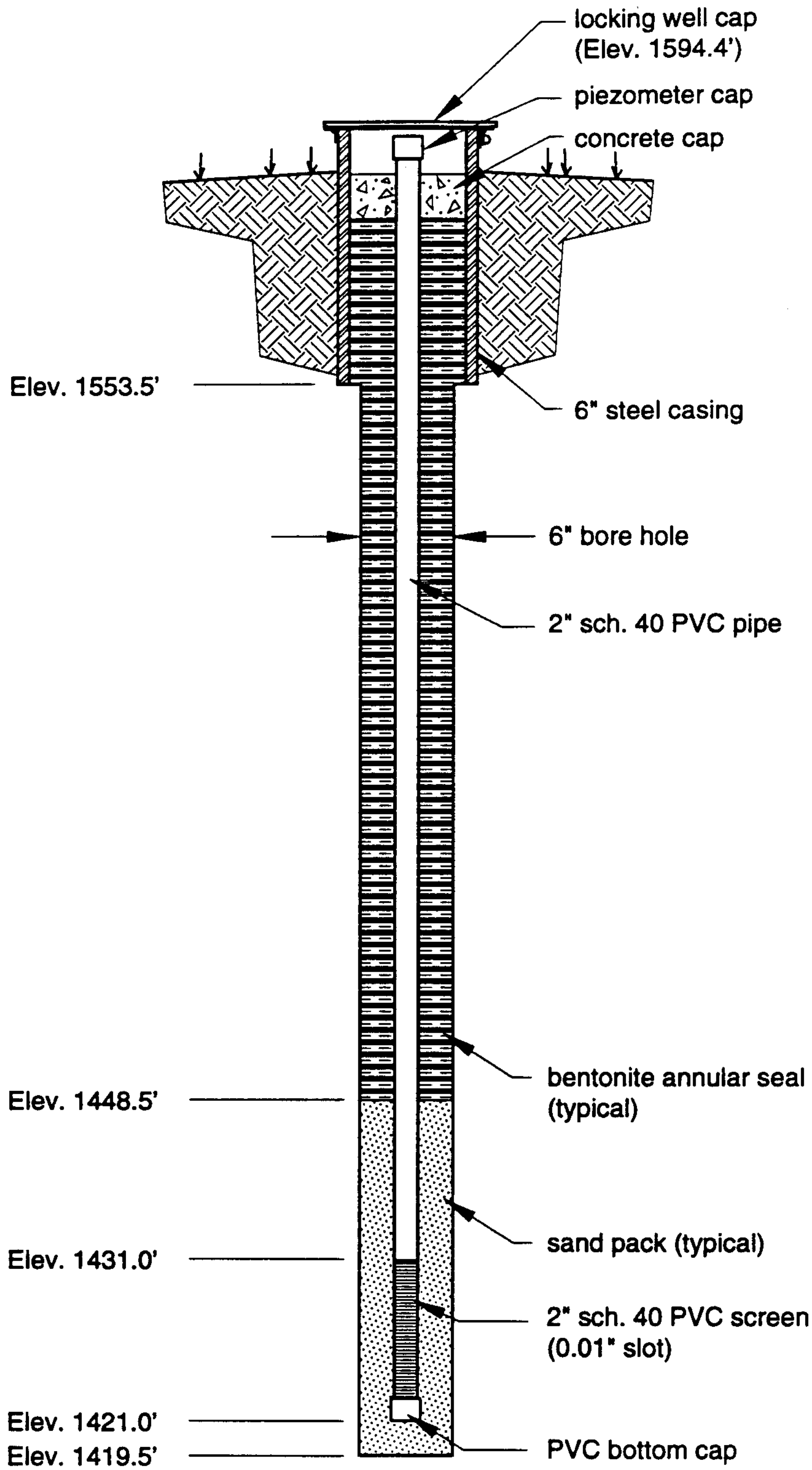


Piezometers B6A and B6B

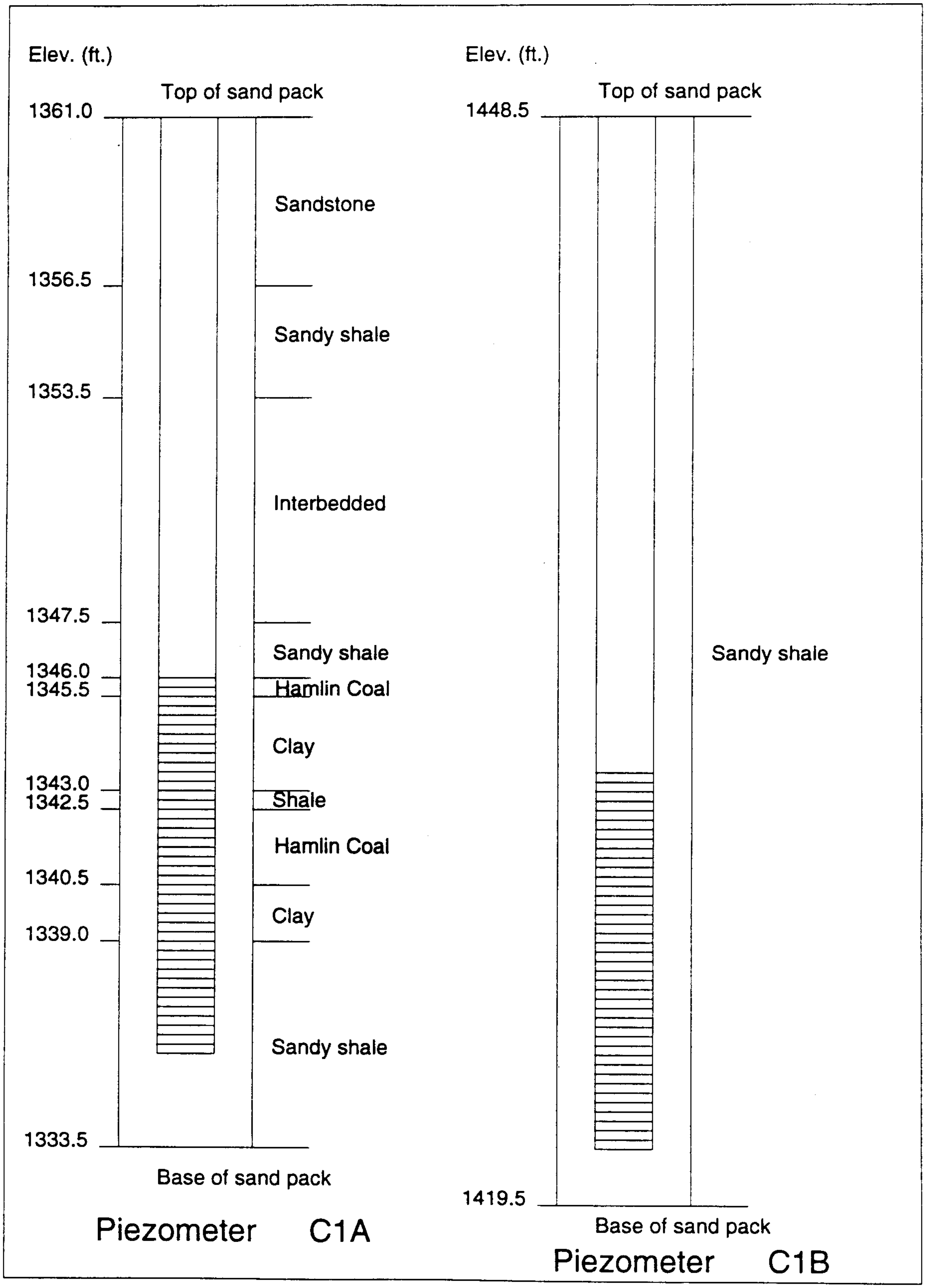

Elev. (ft.)
Top of sand pack
1952.0
Sandstone (fractured)
1930.5
Base of sand pack
Piezometer B6A
Elev. (ft.)
Top of sand pack
1977.0
Sandy shale
1962.0
Sandstone
1956.0
Base of sand pack
Piezometer B6B

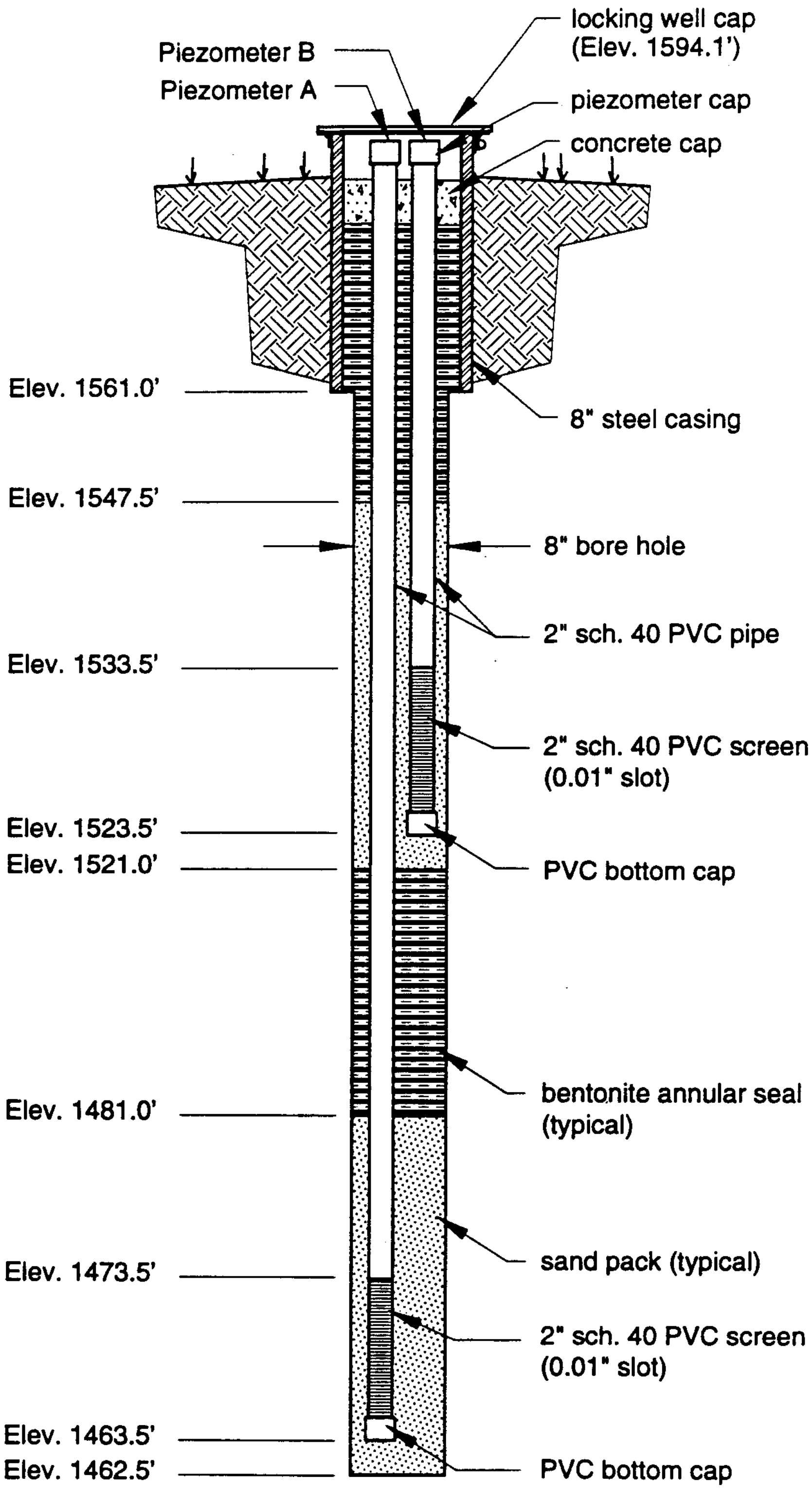


Piezometer C1A

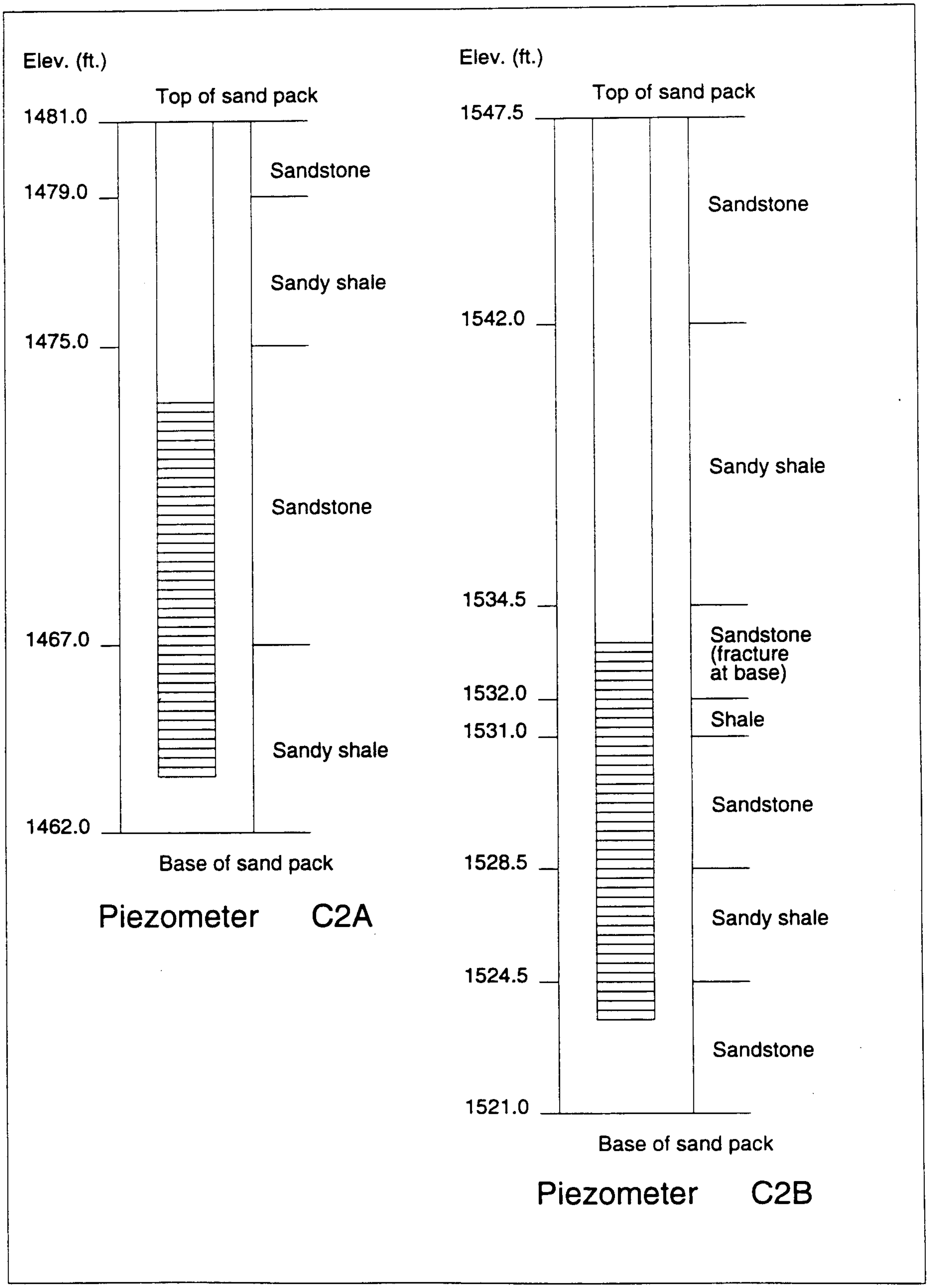


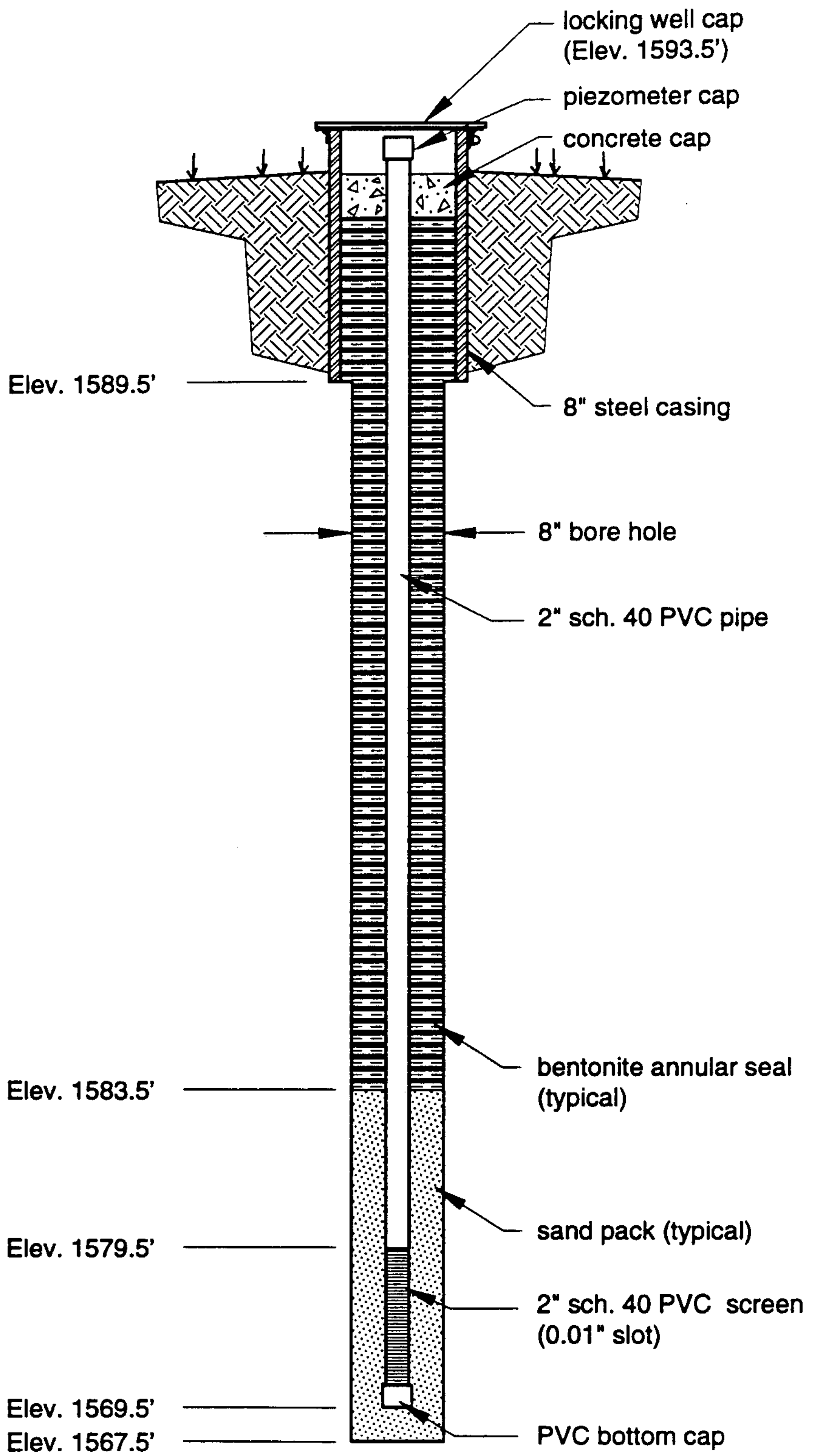
Piezometer C1B


Elev. (ft.)
Top of sand pack
1361.0
Sandstone
1356.5
Sandy shale
1353.5
Interbedded
1347.5
Sandy shale
1346.0
1345.5
Hamlin Coal
Clay
1343.0
1342.5
Shale
Hamlin Coal
1340.5
Clay
1339.0
Sandy shale
1333.5
Base of sand pack
Piezometer C1A
Elev. (ft.)
Top of sand pack
1448.5
Sandy shale
1419.5
Base of sand pack
Piezometer C1B

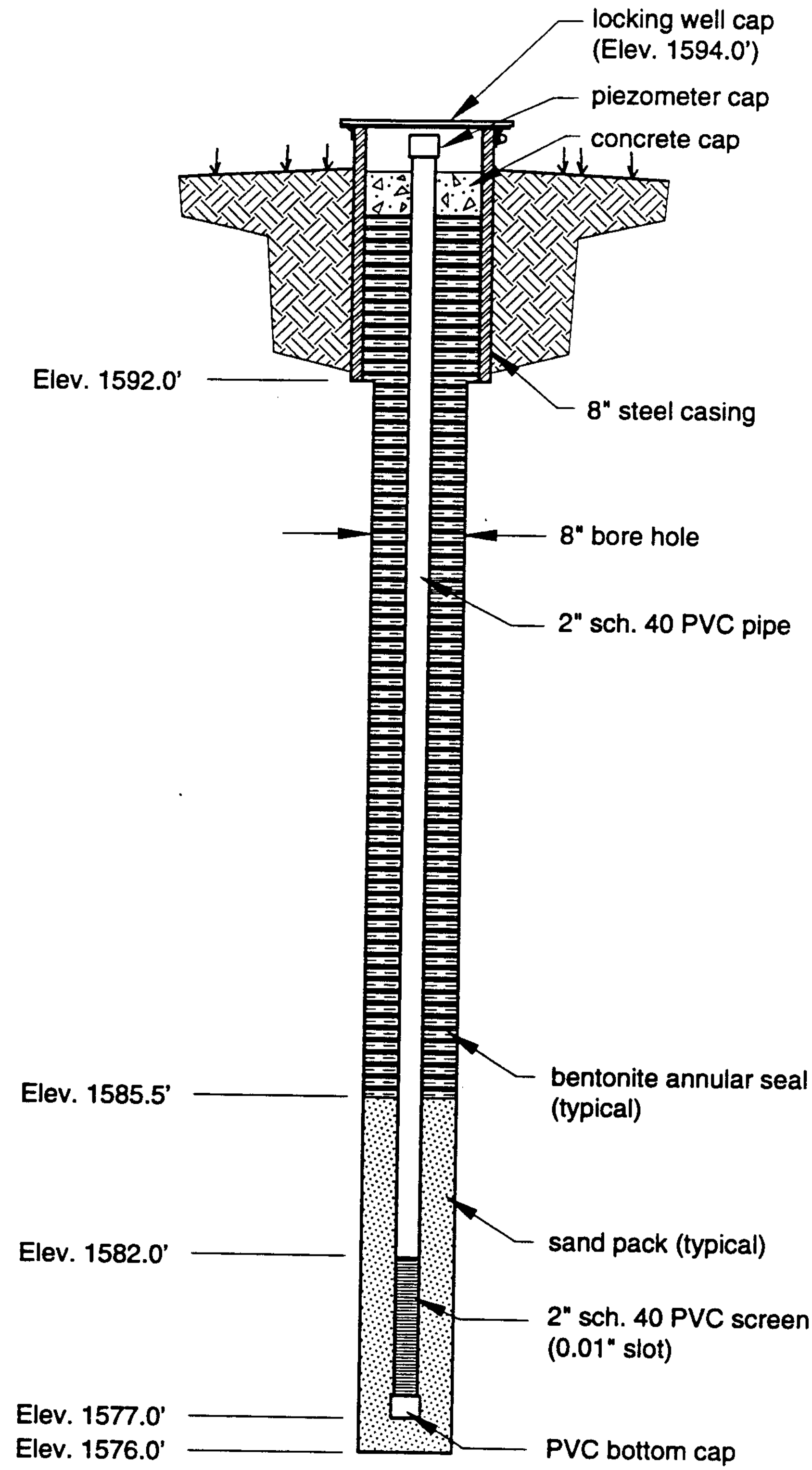


Piezometers C2A and C2B

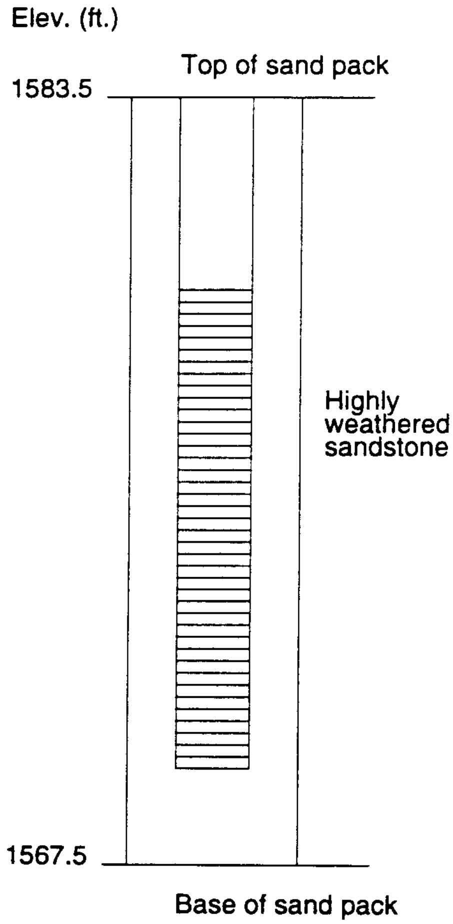

Elev. (ft.)
Top of sand pack
1481.0
Sandstone
1479.0
Sandy shale
1475.0
Sandstone
1467.0
Sandy shale
1462.0
Base of sand pack
Piezometer C2A
Elev. (ft.)
Top of sand pack
1547.5
Sandstone
1542.0
Sandy shale
1534.5
Sandstone (fracture at base)
1532.0
Shale
1531.0
Sandstone
1528.5
Sandy shale
1524.5
Sandstone
1521.0
Base of sand pack
Piezometer C2B



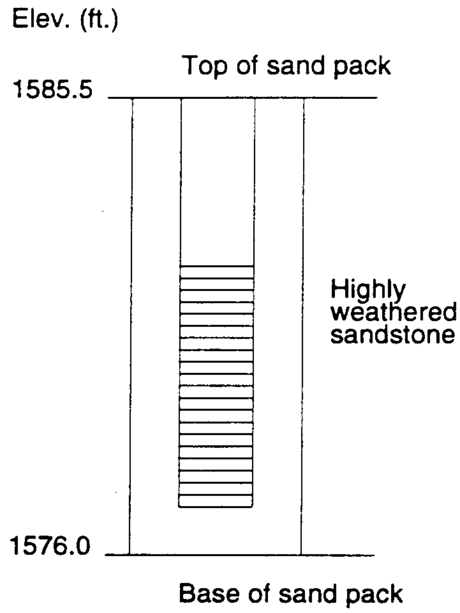
Piezometer C3A



Piezometer C4A



Piezometer C3A



Piezometer C4A

APPENDIX E:
Water-Level Data

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. A1A
Location: Well Nest A
Latitude: 36-57-21 Longitude: 83-25-35 Total Depth (ft.): 415
Elevation of Measuring Point (MP) in feet: 1757.7
MP Location: Top of protective casing
Top of sand pack (ft.): 1367.0
Base of sand pack (ft.): 1340.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	368	1390	
13-Aug-92	11:20 AM	SAM	370.7	1387.0	
27-Aug-92	10:00 AM	SAM	373.3	1384.4	
28-Aug-92	07:51 AM	SAM	373.9	1383.8	(1)
10-Sep-92	03:07 PM	SAM	376.2	1381.5	(2)
10-Sep-92		SAM	383.7	1374.0	
23-Sep-92	02:14 PM	SAM	384.2	1373.5	
24-Sep-92	01:28 PM	SAM	384.2	1373.5	
25-Sep-92	09:00 AM	SAM	384.2	1373.5	(3)
25-Sep-92		SAM	390.8	1366.9	
01-Oct-92	10:23 AM	SAM	386.4	1371.3	
15-Oct-92	12:22 PM	SAM	385.7	1372.0	
28-Oct-92	10:52 AM	SAM	385.6	1372.1	
12-Nov-92	11:33 AM	SAM	385.5	1372.2	(4)
03-Dec-92	12:00 PM	SAM	387.0	1370.7	(5)
15-Dec-92	12:40 PM	SAM	386.9	1370.8	
06-Jan-93	11:21 AM	SAM/JAK	386.5	1371.2	
02-Feb-93	09:59 AM	SAM/JAK	386.0	1371.7	
09-Mar-93	10:48 AM	SAM/EF	385.5	1372.2	

(1) Storm event
(2) Bailed on 9/10 to 383.7 ft.

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. A1B
Location: Well Nest A
Latitude: 36-57-21 Longitude: 83-25-35 Total Depth (ft.): 328
Elevation of Measuring Point (MP) in feet: 1757.7
MP Location: Top of protective casing
Top of sand pack (ft.): 1453.0
Base of sand pack (ft.): 1425.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	225	1533	
13-Aug-92	11:25 AM	SAM	242.2	1515.5	
27-Aug-92	09:55 AM	SAM	249.5	1508.2	
28-Aug-92	07:47 AM	SAM	251.1	1506.6	(1)
10-Sep-92	03:11 PM	SAM	259.3	1498.4	
11-Sep-92		SAM	306.4	1451.3	(2)
23-Sep-92	02:17 PM	SAM	302.6	1455.1	
24-Sep-92	01:33 PM	SAM	302.6	1455.1	
25-Sep-92	10:13 AM	SAM	302.6	1455.1	
01-Oct-92	10:29 AM	SAM	302.3	1455.4	
15-Oct-92	12:17 PM	SAM	297.1	1460.6	
28-Oct-92	10:56 AM	SAM	297.0	1460.7	
12-Nov-92	11:36 AM	SAM	296.9	1460.8	(3)
03-Dec-92	12:04 PM	SAM	323.1	1434.6	(4)
15-Dec-92	12:43 PM	SAM	323.0	1434.7	
06-Jan-93	11:24 AM	SAM/JAK	322.8	1434.9	
02-Feb-93	10:05 AM	SAM/JAK	322.7	1435.0	
09-Mar-93	10:53 AM	SAM/EF	322.6	1435.1	

(1) Storm event
(2) Bailed on 9/10 to 306.4 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. A2A
Location: Well Nest A
Latitude: 36-57-21 Longitude: 83-25-35 Total Depth (ft.): 234
Elevation of Measuring Point (MP) in feet: 1758.8
MP Location: Top of protective casing
Top of sand pack (ft.): 1549.0
Base of sand pack (ft.): 1523.0

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	169	1590	
13-Aug-92	11:31 AM	SAM	169.9	1588.9	
27-Aug-92	09:48 AM	SAM	169.8	1589.0	
28-Aug-92	07:43 AM	SAM	169.4	1589.4	(1)
10-Sep-92	03:14 PM	SAM	169.7	1589.1	(2)
11-Sep-92		SAM	209.4	1549.4	
23-Sep-92	02:22 PM	SAM	169.0	1589.8	
24-Sep-92	01:35 PM	SAM	170.0	1588.8	
25-Sep-92	09:15 AM	SAM	170.0	1588.8	
01-Oct-92	10:25 AM	JAK	170.1	1588.7	
15-Oct-92	12:35 PM	SAM	170.1	1588.7	
28-Oct-92	10:46 AM	SAM	170.1	1588.7	
12-Nov-92	11:39 AM	SAM	169.7	1589.1	(3)
03-Dec-92	11:56 AM	SAM	169.4	1589.4	
15-Dec-92	12:47 PM	SAM	169.1	1589.7	
06-Jan-93	11:15 AM	SAM/JAK	169.6	1589.2	
02-Feb-93	09:54 AM	SAM/JAK	169.7	1589.1	
09-Mar-93	10:57 AM	SAM/EF	169.2	1589.6	

(1) Storm event
(2) Bailed on 9/11 to 209.4 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. A2B
Location: Well Nest A
Latitude: 36-57-21 Longitude: 83-25-35 Total Depth (ft.): 86
Elevation of Measuring Point (MP) in feet: 1758.8
MP Location: Top of protective casing
Top of sand pack (ft.): 1687.0
Base of sand pack (ft.): 1671.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	67	1692	
13-Aug-92	11:33 AM	SAM	66.9	1691.9	
27-Aug-92	09:49 AM	SAM	66.9	1691.9	
28-Aug-92	07:46 AM	SAM	66.6	1692.2	(1)
10-Sep-92	03:17 PM	SAM	66.1	1692.7	
11-Sep-92		SAM	79.5	1679.3	(2)
23-Sep-92	02:24 PM	SAM	66.0	1692.8	
24-Sep-92	01:37 PM	SAM	66.0	1692.8	
25-Sep-92	09:16 AM	SAM	66.0	1692.8	
01-Oct-92	10:27 AM	JAK	66.3	1692.5	
15-Oct-92	12:38 PM	SAM	66.1	1692.7	
28-Oct-92	10:49 AM	SAM	66.5	1692.3	
12-Nov-92	11:41 AM	SAM	66.4	1692.4	(3)
03-Dec-92	11:57 AM	SAM	66.1	1692.7	
15-Dec-92	12:48 PM	SAM	65.8	1693.0	
06-Jan-93	11:19 AM	SAM	65.4	1693.4	
02-Feb-93	09:58 AM	SAM/JAK	65.6	1693.2	
09-Mar-93	10:59 AM	SAM/EF	65.0	1693.8	

(1) Storm event
(2) Bailed on 9/11 to 79.5 ft.
(3) Sampled and purged

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. A3A
Location: Well Nest A
Latitude: 36-57-21 Longitude: 83-25-35 Total Depth (ft.): 65.7
Elevation of Measuring Point (MP) in feet: 1760.7
MP Location: Top of protective casing
Top of sand pack (ft.): 1709.0
Base of sand pack (ft.): 1693.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	64	1697	
13-Aug-92	11:36 AM	SAM	65.7	1695.0	
27-Aug-92	09:40 AM	SAM	65.4	1695.3	
28-Aug-92	07:40 AM	SAM	65.4	1695.3	(1)
10-Sep-92	03:18 PM	SAM	65.2	1695.5	
23-Sep-92	02:27 PM	SAM	65.7	1695.0	
24-Sep-92	01:39 PM	SAM	65.3	1695.4	
25-Sep-92	09:18 AM	SAM	65.2	1695.5	
01-Oct-92	10:21 AM	JAK	65.4	1695.3	
15-Oct-92	12:41 PM	SAM	65.7	1695.0	
28-Oct-92	10:44 AM	SAM	65.2	1695.5	
12-Nov-92	11:42 AM	SAM	65.7	1695.0	
03-Dec-92	11:52 AM	SAM	65.7	1695.0	
15-Dec-92	12:56 PM	SAM	65.2	1695.5	
06-Jan-93	11:12 AM	SAM/JAK	64.8	1695.9	
02-Feb-93	10:07 AM	SAM/JAK	65.2	1695.5	
09-Mar-93	11:01 AM	SAM/EF	65.0	1695.7	

(1) Storm event

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. A3B
Location: Well Nest A
Latitude: 36-51-21 Longitude: 83-25-35 Total Depth (ft.): 33.5
Elevation of Measuring Point (MP) in feet: 1760.7
MP Location: Top of protective casing
Top of sand pack (ft.): 1744.0
Base of sand pack (ft.): 1725.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	33.5	1727	
13-Aug-92	11:37 AM	SAM	33.5	1727.2	
27-Aug-92	09:43 AM	SAM	33.5	1727.2	
28-Aug-92	07:42 AM	SAM	33.5	1727.2	(1)
10-Sep-92	03:19 PM	SAM	33.5	1727.2	
23-Sep-92	02:28 PM	SAM	33.5	1727.2	
24-Sep-92	01:41 PM	SAM	33.5	1727.2	
25-Sep-92	09:19 AM	SAM	33.5	1727.2	
01-Oct-92	10:22 AM	JAK	33.5	1727.2	
15-Oct-92	12:43 PM	SAM	33.5	1727.2	
28-Oct-92	10:45 AM	SAM	33.5	1727.2	
12-Nov-92	11:43 AM	SAM	33.5	1727.2	
03-Dec-92	11:53 AM	SAM	33.5	1727.2	
15-Dec-92	12:58 PM	SAM	33.5	1727.2	
06-Jan-93	11:14 AM	SAM	33.5	1727.2	
02-Feb-93	10:08 AM	SAM/JAK	33.5	1727.2	
09-Mar-93	11:03 AM	SAM/EF	33.5	1727.2	

(1) Storm event

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B1A
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 684
Elevation of Measuring Point (MP) in feet: 2021.3
MP Location: Top of protective casing
Top of sand pack (ft.): 1363.5
Base of sand pack (ft.): 1336.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	639	1382	
13-Aug-92	10:08 AM	SAM	642.7	1378.6	
27-Aug-92	02:00 PM	SAM	644.0	1377.3	
28-Aug-92	08:12 AM	SAM	644.0	1377.3	(1)
10-Sep-92	02:15 PM	SAM	644.8	1376.5	
23-Sep-92	09:55 AM	SAM	645.4	1375.9	
24-Sep-92	11:02 AM	SAM	645.4	1375.9	
01-Oct-92	09:59 AM	SAM	648.1	1373.2	
15-Oct-92	10:52 AM	SAM	647.1	1374.2	
28-Oct-92	10:18 AM	SAM	646.8	1374.5	
17-Nov-92	09:43 AM	SAM	647.2	1374.1	
03-Dec-92	10:38 AM	SAM	647.1	1374.2	
15-Dec-92	12:00 PM	SAM	647.4	1373.9	
06-Jan-93	10:27 AM	SAM/JAK	647.8	1373.5	
02-Feb-93	10:43 AM	SAM/JAK	648.0	1373.3	
09-Mar-93	10:23 AM	SAM/EF	648.0	1373.3	

(1) Storm event
(2) Bailed 750 ml

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B1B
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 492
Elevation of Measuring Point (MP) in feet: 2021.3
MP Location: Top of protective casing
Top of sand pack (ft.): 1560.5
Base of sand pack (ft.): 1518.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	351	1670	
13-Aug-92	10:21 AM	SAM	371.0	1650.3	
27-Aug-92	02:16 PM	SAM	384.0	1637.3	
28-Aug-92	08:17 AM	SAM	384.7	1636.6	(1)
10-Sep-92	11:50 AM	SAM	394.1	1627.2	
23-Sep-92	10:04 AM	SAM	401.4	1619.9	
24-Sep-92		SAM	438.5	1582.8	(2)
25-Sep-92	10:58 AM	SAM	441.5	1579.8	
01-Oct-92	09:54 AM	SAM	439.2	1582.1	
15-Oct-92	10:37 AM	SAM	435.3	1586.0	
28-Oct-92	10:25 AM	SAM	432.8	1588.5	
17-Nov-92	09:35 AM	SAM	431.2	1590.1	(3)
03-Dec-92	10:44 AM	SAM	439.2	1582.1	(4)
15-Dec-92	12:17 PM	SAM	437.6	1583.7	
06-Jan-93	10:22 AM	SAM/JAK	437.9	1583.4	
02-Feb-93	10:49 AM	SAM/JAK	441.2	1580.1	
09-Mar-93	10:29 AM	SAM/EF	447.3	1574.0	

(1) Storm event
(2) Bailed on 9/24 to 438.5 ft.
(3) Purged and sampled
(4) Not recovered from purging

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B2A
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 355
Elevation of Measuring Point (MP) in feet: 2021.3
MP Location: Top of protective casing
Top of sand pack (ft.): 1682.5
Base of sand pack (ft.): 1665.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	334	1687	
13-Aug-92	10:28 AM	SAM	333.3	1688.0	
27-Aug-92	01:55 PM	SAM	332.9	1688.4	
28-Aug-92	07:19 AM	SAM	332.6	1688.7	(1)
10-Sep-92	12:14 PM	SAM	332.1	1689.2	
10-Sep-92		SAM	340.8	1680.5	(2)
23-Sep-92	10:09 AM	SAM	330.6	1690.7	
24-Sep-92	09:12 AM	SAM	330.6	1690.7	
25-Sep-92	08:08 AM	SAM	330.6	1690.7	
01-Oct-92	09:46 AM	SAM	330.6	1690.7	
15-Oct-92	10:24 AM	SAM	330.6	1690.7	
28-Oct-92	10:11 AM	SAM	330.5	1690.8	
17-Nov-92	09:11 AM	SAM	330.6	1690.7	(3)
03-Dec-92	10:29 AM	SAM	333.2	1688.1	(4)
15-Dec-92	11:51 AM	SAM	332.4	1688.9	
06-Jan-93	10:15 AM	SAM/JAK	332.2	1689.1	
02-Feb-93	10:34 AM	SAM/JAK	331.8	1689.5	
09-Mar-93	10:16 AM	SAM/EF	331.6	1689.7	

(1) Storm event
(2) Bailed to 340.8 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B2B
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 311
Elevation of Measuring Point (MP) in feet: 2021.3
MP Location: Top of protective casing
Top of sand pack (ft.): 1731.5
Base of sand pack (ft.): 1708.0

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	295	1726	
13-Aug-92	10:34 AM	SAM	295.4	1725.9	
27-Aug-92	01:51 PM	SAM	295.5	1725.8	
28-Aug-92	07:21 AM	SAM	295.5	1725.8	(1)
10-Sep-92	12:26 PM	SAM	295.5	1725.8	
10-Sep-92		SAM	297.3	1724.0	(2)
23-Sep-92	10:14 AM	SAM	295.5	1725.8	
24-Sep-92	09:17 AM	SAM	295.5	1725.8	
25-Sep-92	08:34 AM	SAM	295.5	1725.8	
01-Oct-92	09:50 AM	SAM	295.7	1725.6	
15-Oct-92	10:30 AM	SAM	295.7	1725.6	
28-Oct-92	10:14 AM	SAM	295.4	1725.9	
17-Nov-92	09:16 AM	SAM	295.7	1725.6	(3)
03-Dec-92	10:34 AM	SAM	295.6	1725.7	
15-Dec-92	11:54 AM	SAM	295.7	1725.6	
06-Jan-93	10:18 AM	SAM/JAK	295.7	1725.6	
02-Feb-93	10:38 AM	SAM/JAK	295.6	1725.7	
09-Mar-93	10:19 AM	SAM/EF	295.6	1725.7	

(1) Storm event
(2) Bailed on 9/10 to 297.3'
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B3A
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 269
Elevation of Measuring Point (MP) in feet: 2021.4
MP Location: Top of protective casing
Top of sand pack (ft.): 1766.5
Base of sand pack (ft.): 1750.0

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	266	1755	
13-Aug-92	10:38 AM	SAM	266.0	1755.4	
27-Aug-92	01:43 PM	SAM	266.0	1755.4	
28-Aug-92	07:14 AM	SAM	266.0	1755.4	(1)
10-Sep-92	12:40 PM	SAM	266.0	1755.4	
10-Sep-92		SAM	267.4	1754.0	(2)
23-Sep-92	10:18 AM	SAM	266.0	1755.4	
24-Sep-92	09:26 AM	SAM	266.0	1755.4	
25-Sep-92	10:50 AM	SAM	266.0	1755.4	
01-Oct-92	09:40 AM	SAM	266.0	1755.4	
15-Oct-92	10:13 AM	SAM	266.0	1755.4	
28-Oct-92	10:06 AM	SAM	266.0	1755.4	
17-Nov-92	09:19 AM	SAM	266.1	1755.3	(3)
03-Dec-92	10:22 AM	SAM	266.1	1755.3	
15-Dec-92	11:45 AM	SAM	266.0	1755.4	
06-Jan-93	10:09 AM	SAM	266.0	1755.4	
02-Feb-93	10:26 AM	SAM/JAK	266.0	1755.4	
09-Mar-93	10:10 AM	SAM/EF	266.0	1755.4	

(1) Storm event
(2) Bailed on 9/10 to 267.4 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B3B
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 244
Elevation of Measuring Point (MP) in feet: 2021.4
MP Location: Top of protective casing
Top of sand pack (ft.): 1788.5
Base of sand pack (ft.): 1776.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	236	1785	
13-Aug-92	10:42 AM	SAM	238.0	1783.4	
27-Aug-92	01:47 PM	SAM	236.0	1785.4	
28-Aug-92	07:16 AM	SAM	235.9	1785.5	(1)
10-Sep-92	12:53 PM	SAM	235.9	1785.5	
10-Sep-92		SAM	237.9	1783.5	(2)
23-Sep-92	10:21 AM	SAM	238.0	1783.4	
24-Sep-92	09:28 AM	SAM	238.0	1783.4	
25-Sep-92	10:54 AM	SAM	238.0	1783.4	
01-Oct-92	09:43 AM	SAM	238.1	1783.3	
15-Oct-92	10:17 AM	SAM	238.0	1783.4	
28-Oct-92	10:08 AM	SAM	237.9	1783.5	
17-Nov-92	09:22 AM	SAM	238.0	1783.4	(3)
03-Dec-92	10:24 AM	SAM	241.0	1780.4	(4)
15-Dec-92	11:48 AM	SAM	240.9	1780.5	
06-Jan-93	10:12 AM	SAM/JAK	240.9	1780.5	
02-Feb-93	10:28 AM	SAM/JAK	240.9	1780.5	
09-Mar-93	10:13 AM	SAM/EF	240.9	1780.5	

(1) Storm event
(2) Bailed on 9/10 to 237.9 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B4A
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 227
Elevation of Measuring Point (MP) in feet: 2021.6
MP Location: Top of protective casing
Top of sand pack (ft.): 1807.5
Base of sand pack (ft.): 1793.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	224	1798	
13-Aug-92	10:46 AM	SAM	224.4	1797.2	
27-Aug-92	01:33 PM	SAM	224.5	1797.1	
28-Aug-92	07:07 AM	SAM	224.4	1797.2	(1)
10-Sep-92	01:03 PM	SAM	224.1	1797.5	
10-Sep-92		SAM	224.8	1796.8	(2)
23-Sep-92	10:15 AM	SAM	224.2	1797.4	
24-Sep-92	09:30 AM	SAM	224.2	1797.4	
25-Sep-92	10:45 AM	SAM	224.2	1797.4	
01-Oct-92	09:54 AM	JAK	224.3	1797.3	
15-Oct-92	10:05 AM	SAM	224.4	1797.2	
28-Oct-92	10:00 AM	SAM	224.5	1797.1	
17-Nov-92	09:26 AM	SAM	224.6	1797.0	(3)
03-Dec-92	10:15 AM	SAM	224.4	1797.2	
15-Dec-92	11:40 AM	SAM	224.2	1797.4	
06-Jan-93	10:05 AM	SAM/JAK	222.9	1798.7	
02-Feb-93	10:30 AM	SAM/JAK	223.6	1798.0	
09-Mar-93	10:04 AM	SAM/EF	221.9	1799.7	

(1) Storm event
(2) Bailed on 9/10 to 224.8 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B4B
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 205
Elevation of Measuring Point (MP) in feet: 2021.6
MP Location: Top of protective casing
Top of sand pack (ft.): 1829.0
Base of sand pack (ft.): 1813.0

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	184	1838	
13-Aug-92	10:50 AM	SAM	186.3	1835.3	
27-Aug-92	01:28 PM	SAM	187.9	1833.7	
28-Aug-92	07:10 AM	SAM	187.9	1833.7	(1)
10-Sep-92	01:06 PM	SAM	189.4	1832.2	
10-Sep-92		SAM	195.2	1826.4	(2)
23-Sep-92	10:28 AM	SAM	195.4	1826.2	
24-Sep-92	08:59 AM	SAM	195.4	1826.2	
24-Sep-92		SAM	202.6	1819.0	(3)
25-Sep-92	10:47 AM	SAM	202.3	1819.3	
01-Oct-92	09:56 AM	JAK	202	1819.6	
15-Oct-92	10:10 AM	SAM	201.8	1819.8	
28-Oct-92	10:03 AM	SAM	201.7	1819.9	
17-Nov-92	09:29 AM	SAM	201.6	1820.0	(4)
03-Dec-92	10:18 AM	SAM	203.9	1817.7	(5)
15-Dec-92	11:42 AM	SAM	203.7	1817.9	
06-Jan-93	10:07 AM	SAM/JAK	203.6	1818.0	
02-Feb-93	10:33 AM	SAM/JAK	203.4	1818.2	
09-Mar-93	10:07 AM	SAM/EF	203.4	1818.2	

(1) Storm event
(2) Bailed on 9/11 to 195.2 ft.

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B5A
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 179
Elevation of Measuring Point (MP) in feet: 2023.0
MP Location: Top of protective casing
Top of sand pack (ft.): 1856.5
Base of sand pack (ft.): 1843.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	170	1853	
13-Aug-92	10:53 AM	SAM	169.7	1853.3	
27-Aug-92	01:12 PM	SAM	169.6	1853.4	
28-Aug-92	07:03 AM	SAM	169.5	1853.5	(1)
10-Sep-92	01:14 PM	SAM	169.5	1853.5	
10-Sep-92		SAM	172.6	1850.4	(2)
23-Sep-92	10:31 AM	SAM	169.5	1853.5	
24-Sep-92	09:35 AM	SAM	169.5	1853.5	
25-Sep-92	10:39 AM	SAM	169.5	1853.5	
01-Oct-92	09:46 AM	JAK	169.6	1853.4	
15-Oct-92	09:52 AM	SAM	169.6	1853.4	
28-Oct-92	09:52 AM	SAM	169.7	1853.3	
17-Nov-92	09:05 AM	SAM	169.5	1853.5	(3)
03-Dec-92	10:12 AM	SAM	169.6	1853.4	
15-Dec-92	11:34 AM	SAM	169.4	1853.6	
06-Jan-93	10:00 AM	SAM/JAK	169.4	1853.6	
02-Feb-93	10:20 AM	SAM/JAK	169.5	1853.5	
09-Mar-93	09:58 AM	SAM/EF	169.0	1854.0	

(1) Storm event
(2) Bailed on 9/10 to 172.6 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B5B
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 150
Elevation of Measuring Point (MP) in feet: 2023.0
MP Location: Top of protective casing
Top of sand pack (ft.): 1896.0
Base of sand pack (ft.): 1870.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	145	1878	
13-Aug-92	10:56 AM	SAM	145.8	1877.2	
27-Aug-92	01:15 PM	SAM	145.8	1877.2	(1)
10-Sep-92	01:16 PM	SAM	145.5	1877.5	
10-Sep-92		SAM	146.4	1876.6	(2)
23-Sep-92	10:34 AM	SAM	146.2	1876.8	
24-Sep-92	09:36 AM	SAM	146.2	1876.8	
25-Sep-92	10:41 AM	SAM	146.2	1876.8	
01-Oct-92	09:49 AM	JAK	146.3	1876.7	
15-Oct-92	09:54 AM	SAM	146.4	1876.6	
28-Oct-92	09:57 AM	SAM	146.7	1876.3	
17-Nov-92	09:08 AM	SAM	146.5	1876.5	(3)
03-Dec-92	10:14 AM	SAM	146.5	1876.5	
15-Dec-92	11:37 AM	SAM	146.2	1876.8	
06-Jan-93	10:02 AM	SAM/JAK	146.2	1876.8	
02-Feb-93	10:22 AM	SAM/JAK	146.1	1876.9	
09-Mar-93	10:02 AM	SAM/EF	145.5	1877.5	

(1) Missed data for storm on 8/28
(2) Bailed on 9/11 to 146.4 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B6A
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 91.8
Elevation of Measuring Point (MP) in feet: 2023.1
MP Location: Top of protective casing
Top of sand pack: 1952.0
Base of sand pack (ft.): 1930.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	92	1931	
13-Aug-92	11:00 AM	SAM	91.8	1931.3	
27-Aug-92	01:25 PM	SAM	91.7	1931.4	
28-Aug-92	07:00 AM	SAM	91.7	1931.4	(1)
10-Sep-92	01:48 PM	SAM	91.8	1931.3	
23-Sep-92	10:36 AM	SAM	91.8	1931.3	
24-Sep-92	09:38 AM	SAM	91.8	1931.3	
25-Sep-92	10:34 AM	SAM	91.8	1931.3	
01-Oct-92	09:42 AM	JAK	91.7	1931.4	
15-Oct-92	09:45 AM	SAM	91.8	1931.3	
28-Oct-92	10:29 AM	SAM	91.5	1931.6	
17-Nov-92	09:02 AM	SAM	91.8	1931.3	
03-Dec-92	10:09 AM	SAM	91.8	1931.3	
15-Dec-92	12:22 PM	SAM	91.8	1931.3	
06-Jan-93	09:57 AM	SAM/JAK	91.8	1931.3	
02-Feb-93	10:52 AM	SAM/JAK	91.8	1931.3	
09-Mar-93	10:34 AM	SAM/EF	91.8	1931.3	

(1) Storm event

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. B6B
Location: Well Nest B
Latitude: 36-57-17 Longitude: 83-25-42 Total Depth (ft.): 64
Elevation of Measuring Point (MP) in feet: 2023.1
MP Location: Top of protective casing
Top of sand pack (ft.): 1977.0
Base of sand pack (ft.): 1956.0

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	64	1959	
13-Aug-92	11:02 AM	SAM	64	1959.1	
27-Aug-92	01:21 PM	SAM	64	1959.1	
28-Aug-92	07:01 AM	SAM	64	1959.1	(1)
10-Sep-92	01:50 PM	SAM	64	1959.1	
23-Sep-92	10:16 AM	SAM	64	1959.1	
24-Sep-92	09:39 AM	SAM	64	1959.1	
25-Sep-92	10:35 AM	SAM	64	1959.1	
01-Oct-92	09:44 AM	JAK	64	1959.1	
15-Oct-92	09:48 AM	SAM	64	1959.1	
28-Oct-92	10:31 AM	SAM	64	1959.1	
17-Nov-92	09:03 AM	SAM	64	1959.1	
03-Dec-92	10:10 AM	SAM	64	1959.1	
15-Dec-92	12:23 PM	SAM	64	1959.1	
06-Jan-93	09:58 AM	SAM/JAK	64	1959.1	
02-Feb-93	10:53 AM	SAM/JAK	64	1959.1	
09-Mar-93	10:34 AM	SAM/EF	64	1959.1	

(1) Storm event

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. C1A
Location: Well Nest C
Latitude: 36-57-24 Longitude: 83-25-32 Total Depth (ft.): 260
Elevation of Measuring Point (MP) in feet: 1594.9
MP Location: Top of protective casing
Top of sand pack (ft.): 1361.0
Base of sand pack (ft.): 1333.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	219.0	1376	
13-Aug-92	12:49 PM	SAM	223.3	1371.6	
27-Aug-92	10:58 AM	SAM	224.1	1370.8	
28-Aug-92	08:50 AM	SAM	224.1	1370.8	(1)
10-Sep-92	10:55 AM	SAM	224.6	1370.3	
23-Sep-92	10:59 AM	JAK	224.9	1370.0	
23-Sep-92		JAK	255.4	1339.5	(2)
24-Sep-92	09:11 AM	JAK	251.1	1343.8	
25-Sep-92	01:18 PM	SAM	238.2	1356.7	
01-Oct-92	11:24 AM	SAM	226.8	1368.1	
15-Oct-92	01:50 PM	SAM	226.3	1368.6	
28-Oct-92	11:30 AM	SAM	226.0	1368.9	
11-Nov-92	10:03 AM	SAM	226.0	1368.9	(3)
03-Dec-92	12:47 PM	SAM	227.8	1367.1	(4)
15-Dec-92	03:06 PM	SAM	227.3	1367.6	
06-Jan-93	12:03 PM	SAM/JAK	227.2	1367.7	
02-Feb-93	11:22 AM	SAM/JAK	226.7	1368.2	
09-Mar-93	11:38 AM	SAM/EF	226.7	1368.2	

(1) Storm event
(2) Pumped on 9/23 to 255.4 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. C1B
Location: Well Nest C
Latitude: 36-57-24 Longitude: 83-25-32 Total Depth (ft.): 174
Elevation of Measuring Point (MP) in feet: 1594.4
MP Location: Top of protective casing
Top of sand pack (ft.): 1448.5
Base of sand pack (ft.): 1419.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	24	1570	(1)
13-Aug-92	12:45 PM	SAM	32.2	1562.2	
27-Aug-92	10:56 AM	SAM	32.3	1562.1	
28-Aug-92	08:53 AM	SAM	32.3	1562.1	(2)
10-Sep-92	10:58 AM	SAM	32.4	1562.0	
10-Sep-92		SAM	66.4	1528.0	(3)
23-Sep-92	11:04 AM	JAK	66.1	1528.3	
23-Sep-92		JAK	169.4	1425.0	(4)
24-Sep-92	09:14 AM	JAK	169.0	1425.4	
25-Sep-92	01:23 PM	SAM	169.0	1425.4	
01-Oct-92	11:20 AM	SAM	168.7	1425.7	
15-Oct-92	01:53 PM	SAM	168.8	1425.6	
28-Oct-92	11:34 AM	SAM	166.7	1427.7	
11-Nov-92	11:40 AM	SAM	168.7	1425.7	(5)
03-Dec-92	12:50 PM	SAM	169.9	1424.5	
15-Dec-92	03:09 PM	SAM	169.9	1424.5	
06-Jan-93	12:00 PM	SAM/JAK	169.8	1424.6	
02-Feb-93	11:20 AM	SAM/JAK	169.8	1424.6	
09-Mar-93	11:42 AM	SAM/EF	169.8	1424.6	

(1) Bailed to 32.2 ft.
(2) Storm event

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. C2A
Location: Well Nest C
Latitude: 36-57-24 Longitude: 83-25-32 Total Depth (ft.): 131
Elevation of Measuring Point (MP) in feet: 1594.1
MP Location: Top of protective casing
Top of sand pack (ft.): 1481.0
Base of sand pack (ft.): 1462.0

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92	0	SAM/JAK	69	1525	
13-Aug-92	12:37 PM	SAM	68.7	1525.4	
27-Aug-92	10:54 AM	SAM	68.3	1525.8	
28-Aug-92	08:54 AM	SAM	67.9	1526.2	(1)
10-Sep-92	11:03 AM	SAM	67.9	1526.2	
23-Sep-92	11:06 AM	JAK	67.7	1526.4	
23-Sep-92		JAK	72.3	1521.8	(2)
24-Sep-92	09:16 AM	JAK	68.0	1526.1	
25-Sep-92	01:28 PM	SAM	67.7	1526.4	
01-Oct-92	11:17 AM	SAM	67.8	1526.3	
15-Oct-92	01:57 PM	SAM	67.6	1526.5	
28-Oct-92	11:37 AM	SAM	67.7	1526.4	
11-Nov-92	11:53 AM	SAM	67.6	1526.5	(3)
03-Dec-92	12:52 PM	SAM	67.6	1526.5	
15-Dec-92	03:10 PM	SAM	67.4	1526.7	
06-Jan-93	11:58 AM	SAM/JAK	67.6	1526.5	
02-Feb-93	11:15 AM	SAM/JAK	67.8	1526.3	
09-Mar-93	11:43 AM	SAM/EF	67.4	1526.7	
08-Apr-93	11:40 AM	SAM/JAK	67.4	1526.7	

(1) Storm event
(2) Pumped on 9/23 to 72.3 ft.

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. C2B
Location: Well Nest C
Latitude: 36-57-24 Longitude: 83-25-32 Total Depth (ft.): 71
Elevation of Measuring Point (MP) in feet: 1594.1
MP Location: Top of protective casing
Top of sand pack (ft.): 1547.5
Base of sand pack (ft.): 1521.0

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	27	1567	
13-Aug-92	12:35 PM	SAM	27.1	1567.0	
27-Aug-92	10:55 AM	SAM	27.1	1567.0	
28-Aug-92	08:55 AM	SAM	26.7	1567.4	(1)
10-Sep-92	11:05 AM	SAM	26.8	1567.3	
23-Sep-92	11:08 AM	JAK	27.4	1566.7	
24-Sep-92	09:18 AM	JAK	27.4	1566.7	(2)
25-Sep-92	01:26 PM	SAM	27.0	1567.1	
01-Oct-92	11:16 AM	SAM	27.6	1566.5	
15-Oct-92	01:58 PM	SAM	27.6	1566.5	
28-Oct-92	11:39 AM	SAM	27.6	1566.5	
11-Nov-92	11:55 AM	SAM	27.9	1566.2	(3)
03-Dec-92	12:55 PM	SAM	27.9	1566.2	
15-Dec-92	03:12 PM	SAM	27.4	1566.7	
06-Jan-93	11:59 AM	SAM/JAK	27.9	1566.2	
02-Feb-93	11:17 AM	SAM/JAK	28.3	1565.8	
09-Mar-93	11:45 AM	SAM/EF	27.6	1566.5	

(1) Storm event
(2) Pumped but did not lower water level
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. C3A
Location: Well Nest C
Latitude: 36-57-24 Longitude: 83-25-32 Total Depth (ft.): 24
Elevation of Measuring Point (MP) in feet: 1593.5
MP Location: Top of protective casing
Top of sand pack (ft.): 1583.5
Base of sand pack (ft.): 1567.5

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	14	1580	
13-Aug-92	12:43 PM	SAM	15.7	1577.8	
27-Aug-92	10:52 AM	SAM	13.7	1579.8	
28-Aug-92	08:57 AM	SAM	10.7	1582.8	(1)
10-Sep-92	11:08 AM	SAM	16.4	1577.1	
23-Sep-92	11:11 AM	JAK	17.1	1576.4	
24-Sep-92	09:19 AM	JAK	17.0	1576.5	
24-Sep-92		JAK	19.9	1573.6	(2)
25-Sep-92	01:31 PM	SAM	16.5	1577.0	
01-Oct-92	11:15 AM	SAM	17.0	1576.5	
15-Oct-92	02:00 PM	SAM	17.0	1576.5	
28-Oct-92	11:44 AM	SAM	16.7	1576.8	
11-Nov-92	03:02 AM	SAM	16.2	1577.3	(3)
03-Dec-92	12:58 PM	SAM	16.3	1577.2	
15-Dec-92	03:14 PM	SAM	13.9	1579.6	
06-Jan-93	11:57 AM	SAM/JAK	14.8	1578.7	
02-Feb-93	11:15 AM	SAM/JAK	16.3	1577.2	
09-Mar-93	11:46 AM	SAM/EF	11.9	1581.6	

(1) Storm event
(2) Pumped on 9/24 to 19.9 ft.
(3) Purged and sampled

Water Level data for Edd Fork, Leslie County, Kentucky

Piezometer No. C4A
Location: Well Nest C
Latitude: 36-25-24 Longitude: 83-25-32 Total Depth (ft.): 17
Elevation of Measuring Point (MP) in feet: 1594.0
MP Location: Top of protective casing
Top of sand pack (ft.): 1585.5
Base of sand pack (ft.): 1576.0

Date	Time	Measured By	Depth below MP	Elevation (ft.)	Remarks
28-Jul-92		SAM/JAK	12	1582	
13-Aug-92	12:44 PM	SAM	14.1	1579.9	
27-Aug-92	10:50 AM	SAM	12.7	1581.3	
28-Aug-92	08:59 AM	SAM	11.6	1582.4	(1)
10-Sep-92	11:12 AM	SAM	12.7	1581.3	
23-Sep-92	11:12 AM	JAK	12.5	1581.5	
24-Sep-92	09:20 AM	JAK	12.7	1581.3	
24-Sep-92		JAK	16.0	1578.0	(2)
25-Sep-92	01:33 PM	SAM	13.4	1580.6	
01-Oct-92	11:14 AM	SAM	13.6	1580.4	
15-Oct-92	02:02 PM	SAM	13.1	1580.9	
28-Oct-92	11:44 AM	SAM	13.6	1580.4	
11-Nov-92	02:25 AM	SAM	13.0	1581.0	(3)
03-Dec-92	12:59 PM	SAM	12.3	1581.7	
15-Dec-92	03:16 PM	SAM	11.6	1582.4	
06-Jan-93	11:54 AM	SAM/JAK	11.8	1582.2	
02-Feb-93	11:14 AM	SAM/JAK	13.1	1580.9	
09-Mar-93	11:47 AM	SAM/EF	10.8	1583.2	

(1) Storm event
(2) Pumped on 9/24 to 16.0 ft.
(3) Purged and sampled

APPENDIX F:
Water-Quality Data

Laboratory Water-Quality Analyses for Piezometer Nest A

	A1A	A1B	A2A	A2B
NON-METALS (mg/L except where noted)				
Chloride	5.36	6.71	1.68	1.32
Fluoride	1.10	1.00	0.160	0.110
Nitrate as NO3	<0.100	3.37	<0.100	<0.100
Sulfate	29.6	125	58.4	104
Bicarbonate as HCO3	443	552	193	73
Total dissolved solids	488	750	222	204
Bromide	<1.00	<1.00	<1.00	<1.00
Specific conductance (uU/cm)	734	1060	409	337
pH (units)	8.06	8.40	7.85	6.72
Total acidity as CaCO3	<8	<8	8	11
Total alkalinity as CaCO3	363	453	158	60
DISSOLVED METALS (mg/L)				
Aluminum	0.198	1.87	<0.032	<0.032
Barium	0.0860	0.100	0.215	0.0816
Boron	0.062	0.078	<0.036	<0.036
Calcium	2.15	4.00	39.8	26.0
Iron	1.93	1.91	0.434	3.55
Lithium	0.011	0.010	0.005	0.005
Magnesium	0.454	1.45	15	20.1
Manganese	0.023	0.032	0.173	0.392
Phosphorus	0.645	0.256	<0.078	<0.078
Potassium	2.30	3.47	4.85	3.23
Silicon	2.81	3.98	<0.005	3.91
Sodium	164	231	0.902	3.69
Strontium	0.089	0.166	16.2	0.134
Sulfur	8.65	31.6	0.058	30.1
Zinc	0.012	0.018	0.028	0.023

Laboratory Water-Quality Analyses for Piezometer Nest B

	B2A	B3A	B5A	B5B
NON-METALS (mg/L except where noted)				
Chloride	2.12	2.87	2.73	4.59
Fluoride	0.200	0.140	0.230	0.220
Nitrate as NO3	0.27	0.960	<0.100	0.450
Sulfate	49.2	364	1050	677
Bicarbonate as HCO3	180	171	156	171
Total dissolved solids	236	650	1610	1130
Bromide	<1.00	<1.00	<1.00	<1.00
Specific conductance (uU/cm)	382	934	1810	1390
pH (units)	7.55	7.02	6.75	6.89
Total acidity as CaCO3	11	13	35	22
Total alkalinity as CaCO3	148	140	128	140
DISSOLVED METALS (mg/L)				
Aluminum	<0.032	0.051	<0.032	1.15
Barium	0.122	0.0230	0.0339	0.0970
Boron	0.057	<0.036	<0.036	<0.036
Calcium	27.2	72.2	191	112
Iron	0.042	1.20	13.1	2.54
Lithium	0.004	0.006	0.021	0.014
Magnesium	10.8	43.3	149	87.5
Manganese	0.121	0.812	5.37	0.892
Phosphorus	0.178	<0.078	0.197	0.136
Potassium	6.49	7.55	11.2	6.22
Silicon	3.89	5.63	11.3	10.3
Sodium	31.2	52.8	10.4	5.70
Strontium	0.609	0.648	0.651	0.422
Sulfur	14.7	106	288	155
Zinc	0.019	0.018	0.015	0.029

Laboratory Water-Quality Analyses for Piezometer Nest C

	C1A	C1B	C2A	C2B
NON-METALS (mg/L except where noted)				
Chloride	11.0	5.54	5.86	<1.00
Fluoride	1.10	1.30	1.60	0.080
Nitrate as NO3	0.160	1.40	<1.00	<1.00
Sulfate	76.3	159	5.36	12.4
Bicarbonate as HCO3	377	463	454	115
Total dissolved solids	472	768	384	92
Bromide	<1.00	<1.00	<1.00	<1.00
Specific conductance (uU/cm)	764	1020	698	192
pH (units)	8.16	8.64	8.94	7.42
Total acidity as CaCO3	<8	<8	<8	9
Total alkalinity as CaCO3	309	380	372	94
DISSOLVED METALS (mg/L)				
Aluminum	0.961	0.273	<0.032	<0.032
Barium	0.0407	0.0929	0.0850	0.289
Boron	0.078	0.073	0.115	<0.036
Calcium	1.04	3.35	2.36	20.7
Iron	0.654	0.671	0.048	4.25
Lithium	0.002	0.010	0.023	0.007
Magnesium	0.377	0.880	0.617	6.17
Manganese	0.032	0.027	0.006	0.184
Phosphorus	0.182	0.232	0.127	<0.078
Potassium	2.16	2.27	2.05	2.21
Silicon	3.49	1.15	2.34	3.05
Sodium	170	232	155	5.18
Strontium	0.049	0.131	0.105	0.200
Sulfur	20.7	43.5	1.21	3.40
Zinc	0.025	0.006	0.027	0.017

Laboratory Water-Quality Analyses for Piezometer Nest C (con't) and Surface-Water Site

	C3A	C4A	SWL
NON-METALS (mg/L except where noted)			
Chloride	<1.00	1.13	2.33
Fluoride	0.03	0.030	0.110
Nitrate as NO3	0.150	0.320	0.580
Sulfate	9.59	13.1	577
Bicarbonate as HCO3	11	17	66
Total dissolved solids	52	30	888
Bromide	<1.00	<1.00	<1.00
Specific conductance (uU/cm)	42	62	1200
pH (units)	5.95	6.23	7.62
Total acidity as CaCO3	10	8	8
Total alkalinity as CaCO3	9	14	54
DISSOLVED METALS (mg/L)			
Aluminum	0.067	<0.032	<0.032
Barium	0.0322	0.0311	0.0243
Boron	<0.036	<.0.036	<0.036
Calcium	2.30	3.71	118
Iron	0.112	0.648	<0.006
Lithium	<0.002	<0.002	<0.002
Magnesium	1.58	1.79	80.1
Manganese	0.331	1.42	1.67
Phosphorus	<0.078	<0.078	0.105
Potassium	1.82	2.44	5.01
Silicon	2.07	3.80	5.26
Sodium	1.10	0.914	2.47
Strontium	0.020	0.021	0.268
Sulfur	2.56	3.61	167
Zinc	0.014	0.025	<.0.006

VITA

Shelley A. Minns was born on October 7, 1954, in Parkerburg, West Virginia. She attended Spencer High School and completed her high school education at Morgantown High School. Shelley obtained a Bachelor of Science in Geology from West Virginia University in 1977, graduating magna cum laude. Shelley pursued a career in geology, holding the following positions:

Terra-Aqua Resource Engineering, Inc.--Crossville, Tenn.
Geologist-October 1983 to August 1987
Self-employed geologist-Abingdon, Va.
March 1981 to October 1983
Powell Mountain Coal Co.-Big Stone Gap, Va.
Project Geologist-March 1980 to March 1981
Thompson and Litton Engineers, Inc.-Wise, Va.
Geologist-November 1978 to March 1980
Geological Consulting Services, Inc.-Bluefield, Va.
Geologist-October 1977 to November 1978

Shelley enrolled in Ohio University in 1987 and obtained a Master of Science degree in Environmental Studies in 1989. While pursuing her doctoral degree, Shelley was employed by the Institute for Mining and Minerals Research and the Kentucky Geological Survey as a research assistant. Shelley is a Registered Professional Geologist in Tennessee and is certified by the American Institute for Professional Geologists. Her professional publications are:

Minns, S. A., Sahba, A. M., Sendlein, L. V. A., Currens, J. C., and Dinger, J. S., 1991, Hydrogeology and ground-water monitoring of an ash-disposal site at a coal-fired power plant in a karst system, *in* Proceedings, Third Conference on Hydrogeology, Ecology, Monitoring, and management of Ground-Water in Karst Terranes: U.S. EPA and Association of Ground Water Scientists and Engineers, a division of National Ground Water Association, Nashville, Tenn., December 4-6,1991, p. 331-347.

Minns, S. A., Sahba, A. M., Sendlein, L. V. A., and Dinger, J. S., 1991, Hydrogeology and ground-water monitoring of a coal-fired power plant ash-disposal site in a karst system [abs.], *in* Proceedings, Kentucky Water Resources Symposium: University of Kentucky, Lexington, Ky., March 14-15, 1991, p. 73.

Sahba, A. M., Minns, S. A., Sendlein, L. V. A., and Dinger, J. S., 1990-The effects of coal-fired power plant disposal on the ground-water quality of an alluvial system [abs.]: Geological Society of America Abstracts with Programs, v. 12, no. 7.

Sahba, A. M., Minns, S. A., Sendlein, L. V. A., and Dinger, J. S., 1990, The effects of coal-fired power plant disposal on the ground-water quality of an alluvial system [abs.], in Proceedings, Kentucky Water Resources Symposium: University of Kentucky, Lexington, Ky., March 14-15, 1991, p. 75.

Sahba, A. M., Minns, S. A., Sendlein, L. V. A., and Dinger, J. S., 1991, Coal-fired power plant ash disposal: University of Kentucky Institute for Mining and Mineral Research Highlights, v. 10, no. 1.

Thomas, W. A., and Minns, S. A., 1993, Geologic context of the distribution of fractures that control ground-water flow in the Eastern Kentucky Coal Field: University of Kentucky Institute for Mining and Mineral Research Highlights, v. 12, no. 1.