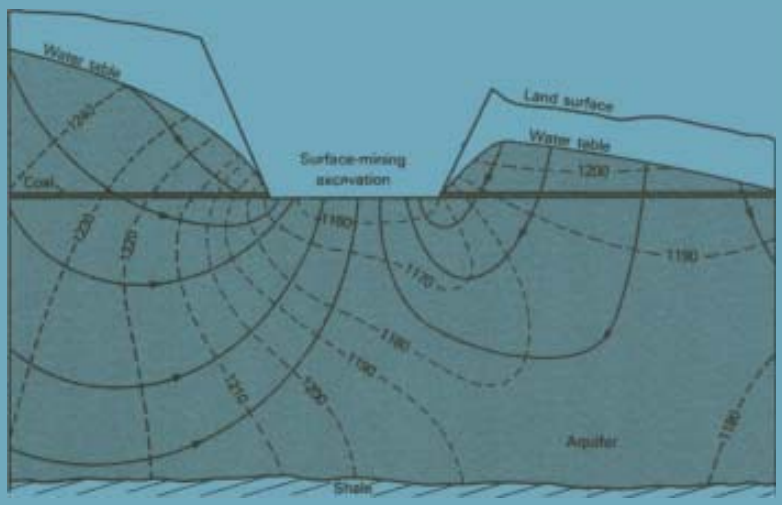
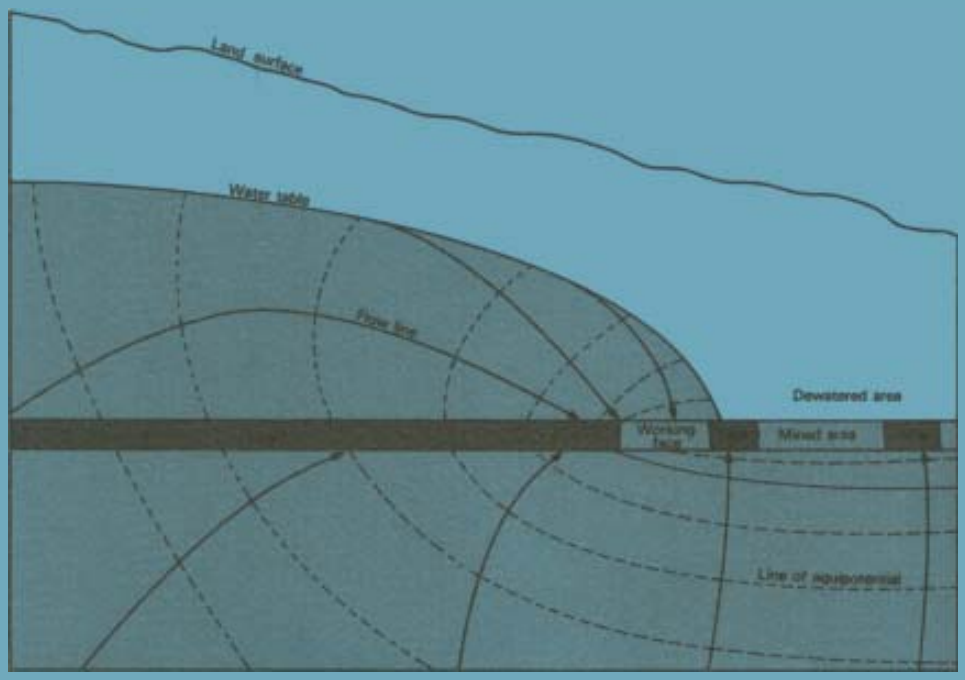
U. S. Department of the Interior
Office of Surface Mining Reclamation and Enforcement

GROUND-WATER INFORMATION MANUAL:

COAL MINE PERMIT APPLICATIONS — VOLUME I





Prepared in cooperation with
U.S. Geological Survey

GROUND-WATER INFORMATION MANUAL:
COAL MINE PERMIT APPLICATIONS

Volume I

by

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U.S. Geological Survey
U.S. DEPARTMENT OF THE INTERIOR
Office of Surface Mining Reclamation and Enforcement

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U.S. Geological Survey

1985

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CONVERSION FACTORS AND ABBREVIATIONS

For use of readers who prefer to use metric(SI) units,
conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeters (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047.	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785.	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow		
Velocity		
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.048	meter per day (m/d)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
Discharge		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (oz)	453.6	gram (g)
ton, short	0.9072	megagram (Mg)
Temperature		
degree Fahrenheit (˚F)	˚C =	degree Celsius(˚C)

Use of brand names throughout this manual is for identification purposes only and does not imply endorsement by U.S. Geological Survey.

I. INTRODUCTION

1. Content and Purpose of This Manual

The Surface Mining Control and Reclamation Act of 1977 (SMCRA 1977), requires the inclusion of ground-water information with any mining-permit application, on aquifers above and below the coalbeds (or seams) to be mined. With this information, the regulatory authority can evaluate the potential effect of the proposed mine on the aquifer system(s), and assess the cumulative hydrologic effects of the proposed mines, on the adjoining properties.

The titles of sections of the Code of Federal Regulations (30OTR), Mineral Resources (30CPR) parts 778, 779, and 780 for surface-mine-activities information, and parts 782, 783, and 784 for underground-mine activities, that pertain to the information requirements on environmental resources and reclamation and operation plans are:

Description of hydrology and geology
Description of geology
Ground-water information
Surface-water information
Alternative water-supply information
Maps
Cross sections, maps, and plans
Hydrologic balance
Reclamation plan
Protection of hydrologic balance
Operation plan

The heading of each chapter in this manual is followed by a list of terms from the above group to which information in that chapter is applicable. In this manual, the ground-water information is organized such that many of the sections apply to several specifications within the regulations. Examples of maps, tables, graphs, and diagrams such as required for each term listed above are given throughout the text and specifically in the last chapter (XIX).

The purpose of this manual is to assist applicants for coal-mining permits in (1) describing the ground-water conditions in the vicinity of a permit area, and (2) assessing the potential impacts of mining on the ground-water resources in the area adjacent to the proposed site.

This manual is directed at a moderately technical audience. The applicant, or the consultant for the applicant is assumed to have (1) a basic background in science, including mathematics, chemistry, and physics and (2) a bachelor's degree in hydrology, engineering, or geology.

This manual defines the type of geohydrologic information to be included by the applicant to help ensure that the data are adequate for the regulatory authority to: (1) understand the physical (geologic and hydrologic) settings of the aquifers likely to be affected by mining, (2) judge the adequacy of the impact analysis as presented in the application, and (3) apply the information in the cumulative assessment process.

This manual addresses four principal subjects: (1) the geologic setting of the bedrock units containing the coal to be mined, (2) the hydrologic setting (primarily ground water), but including low-flow surface water to the extent of the relationship with ground water (or lack thereof); (3) the potential impacts of mining on the ground-water resources; and, (4) the data requirements and monitoring plan needed for an environmental impact analysis.

The terminology in parts of this manual was requested by the OEM to conform to regulatory requirements and is not necessarily that used by the U.S. Geological Survey.

2. Examples of Ground-Water Elements for Coal-Mine Permit Applications

A description and examples of ground-water information required for surface- and underground-permit applications are given at the end of this manual (chapter XDC). These examples incorporate the geologic- and hydrologic-setting classification systems and the components of ground-water hydrology explained herein, as they apply to coal mining. The examples are taken with little or no modification from published reports of geohydrologic investigations done in the various coal provinces in the conterminous United States.

The purpose of the chapter referred to above is to provide examples of tables, cross sections, maps, graphs, diagrams, and calculations used in data presentation and analyses. From these examples, the applicant can plan the tasks necessary for collecting, compiling, and analyzing ground-water data for the permit application and can develop appropriate documentation. The products from the investigation can parallel the examples presented herein.

3. Ground-Water Studies

In a companion volume, there are eleven ground-water studies compiled. These are the result of geohydrologic investigations performed cooperatively with other state and federal agencies, in the various coal provinces in the United States (figure 1-1). These studies include the geologic- and hydrologic-settings and other hydrologic information units. In preparing the permit application, the applicant can use these studies as examples for his/her presentation of ground-water information. However, these studies are not comprehensive in presenting the ground-water situations for all geologic- and hydrologic-settings. Also, some studies do not contain sufficient hydrologic information to the levels of detail to satisfy all the requirements of all regulatory agencies.

4. Acknowledgments

The U.S. Geological Survey (USGS), Water Resources Division, prepared this manual for the U.S. Office of Surface Mining (OSM), Department of the Interior. Thanks are given to John Mosesso and Ranvir Singh, of OSM for providing assistance and guidance.

The author is indebted to the many employees from the U.S. Geological Survey, State agencies, and other Federal agencies who provided assistance.

Appreciation also goes out to the many reviewers and participants in the many strategy and evaluation meetings; in particular: Keith Eggleston, Kenn Foit, Murray Garber, Gary Macintosh, Allen Perry, and Ranvir Singh of OSM; Wayne VanVoast of Montana Bureau of Geology and Mines; and Gregory J. Allord, James F. Bailey, Konrad J. Banaszak, Hugh E. Bavins, Terence W. Danielson, Anne J. Finch, James B. Foster, Jr., Carole L. Goetz, William B. Hobba, Jr., Robert L. Houghton, Frederick A. Kilpatrick, Larry F. Land, Robert L. Laney, Soloman M. Lang, Gregory C. Lines, Marlin E. Lowry, David J. Lystron, Melvin V. Marcher, John E. Moore, Joe A. Moreland, Perry C. Olcott, Celso Puente, Arthur L. Putnam, Allan C. Razem, John R. Ritter, Robert Schoen, Jeffrey D. Stoner, Lindsay A. Swain, and James Whitmer of U.S. Geological Survey.

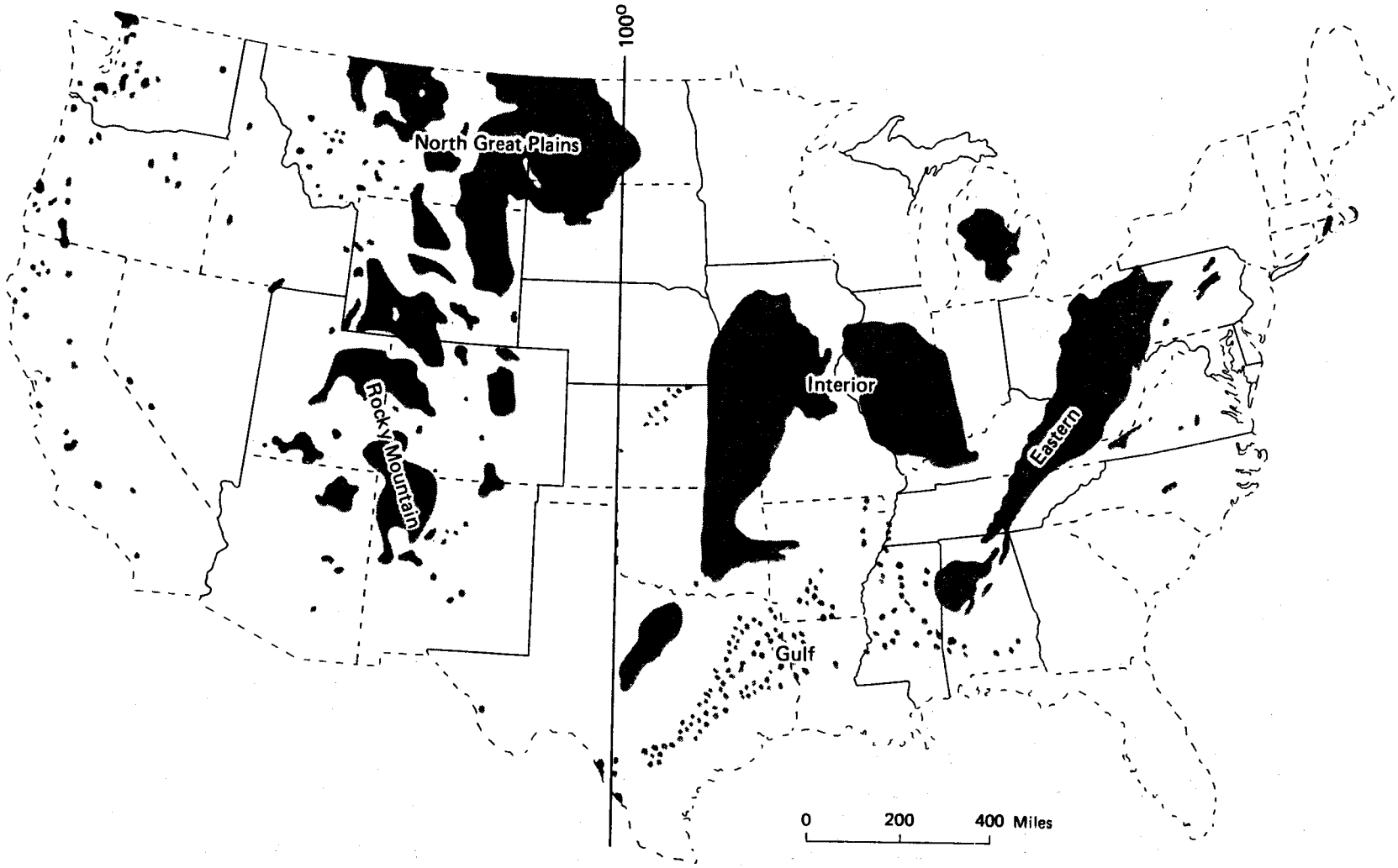


Figure I-1 — Location of coal provinces in conterminous United States
(Modified for Trumball, 1960 sheet 1)

II. GROUND-WATER ASPECTS OF THE PERMANENT REGULATORY PROGRAM

1. Statutory Information Requirements

The statutory requirements relating to ground water are contained in Sections 507(b), 508, and 510(b) of Surface Mining Control and Reclamation Act (SMCRA) (PL95-87). These sections require that information on ground-water systems be made available from an appropriate Federal or state agency or be collected by the permit applicant. Specifically, these sections state:

> Section 507(b): "The permit application shall be submitted in a manner satisfactory to the regulatory authority and shall contain, among other things . . .
>
> (11) . . . with respect to the hydrologic regime, quantity and quality of water in surface- and ground-water systems including the dissolved and suspended solids under seasonal flow conditions and the collection of sufficient data for the mine site and surrounding areas so that an assessment can be made by the regulatory authority of the probable cumulative impacts of all anticipated mining in the area upon the hydrology of the area and particularly upon water availability: . . .
>
> (14) . . . the location of subsurface water, if encountered, and its quality; . . .
>
> Section 508: ... (a) Each reclamation plan * * * shall include . . . a statement of . . . (13) a detailed description of the measures . . . to assure the protection of: (C) the quantity of surface- and ground-water systems . . .
>
> Section 510(b): No permit or revision application shall be approved unless the application affirmatively demonstrates and the regulatory authority finds in writing on the basis of the information set forth in the application or from information otherwise available which will be docunented in the approval and made available to the applicant that . . .
>
> * * *
>
> (3) the assessment of the probable cumulative impact of all anticipated mining in the area on the hydrologic balance specified in Section 507(b) has been made by the regulatory authority, and the proposed operation thereof has been designed to prevent material damage to the hydrologic balance outside the permit area; . . .
>
> (5) The proposed surface coal-mining operation, if located west of the hundredth meridian west longitude, would—
> (A) not interrupt, discontinue, or preclude farming on alluvial valley floors . . .
> (B) not materially damage the quantity or quality of water in surface- or underground-water systems that supply these valley floors . . .

2. Regulatory Information Requirements

The statutory requirements of Sections 507 (b), 508, and 510 (b) of SMCRA have been incorporated in the Permanent Regulatory Program Regulations (September 26, 1983) at 30 CFR 780.21, 816.41, 784.14, and 817.41. Sections 780.21 and 816.41 deal with surface mining, and 784.14 and 817.41 deal with underground mining.

Both Sections 780.21(b) and 784.14(b) require that the application for a surface coal-mine permit shall include the following baseline hydrologic information and any additional information required by the regulatory authority.

> (1) Ground-water information. The location and ownership for the permit and adjacent areas of existing wells, springs, and other ground-water resources, seasonal quality and quantity of ground water, and usage. Water quality descriptions shall include, at a minimun, total dissolved solids or specific conductance corrected to 25°C, pH, total iron, and total manganese. Ground-water quantity descriptions shall include, at a minimim, approximate rates of discharge or usage and depth to the water in the coal seam and each water-bearing stratum above and potentially impacted stratum below the coal seam. . . .
>
> (i) Ground-water monitoring plan. (1) The application shall include a ground-water monitoring plan . . . and the analysis of all baseline hydrologic, geologic, and other information in the permit application. The plan shall provide for the monitoring of parameters that relate to the suitability of the ground water for current and approved postmining land uses and to the objectives for protection of the hydrologic balance set forth in paragraph (g) of this section. It shall identify the quantity and quality parameters to be monitored, sampling frequency, and site locations. It shall describe how the data may be used to determine the impacts of the operation upon the hydrologic balance. At a minimum, total dissolved solids or specific conductance corrected to 25°C, pH, total iron, total manganese, and water levels shall be monitored and data submitted to the regulatory authority at least every 3 months for each monitoring location. The regulatory authority may require additional monitoring.
>
> Sections 816.41 and 817.41 dealing with hydrologic-balance protection relating surface mining and underground mining activities, respectively, require as follows:
>
> (b) . . . (1) Ground-water quality shall be protected by handling earth materials and runoff in a manner that minimizes acidic, toxic, or other harmful infiltration to ground-water systems and by managing excavations and other disturbances to prevent or control the discharge of pollutants into the ground water.

(2) Ground-water quantity shall be protected by handling earth materials and runoff in a manner that will restore the approximate pre-mining recharge capacity of the reclaimed area as a whole, excluding coal mine waste disposal areas and fills, so as to allow the movement of water to the ground-water system.

(c) Ground-water monitoring. (1) Ground-water monitoring shall be conducted according to the ground-water monitoring plan approved under 780.21(i) of this chapter. The regulatory authority may require additional monitoring when necessary.

(2) Ground-water monitoring data shall be submitted every 3 months to the regulatory authority or more frequently as prescribed by the regulatory authority. Monitoring reports shall include analytical results from each sample taken during the reporting period. When the analysis of any ground-water sample indicates noncompliance with the permit conditions, then the operator shall promptly notify the regulatory authority and immediately take the action provided for in 773.17(e) and 780.21(h) of this chapter.

(3) Ground-water monitoring shall proceed through mining and continue during reclamation until bond release. Consistent with the procedures of 774.13 of this chapter, the regulatory authority may modify the monitoring requirements, including the parameters covered and the sampling frequency, if the operator demonstrates, using the monitoring data obtained under this paragraph, that—

(i) The operation has minimized disturbance to the hydrologic balance in the permit and adjacent areas and prevented material damage to the hydrologic balance outside the permit area; water quantity and quality are suitable to support approved postmining land uses; and the water rights of other users have been protected or replaced; or

(ii) Monitoring is no longer necessary to achieve the purposes set forth in the monitoring plan approved under 780.21(i) of this chapter.

(4) Equipment, structures, and other devices used in conjunction with monitoring the quality and quantity of ground water on site and offsite shall be properly installed, maintained, and operated and shall be removed by the operator when no longer needed.

III. FORMATION AND OCCURRENCE OF COAL

Pertinent 30 CFR[1] sections:

Geology description.

Cross sections, maps, and plans.

Coal beds are the result of a vast accumulation of trees and other vegetation in paludal environment (swamps and marshes), such as in the present day Mississippi River delta. The decayed vegetal matter initially forms peat, then the increasing pressure and temperature caused by progressively deeper burial transform the peat deposits into lignite and then into the more volatile forms of coal.

A typical delta setting for the formation of peat is depicted in figure III-l. Fluctuations in sea level through time cause lateral shifts in stream channels and produce variations in the thickness, lateral extent, and continuity of the peat, lignite, and coal deposits. The erosion of coal seams, the deposition of alluvial material, which will become sandstone with time, and the recent deposition of glacial material, are illustrated in cross section in figure III-2.

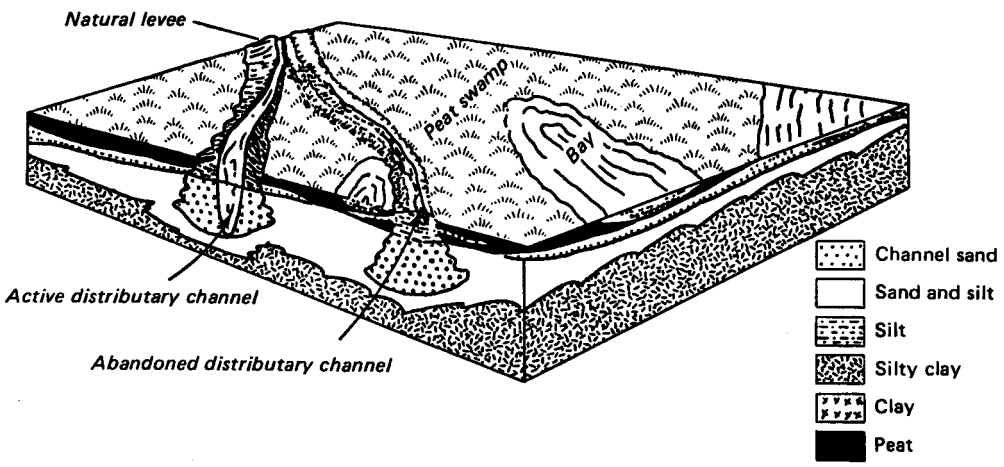


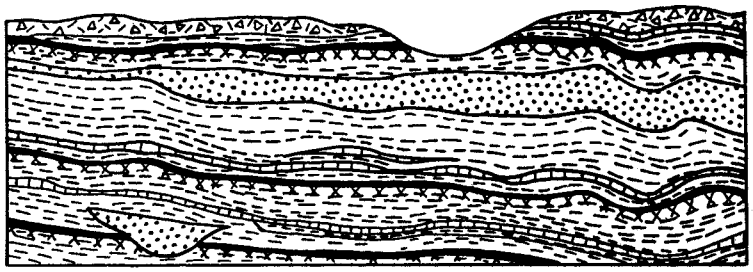
Figure III-l.—Distribution of peat and related alluvial sediments on a portion of a large delta.
(From Cassidy, 1973, fig. 3)

The proximity of water-bearing deposits (aquifers) to the coal seams is one of the major concerns of coal mining operations. The aquifers can be overlying, underlying, or laterally adjacent to the coal deposits to be mined. The presence of water-bearing sandstone or alluvial material in place of coal beds, is called a washout.

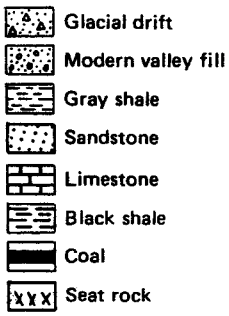
Flat-lying coal seams, as shown in figures HI-2(a) and III-2(c), are found in the Northern Great Plains, Interior, Gulf, and, to a lesser extent, the Eastern Coal Provinces (See figure 1-1). In the regions where mountain building has occurred, the sedimentary rock sequence containing the coal seams is folded and locally faulted. The folding of these rock units produces synclines and anticlines, as shown in figure III-2(b). This type of coal-bearing structure is common in the Eastern and Rocky Mountain Coal Provinces.

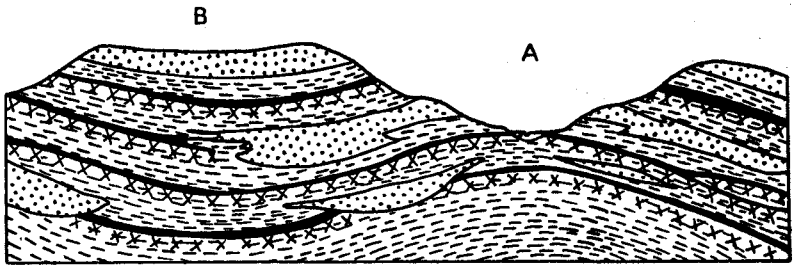
Chapter IV, "Geologic Setting Classification System", and Chapter VI", Hydrologic Setting Classification System", presents the types of information needed to systematically analyze the geologic setting of the coal to be mined and the hydrologic setting of aquifers within the geologic setting. This combined system enables the applicant and the regulatory authority to anticipate any safety hazards, of the proposed mining operation, any water-supply problems, and any adverse effects of the mining operation on the aquifers and water resources within the permit area and vicinity.

[1]CFR= Code of Federal Regulations

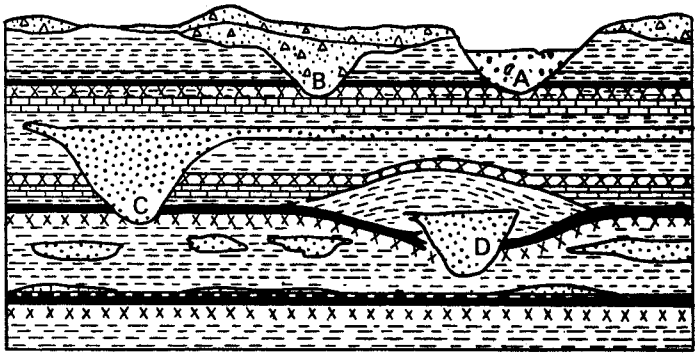


(a) Simplified cross section of coal - bearing sequence representative of the Interior Coal Province. A layer of glacial drift overlies the rocks in most of this area.





(b) Simplified cross section of coal - bearing sequence in parts of the Appalachian Coalfield. Rocks have been gently folded into anticline (upfold) at A and syncline (downfold) at B.



(c) Some features affecting continuity of coals. Coal removed by modern stream erosion at A; preglacial erosion at B; by a stream after coal deposition at C; and at D, the stream was present throughout the time of peat accumulation.

Figure III-2.—Vertical distribution of coal within three types of rocks sequences. (From Cassidy, 1973, figs. 5, 6, 12)

IV. GEOLOGIC-SETTING (GS) CLASSIFICATION SYSTEM

Pertinent 30CFR[1] Sections:

Geology description

Cross sections, maps, and plans

The geologic-setting (GS) classification system is an outgrowth of the National Research Council (1981) "representative geologic settings" and categorizes into a numeric code the geologic factors, such as structure, lithology, and thickness of sedimentary bedrock units, that contain coal to be mined into eight types. This system applies only to sedimentary rocks and is designed to describe (1) the hydraulic character of the bedrock units above and below the coal bed(s) in terms of their permeability and (2) the structural features within the bedrock units of the general area, including folding and faulting. This system considers these bedrock units either as aquifers, such as sandstone, or as confining beds, such as shale, and is compatible with the hydrologic setting classification system (described in chapter VI). Each category indicates the nature of the setting and the potential for any ground-water problems related to the coal -mining operations.

The type of geologic setting category assigned to a permit area will depend upon the acreage and the geology of the area. More than one geologic setting may apply to a permit area. For example, the area depicted in figure III-2(b), which would require a large-acreage permit, contains deep coal beds under a stream valley that are locally flat lying and that vary from a synclinal setting to an anticlinal setting. Each of these settings can have different ground-water considerations in relation to mining.

The geologic-setting classification system is outlined in table IV-1. The settings are illustrated and described in figures TV-1 through IV-8.

CFR[1] = Code of Federal Regulations

Table 3V-1. Classification for geologic settings (GS) of coal beds (Examples are depicted in figures IV-1 through IV-8.)

GS-1. Flat lying coal beds of less than 5 degrees.

GS-2. Anticlinal structural setting.

GS-3. Synclinal structural setting.

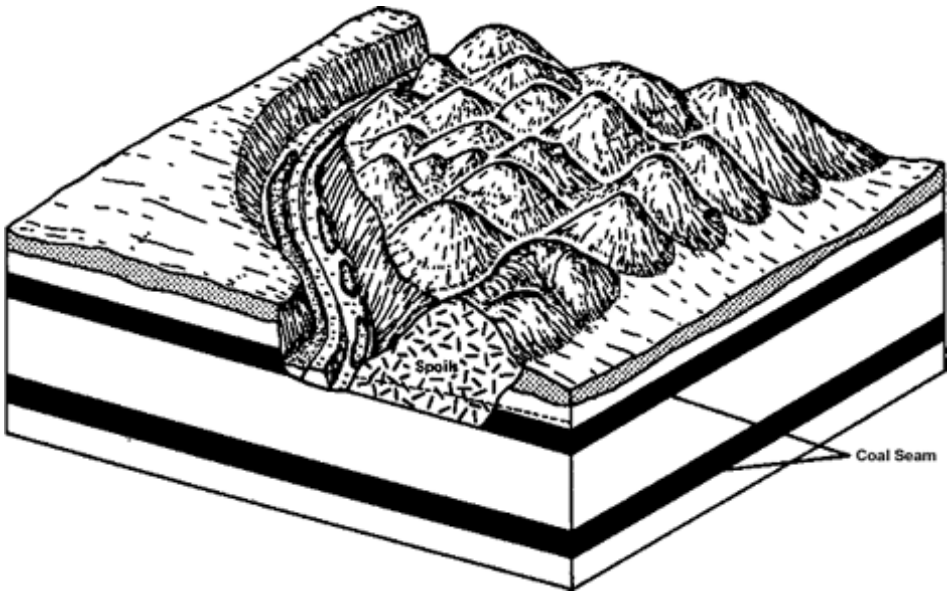
GS-4. Low-angle coal beds dipping more than 5 degrees.

GS-5. "Alluvial valley floor" as defined by regulations for areas west of 100! meridian (See chapter XVIII).

GS-6. Coal bed under stream valley (east of the 100° meridian) and coal bed under stream valley (west of the 100° meridian) but not qualifying as an "Alluvial valley floor" (GS-5).

GS-7. Coal beds and fault structures (thrust faults, normal faults, fracture traces, and lineaments).

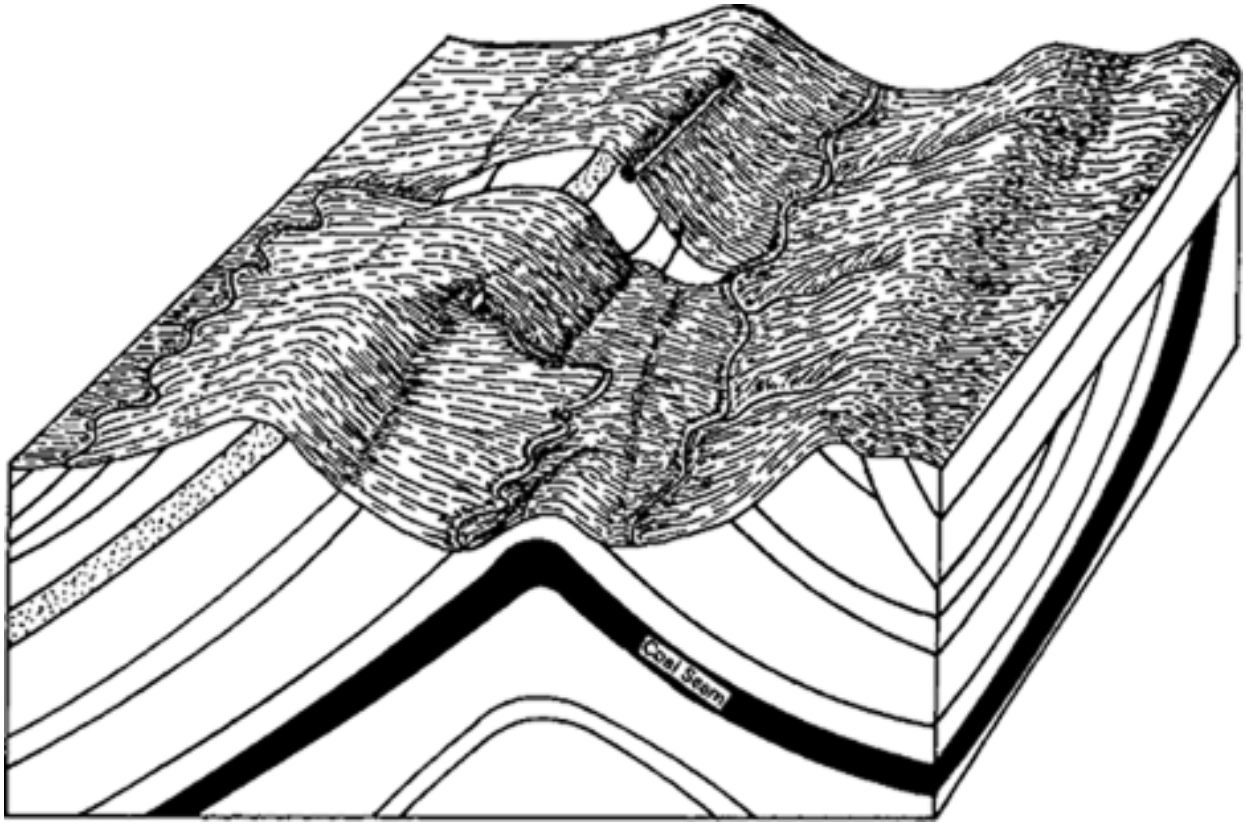
GS-8. Fractured bedrock caused by mine subsidence.



Flat-lying coal beds of (less than 5° dip)

– If permit area is above the local drainage level (streambed elevation), mining requires only minor consideration for dewatering.
– If the permit area is below the local drainage level or if the coal bed is in contact with other aquifers, dewatering will be a major consideration.
– Joints associated with bedrock fracturing could be a major problem if the pore spaces contain ground water or if faulting has occurred in the surrounding area.

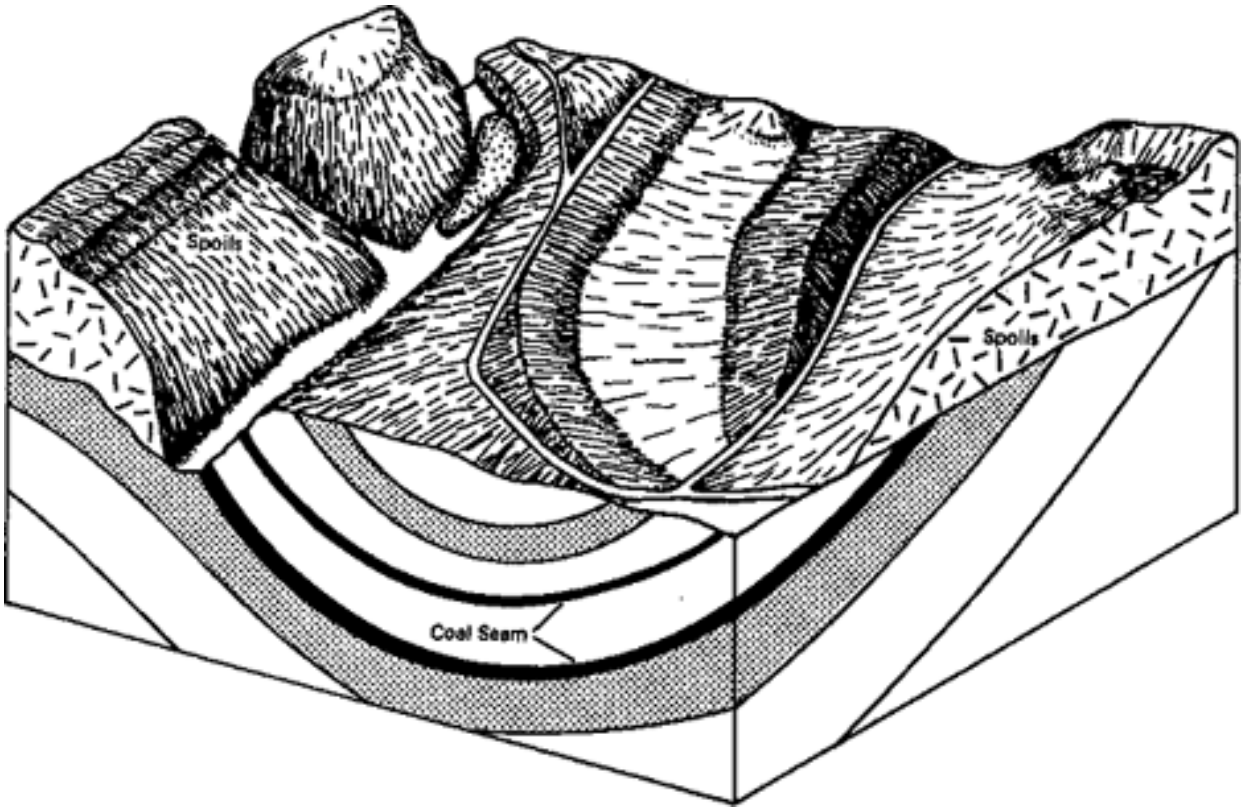
Figure IV-1.— Geologic setting and ground-water factors for flat-lying coal bed (GS 1). (Modified from Hounslow and Fitzpatrickf 1978, fig. 54)



Anticlinal structural setting

– Mining downdip on an anticlinal limb will require constant pumping if the coalbed is an aquifer or is in contact with other aquifers.
– Mining updip on an anticlinal limb will be self draining.
– Bedrock fracturing will be significant owing to the bending of the bedrock units; jointing will normally be greatest at the crest of the anticline.

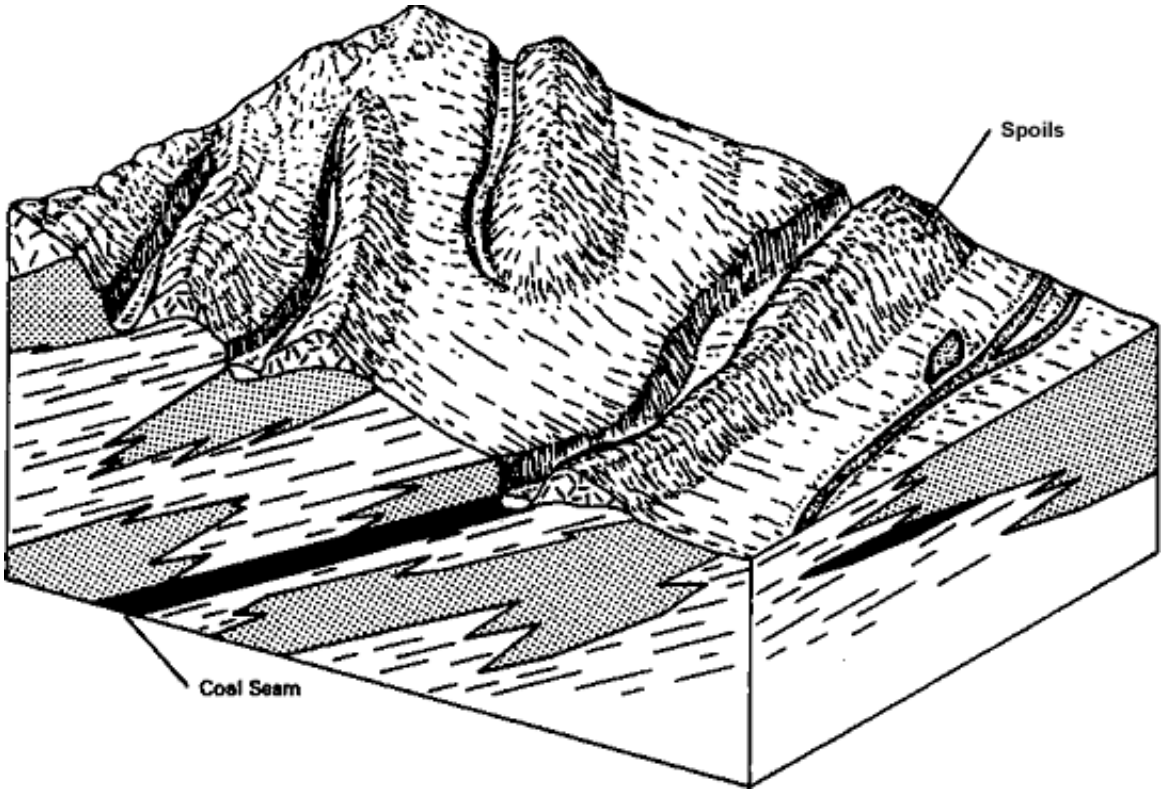
Figure IV-2.— Geologic setting and ground-water factors for anticlinal structure (GS 2).



Synclinal structural setting

– Mining downdip on a synclinal limb will require constant pumping if the coal is an aquifer or is in contact with other aquifers.
– Bedrock fracturing will be significant owing to the bending of the bedrock units; the occurrence of joints will normally be greatest at the trough of the syncline.

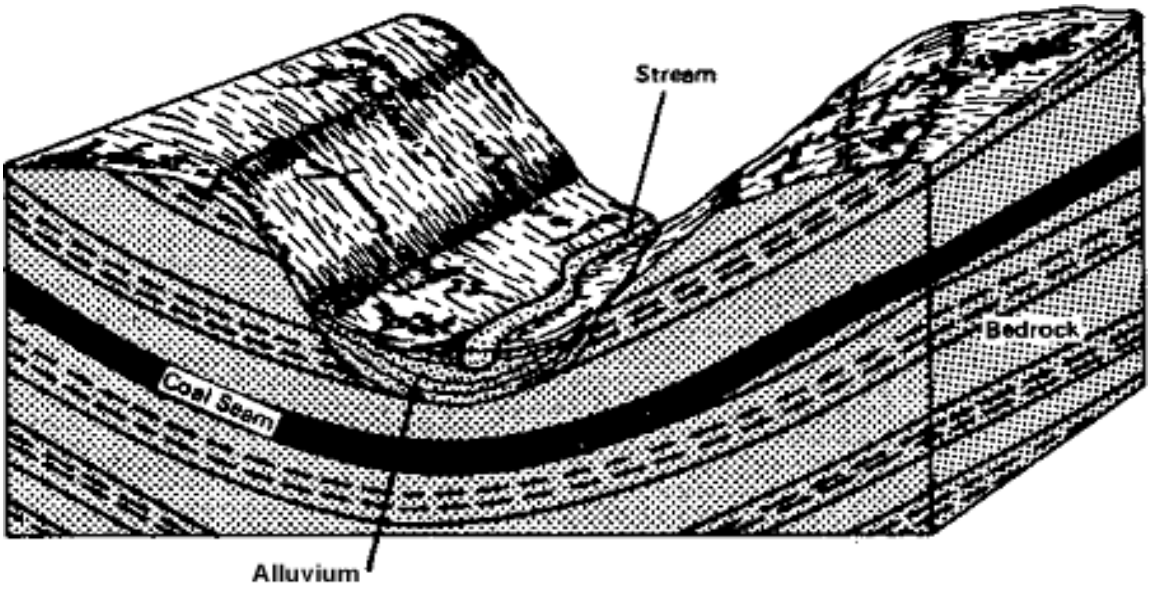
Figure IV-3.— Geologic setting and ground-water factors for synclinal structure (GS 3). (Modified from Hounslow and Fitzpatrick, 1978, fig. 40).



Low-angle dipping coal bed (greater than 5° dip)

- This occurs on the limb of a regional anticline or regional syncline, where the permit area is significantly smaller than the geologic structure.
- The density of bedrock fracturing will be dependent upon the distance between the permit area and the anticlinal crest or the synclinal trough or any linear fault structure.
- Under wet conditions, dewatering pumps have a greater head to pump against as mining progresses deeper.

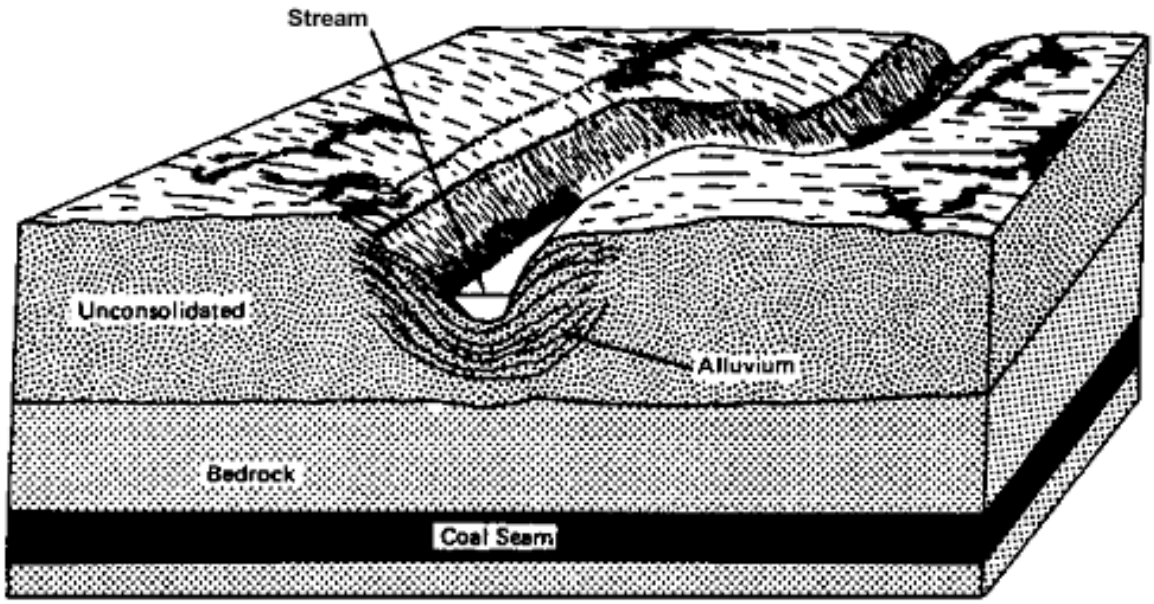
Figure IV-4.— Geologic setting and ground-water factors for low-angle dipping coal bed (GS 4). (Modified from Hounslow and Fitzpatrick, 1978, fig. 44)



"Alluvial Valley Floor" (west of the 100° meridian)

– Considerations for permit areas in this setting are:
  (1) the occurrence and effectiveness of confining beds separating the coal bed from the alluvial channel deposits, and
  (2) the presence of fracture zones between the coal bed and the alluvial channel deposits.

Figure IV-5.— Geologic setting for "Alluvial Valley Floor" (GS 5),
(From National Research Council, 1981, fig. 4.5c)

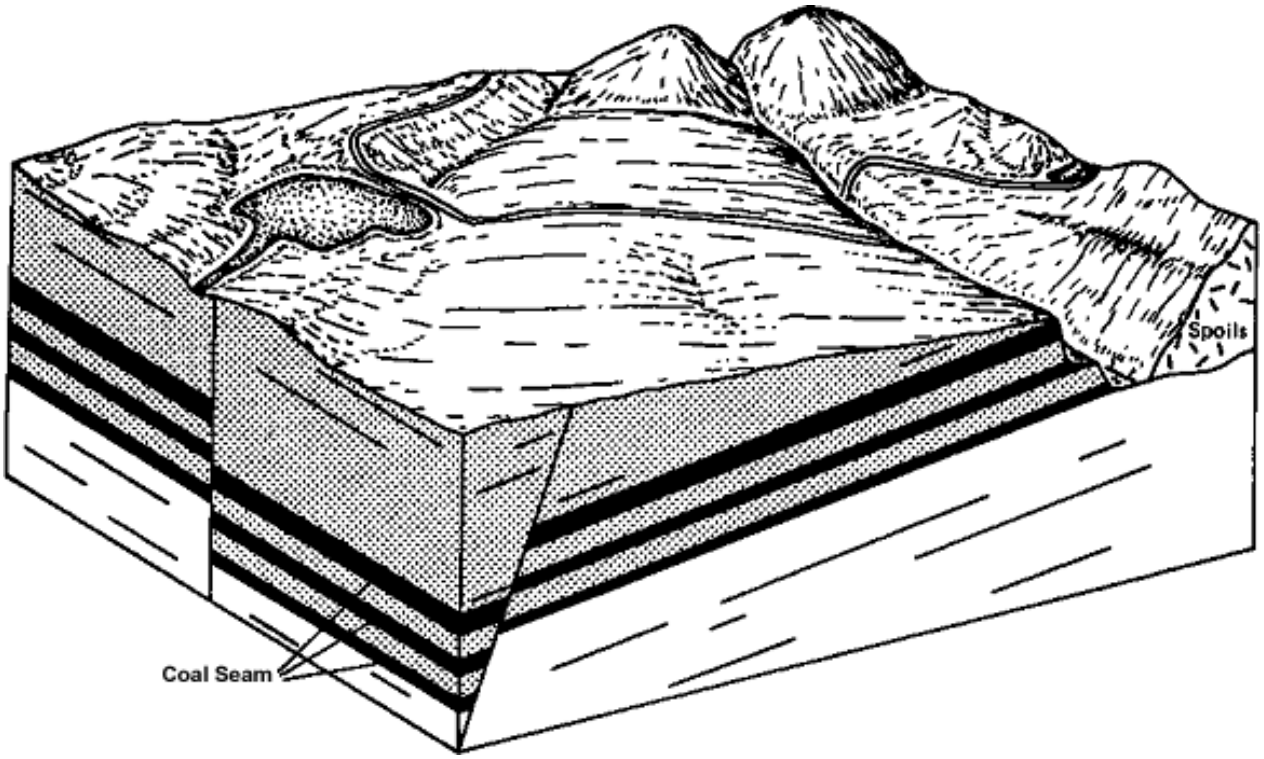


Coal bed under stream valley

(same as GS-5 but for permit areas east of 100° meridian and permit areas west of the 100° meridian that do not qualify as "Alluvial Valley Floor" settings)

– Significant ground-water inflow to proposed permit area can be dangerous to mining operations if:
  (1) no impermeable barrier separates the saturated alluvial deposits from the underlying coal bed to be mined, and
  (2) the stream valley is a surficial expression of a fracture trace, a lineament, or a fault structure. (Fractured, permeable rock would allow ground water to flow from the stream and alluvial deposits into the proposed excavation site.)

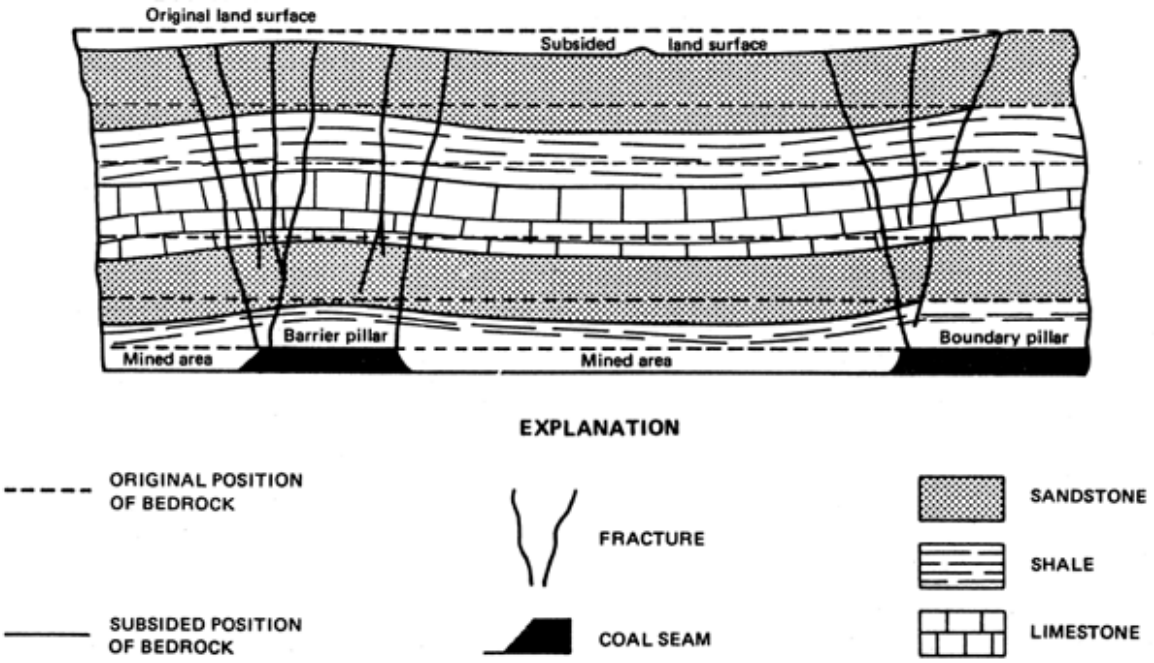
Figure IV-6.— Geologic setting and ground-water factors for coal bed under stream valley (GS 6). (From National Research Council, 1981, fig. 4.5b)



Coal beds and fault structures
(thrust, faults, normal faults, fracture traces, and lineaments)

- If the permit area includes a fault structure, significant quantities of ground water would initially discharge into the mine excavation; after a short time, however, depending upon the recharge source, the ground-water discharge may diminish to a controllable quantity.
- One of the greatest hazards in underground mining is the unexpected intersection of a water-bearing fracture zone with a heading, or to have the fracture zone intersect a major surface-water feature such as a perennial stream, river, or lake.

Figure IV-7.— Geologic setting and ground-water factors for coal beds and fault structure (GS 7).
(Modified from Hounslow and Fitzpatrick, 1978, fig. 30)



Physical setting of fractured bedrock caused by mine subsidence.

- This setting applies to previously mined areas; and the effects of subsidence are superimposed upon the previously discussed settings.
- If permit area is within, beneath, or adjacent to an area that has experienced mine subsidence, significant and prolonged ground-water infiltration into the proposed mine may result.
- Ground water from flooded "rooms" of an adjacent room and pillar operation may enter along faults and fractures resulting from:
  (1) roof sag and collapse,
  (2) roof sag and pillar squeeze,
  (3) pillar collapse or pillar removal, and
  (4) doming-type roof fall.

Figure IV-8.— Physical setting for fractured bedrock caused by mine subsidence (GS 8). (Modified from Dunrud, 1976, fig. 4, and Lines and others, 1984, fig. 3.3-1)

V. GROUND-WATER FLOW SYSTEMS

Pertinent 30CFR[1] Sections:

Description of hydrology and geology.

Ground-water information.

Part of the precipitation (rain, snow, etc.) that falls on the land infiltrates through the soil or rock to the water table. The long-term effect of infiltration is the development of a ground-water flow system. The direction of flow is downgradient from areas of recharge to areas of discharge (See figure V-l).

Ground-water flow systems are of three types: local, intermediate, and regional. In a local flow system, the recharge area is at a topographic high, and the discharge area is at the adjacent topographic low. In a regional flow system, the recharge area is at major drainage divides and the discharge areas are at major rivers or lakes at the lowest level of the drainage basin. Intermediate flow systems occur between these two flow systems and have one or more topographic highs between the recharge and discharge areas.

The ground-water conditions in a permit area depend on the flow system in relation to the location of the proposed excavation. A mountain-top mining excavation will encounter some ground-water in the local water table flow system. In a topographic high within the recharge area of the flow system, the ground-water discharge resulting from this type of excavation may be high initially but will decrease within a short time. The length of time depends on the extent of the aquifer(s) and the hydraulic properties of the aquifer system(s).

A proposed underground-mine excavation beneath or near a major river could have a combination of ground-water flow conditions, with local, intermediate, and regional discharge. The dominant condition will be related to the regional flow system. Here the ground-water discharge will be continuous and long term and will have to be controlled by pumping, or confined by grouting to provide safe working conditions.

In many coal-bearing areas, confining beds and fractures may have a significant effect upon the flow lines within the ground-water flow systems. As shown in figure V-2, underclays and semiconfining beds may create perched ground-water systems. Springs merge at the exposed junction of water-bearing rock units and the impermeable underclays but can also occur along other geologic controls such as fault traces. Fractures also provide subsurface channels for ground-water flow, as shown in figure V-2.

[1]CFR=Code of Federal Regulations

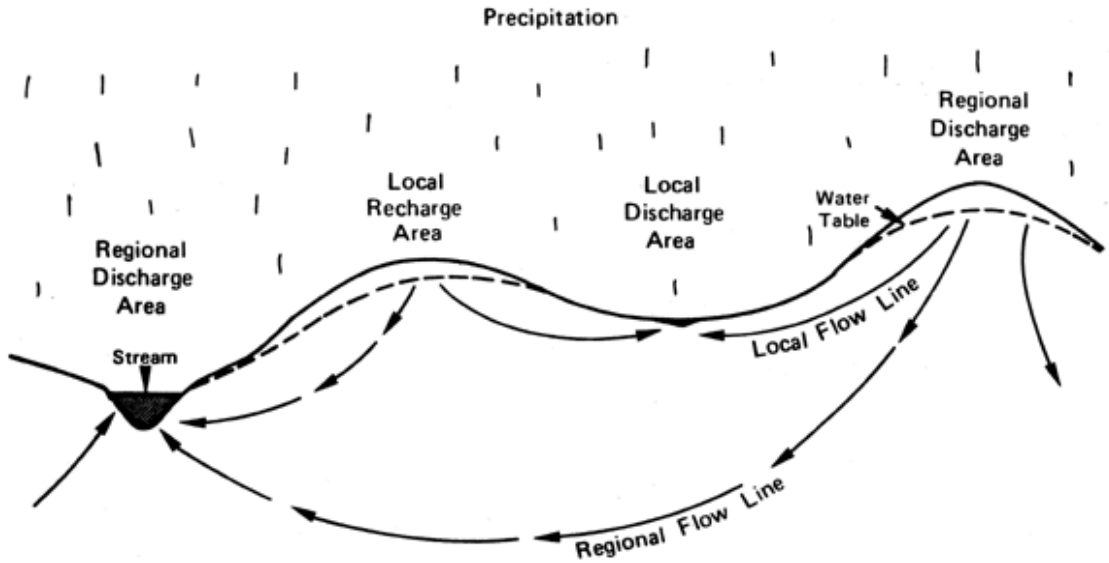


Figure V-l.— Idealized local and regional ground-water flow systems. (Modified from Toth, 1963)

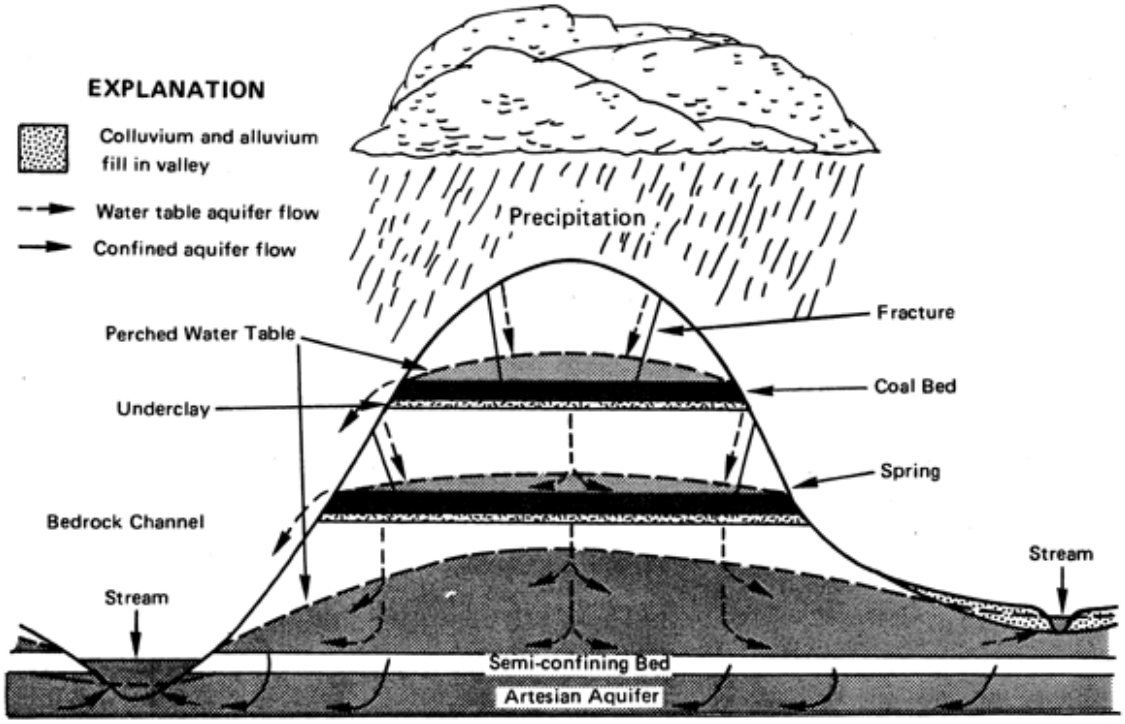


Figure V-2.— Generalized storage and movement of ground water in cross section. (Modified from Leist and others, 1982, fig. 7.1-1)

VI. HYDROLOGIC-SETTING (HS) CLASSIFICATION SYSTEM

Pertinent 30CFR[1] Sections:

Description of hydrology and geology.
Ground-water information.
Cross sections, maps, and plans.

The hydrologic-setting (HS) classification system categorizes many hydrologic factors into an alphabetic code to describe the occurrence of ground water within or adjacent to the coal seam to be mined. Permit areas range in size from several acres to several square miles and thus may contain a variety of the hydrologic as well as geologic settings.

Factors considered in the hydrologic-setting classification system include:

(1) the position of the coal bed to be mined, which could be wet or dry, with respect to aquifers,
(2) the geologic materials above and below the coal bed and whether they act as confining beds or as aquifers, and
(3) the type of aquifers—confined (artesian) or water table (unconfined).

The type of hydrologic setting cannot be determined until the aquifer units are defined. Aquifer extent and type must be identified from (1) the inventory of wells and springs in the general area (chapter VII), (2) the occurrence of ground water during well drilling or during the exploratory core-boring program (chapters VIII and XVI), (3) water-level measurements (chapter IX), and (4) other sources of geohydrologic information (chapter XV).

The hydrologic-setting classification system is outlined in table VI-1; each setting is illustrated and described in figures VI-1 through VI-7. This classification system, together with the geohydrologic data, aquifer-test analyses, and other hydrologic information collected, will enable the applicant to identify potential ground-water problems because each setting has certain characteristic hydrologic problems related to coal mining. The applicant will also have sufficient information to design the water supply system necessary to support the proposed mining operation. (Chapters VII through X will describe the analysis and assessment of these problems.)

[1]CFR=Code of Federal Regulations

TABLE VI-1.– Classification for hydrologic settings (HS) of coal beds (Examples are depicted in Figures VI-1 through VI-7)

HS-A. Coal bed above water table—dry conditions

HS-B. Confining bed separating aquifer from coal bed—dry conditions
(1) Confined aquifer above coal bed
(2) Confined aquifer below coal bed
(3) Water-table aquifer overlying coal bed

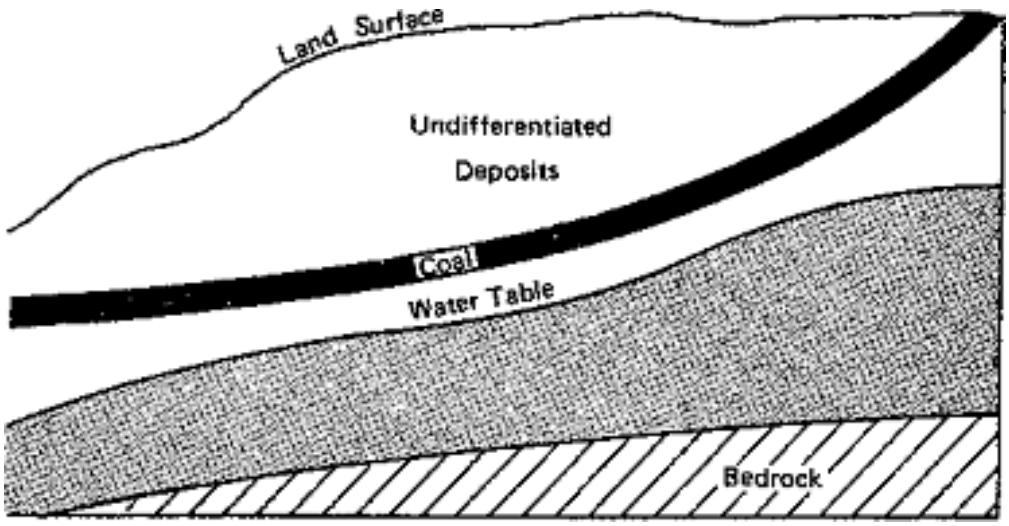
HS-C. Coal bed in contact with saturated unconsolidated deposits—wet conditions

HS-D. Coal bed in contact with confined bedrock aquifer—wet conditions

HS-E. Coal bed in contact with water-table bedrock aquifer—wet conditions

HS-F. Coal bed is an aquifer—wet conditions
(1) Bed is a confined aquifer
(2) Bed is a water-table aquifer

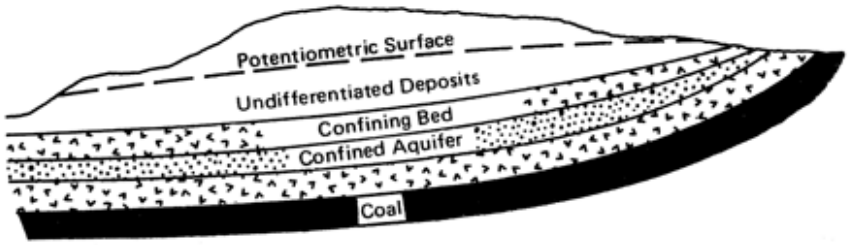
HS-G. Coal bed within a multilayered aquifer system—wet conditions



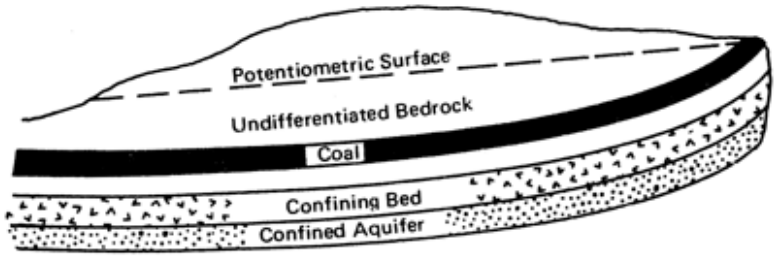
Coal bed unsaturated and above a water-table aquifer.

Seasonal variations could cause the water table to rise to within or above the coal bed, which would change the setting to HS-C. Otherwise the coal bed is generally dry.

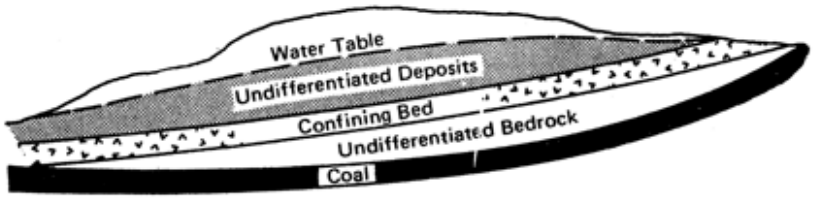
Figure VI-1.— Hydrologic setting for coal bed above water table (HS-A).
(Modified from Hounslow and Fitzpatrick, 1978, fig. 59)



A. Confined aquifer above the coal bed (HS B(1)).



B. Confined aquifer below the coal bed (HS B(2)).

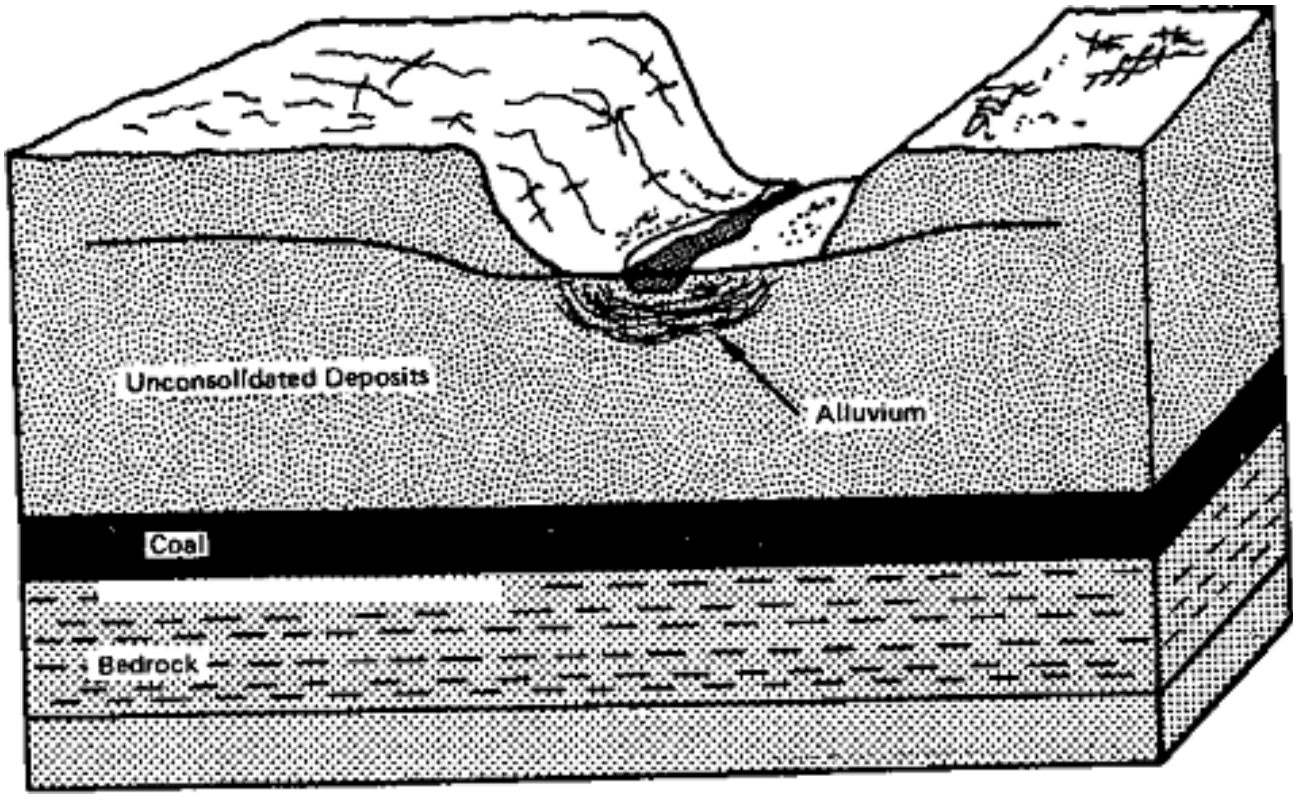


C. Water-table aquifer overlying the coal bed (HS B(3)).

Confining bedrock units, such as shale or clay, in contact with the coal bed to provide a low-permeability barrier between the coal and overlying or underlying aquifers.

The coal bed may be initially dry or wet. If the coal bed is saturated, the coal seam is a confined aquifer and has a setting (HS-F) (figure VI-6). If the confined aquifer overlies the coal bed, the setting is B(l). If the confined aquifer underlies the coal bed, the setting is B(2). If a water-table aquifer overlies the coal bed, the setting is B(3).

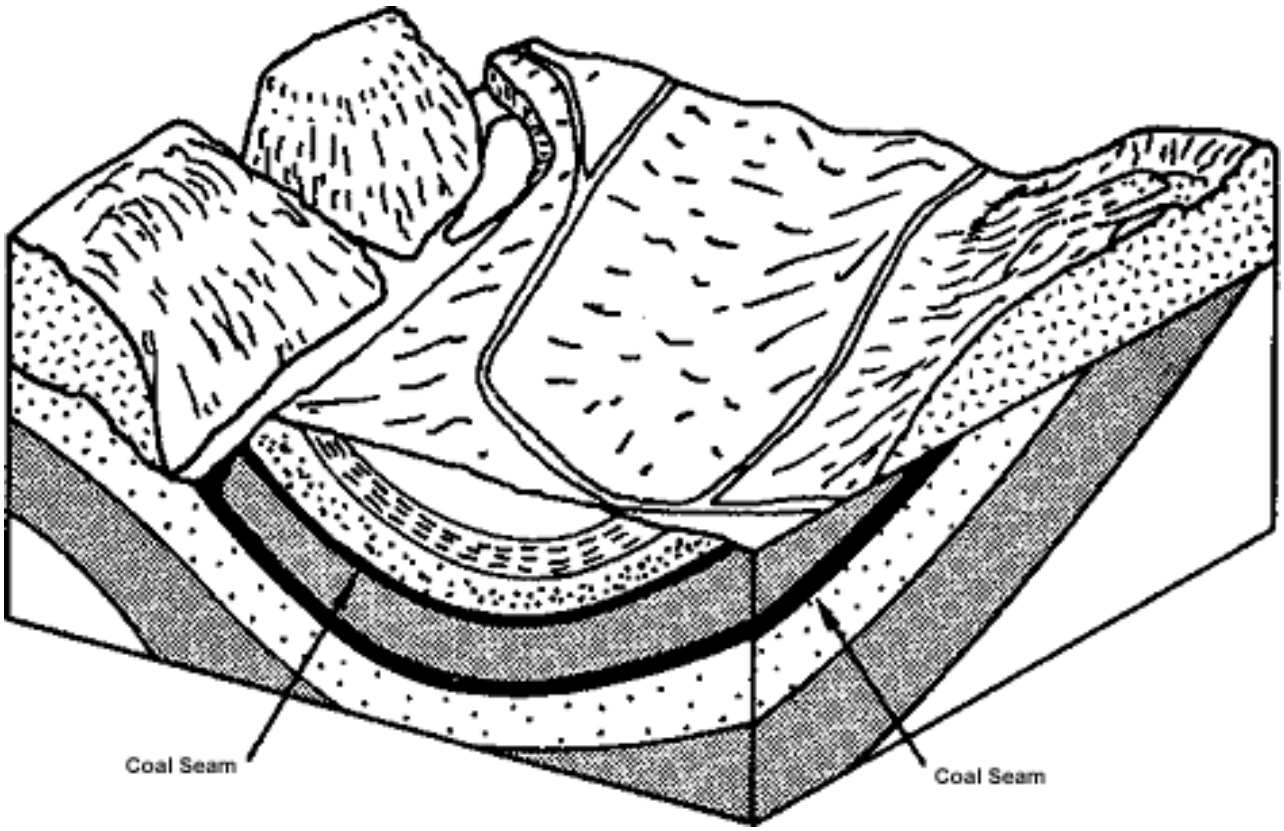
Figure VI-2.— Hydrologic setting for confining bed separating aquifer from coal bed (HS-B). (Modified from Hounslow and Fitzpatrick, 1978, fig. 59)



Saturated coal bed in contact with a water-table aquifer composed of alluvial deposits.

Coal-mining operations will be wet.

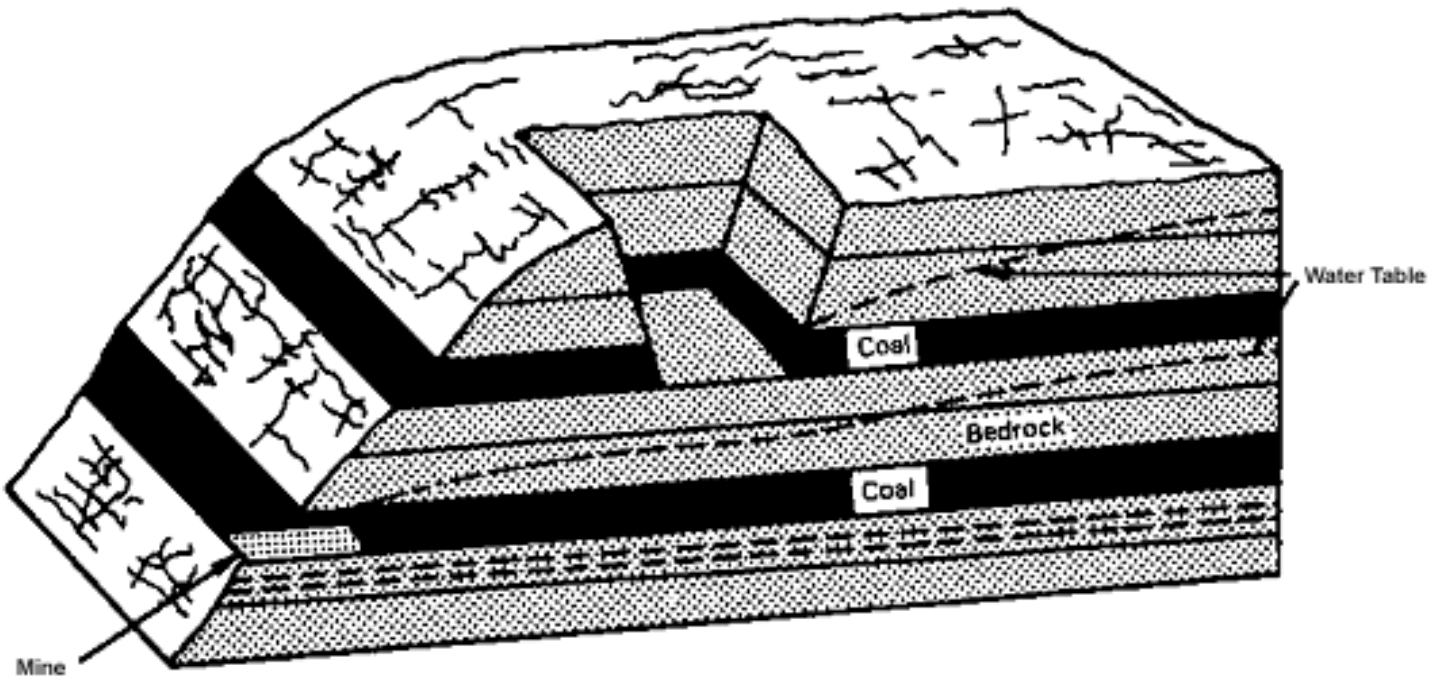
Figure VI-3.—Hydrologic setting for coal bed in contact with saturated unconsolidated deposits (HS-C).
(Modified from National Research Council, 1981, fig. 4.5e)

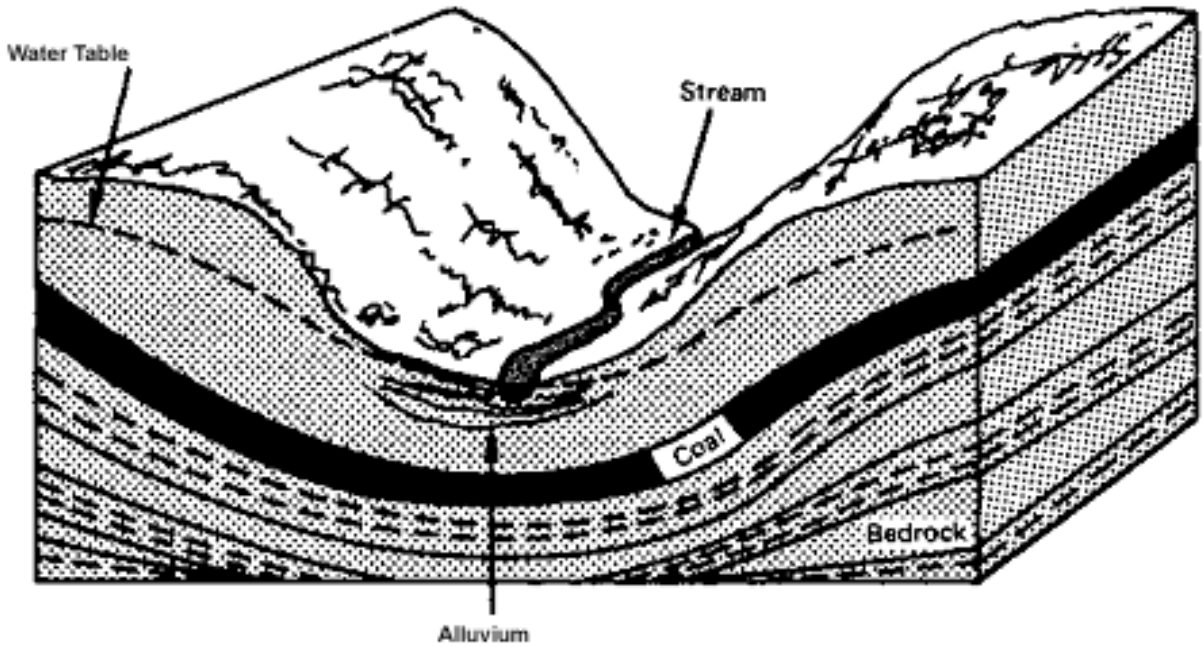


Saturated coal bed in contact with overlying
or underlying confined bedrock aquifer.

Coal mining operations will be wet.

Figure VI-4.— Hydrologic setting for coal bed in contact with confined bedrock aquifer (HS-D). (Modified from Hounslow and Fitzpatrice, 1978, fig.40)

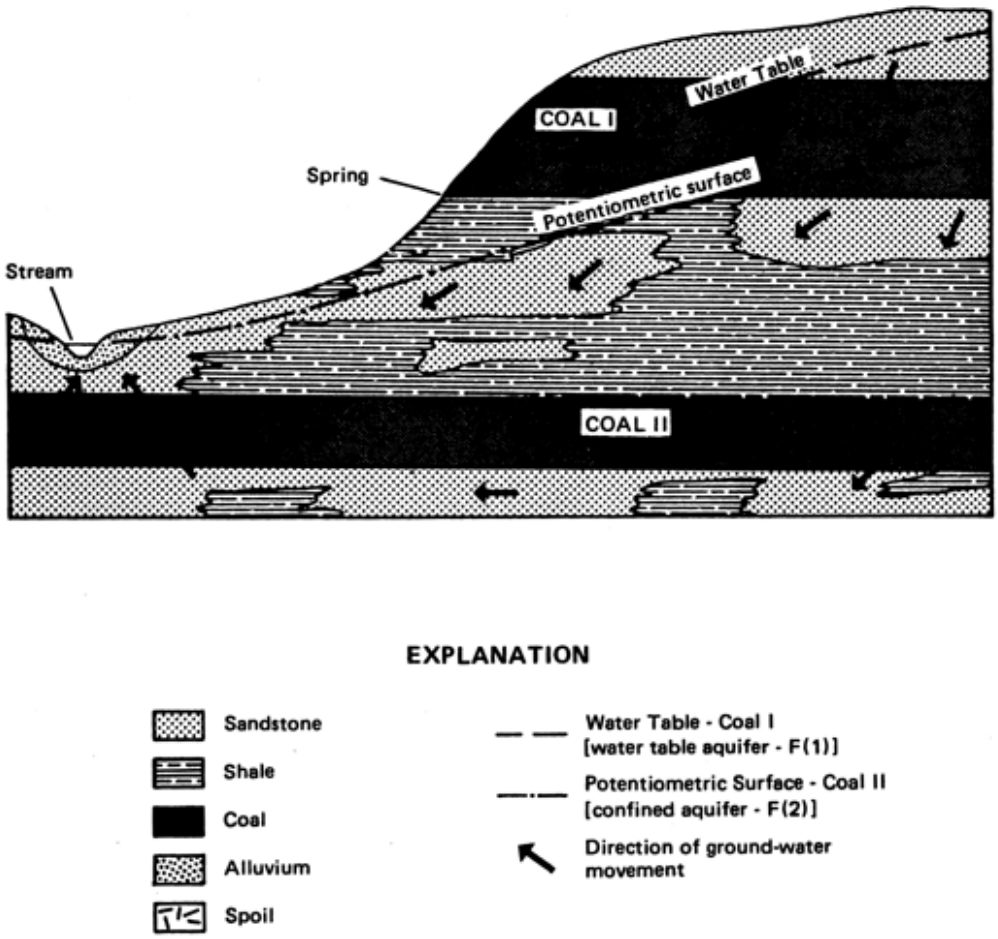




Saturated coal bed in contact with a water-table bedrock aquifer.

Coal mining operations will be wet.

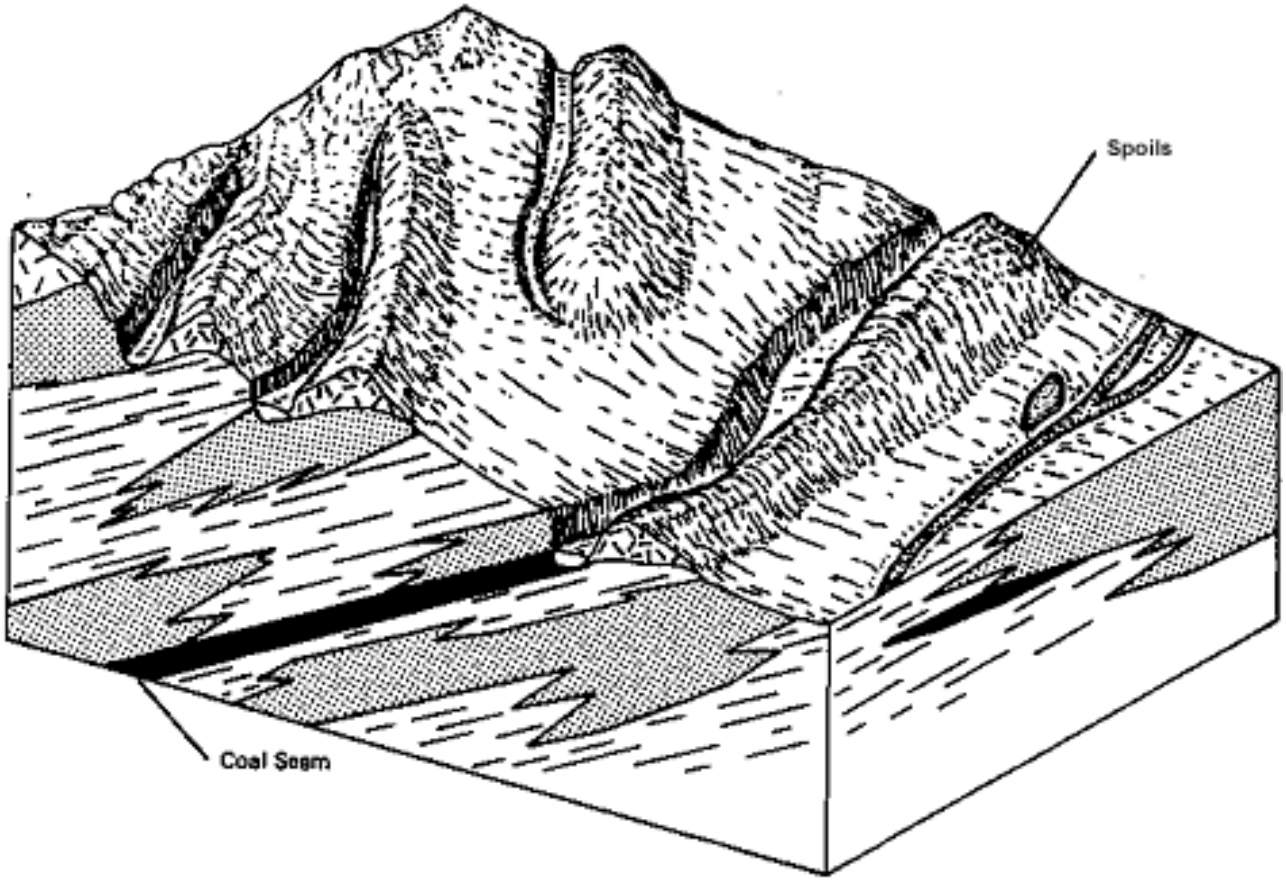
Figure VI-5.— Hydrologic setting for coal bed in contact with water table bedrock aquifer (HS-E).
(From National Research Council, 1981, figs.4.5a and 4.5c)



<u>Coal bed is an aquifer that may or may not be hydraulically connected to adjacent aquifers</u>.

Setting is F(l) if the coal bed is a confined aquifer; setting is F(2) if the coal bed is a water-table aquifer. Coal mining operations will be wet.

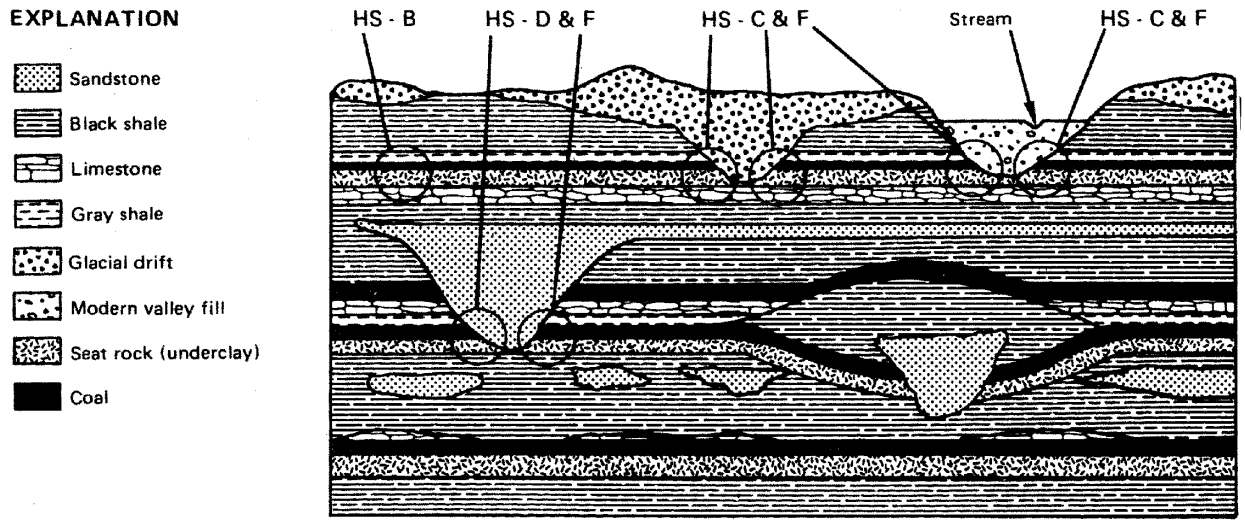
Figure VI-6.— Hydrologic setting for coal bed as an aquifer (HS-F).
(Modified from Slagle and others, 1981, fig. 10.3-1)



Coal bed within a multilayered aquifer system that consists of differing rock types of variable thickness and lateral extent.

Coal mining operations will be generally wet.

Figure VI-7.— Hydrologic setting for coal bed within a multilayered aguifer system (HS-G). (Modified from Hounslow and Fitzpatrick, 1978, fig. 44)



The hydrologic settings for various mining conditions in geologic settings GS-1 (flat-lying coal bed) and GS-5 or 6 (coal bed under stream valley), are indicated by circles and described below:

HS-B & HS-F, Coal bed is overlain by shale and underlain by seat rock or underclay and probably will be saturated as a result of intersecting joints produced by the bending of the sedimentary rock sequence.

HS-C & HS-F, Coal bed is saturated and in hydraulic contact with modern valley fill and glacial-drift deposits. HS-C at the stream site will present an excavation-dewatering problem because the saturated valley fill (alluvium) deposits are thick and the stream is in hydraulic contact with the alluvium. The valley-fill deposits typically transmit larger quantities of ground water than the glacial drift.

HS-D & HS-F, Coal bed is saturated and in contact with a confined sandstone aquifer. Ground-water flow from small sandstone "washout" deposit will present a short duration dewatering problem. The HS-D setting could have prolonged ground-water flow, owing to the regional extent of the sandstone aquifer. The areal extent of the aquifer would be defined from the coal-resource-evaluation drilling program.

Figure VI-8.— Distribution of coal seams in selected geologic and hydrologic settings. (Detail of Figure III-2c).
(Modified from Cassidy, 1973, fig. 12)

VII. WELL AND SPRING INVENTORY, AND GROUND-WATER USE

Pertinent 30CFR[1] Sections:

- Ground-water information
- Cross sections, maps, and plans.
- Protection of hydrologic balance.

One of the requirements of the regulations is the determination of current ground-water uses in the vicinity of a proposed permit area. The objective of this requirement is to define the premining ground-water uses and any potential responses of the aquifer system(s) to the ground-water withdrawals. The uses could be withdrawals from wells, springs, and from excavation-related dewatering operations.

The applicant can obtain information on well and springs from State agencies, such as State Geological Surveys, Departments of Natural Resources, and State Engineer's Offices, and from Federal agencies such as Soil Conservation Service and U.S. Geological Survey. Not all privately drilled wells are recorded, however, and changes in well construction or location are often not officially recorded. The applicant can also obtain well information from local well drillers.

All active wells in the permit area and adjacent area that are withdrawing ground water should be inventoried. When all premining withdrawals are defined and documented, the effects of active mining on the aquifer(s) can be compared with other discharging and recharging effects on the aquifer(s).

Types of information needed for water-well inventories are listed in table VII-1. An example of a water-well inventory at the surface-mine near Decker, Mont., is presented in table VII-2. The location map of inventoried wells within and adjacent to the proposed permit area is shown in figure VII-1. As noted in table VII-2, minimum ground-water-quality information was obtained through specific conductance measurements and selected chemical analyses. Results of these analyses are presented in table VII-3.

Types of information needed for spring inventory are presented in table VII-4. An example of the records of springs and mine discharges is presented in table VII-5. Attention must be paid to the time or period of measurement; for example, no-flow conditions of springs are commonly related to seasonally dry conditions. Routine monitoring of spring discharges in the adjacent and general area, throughout the year, will indicate to the applicant and spring owner the nature of spring flow. This flow could be affected by seasonal variations as well as by mining operations.

[1]CFR= Code of Federal regulations

Table VII-1.– Types of information needed for well inventory
(Example of well inventory data is given in Table VII-2.)

1. Location of well on a planimetric map, such as necessary for the proposed mine-permit application, or on a U.S. Geological Survey 7½-minute topographic map.
2. Well owner's name and address.
3. Use of well water (stock, domestic, irrigation, commercial, industrial, not in use, or abandoned).
4. Quantity of ground-water pumped (monthly, annually)
5. Depth of well below land surface, with the recorded source of information, such as well owner, driller, or hydrologist.
6. Date well was drilled
7. Land surface elevation or altitude (from topographic map).
8. Water-level information:
   - depth to water below land surface,
   - date of water-level measurement,
   - name of measurer,
   - description of measuring point,
   - the record of historic water-level measurement data.
9. Diameter and type of casing.
10. Depth to which the well is cased.
11. Sealing or grouting of casing, if any.
12. Depth range(s) of perforated casing or screen, if any.
13. Depth setting for pump intake, if applicable.
14. Specific capacity of well as measured by driller or hydrologist, if performed.
15. Size and type of pump.
16. "Normal" yield or discharge, not necessarily as reported by driller,
17. Aquifer designation; or aquifers pumped from if more than one.
18. Other available information:
    - driller's log,
    - chemical analysis and sampling date
    - specific conductance measurement(s) and dates
    - aquifer-test results, including discharge, date, static water level, length of test, and method of anaylsis.

Table VII-2.– Example of water-well data for the Decker mine area, Montana. (From VanVoast and Hedges, 1975, p. 11)

[Location: Township, Range, Section with quarter-quarter-quarter subdivision. (refer to referenced report for well location details)
Altitude: Land surface elevation at well estimated from U.S.G.S. 7½-minute quadrangle topographic maps, accurate to 10 ft.
Aquifer: Interpretations by Montana Bureau of Mines and, Geology. Coded sources D-l Cl = D-l Clinker:Sub D-2 = unspecified aquifers below mineable coal beds.
Depth to water: Depths to nearest 0.1 foot measured; depths to nearest 1.0 foot reported; + indicates flowing well.
Discharge: gal/min, gallons per minute to nearest 0.1 measured; gal/min to nearest 1.0 reported.
Drawdown: Drawdown (at indicated discharge) to nearest 0.1 foot, measured; drawdown to nearest 1.0 foot, reported.
Specific Conductance: Field electrical conductance of water, in micronhos per centimeter at 25° C; L indicates laboratory conductance.
Data source: MBMG, Montana Bureau of Mines and Geology; USGS, U.S. Geological Survey.
Water analyses: refer to water quality table in referenced report.]

Location	Water use	Altitude (feet)	Well Depth (feet)	Aquifer	Depth to water (feet)	Discharge (gal/min)	Drawdown (feet)	Specific conductance (umho/cm)	Data source	Water analysis
9S 39E 14DCBB	Unused	3,647	391	Sub D-2	160.9	-	-	4,000	USGS	
9S 39E 24DCDC	Unused	3,610	244	D-l & D-2 Coal	106	10	-	-	MBMG	
9S 39E 24ACDA	Unused	3,590	235	D-l & D-2 Coal	88	10	-	-	MBMG	
9S 39E 25DDC	Stock	-	150	D-l Overburden	-	10	-	-	USGS	
9S 40E 01CCA	Stock	3,445	125	D-2 Coal	26.4	-	-	1,900	USGS	
9S 40E 03ACAB	Stock	3,424	200	Sub D-2	+	33	-	1,380	MBMG	yes
9S 40E 03DCA	Stock	3,440	462	Sub D-2	3	4	44	-	USGS	
9S 40E 04CDAB	Stock	3,542	-	D-2 Coal	95	10	-	3,980	MBMG	
9S 40E 05BACC	Stock	3,580	260	Sub D-2	70	6	-	2,000	MBMG	
9S 40E 07CCAB	Stock	3,720	274	D-l Coal & Overburden	138	50	-	-	MBMG	
9S 40E 10CDDD	Industr'l.	3,465	498	Sub D-2	29	60	88.5	-	MBMG	
9S 40E 10DDBA	Industr'l.	3,452	160	D-2 Coal & Sub D-2	23	20	6	1,714L	MBMG	yes
9S 40E 11ADA	Stock	3,430	32	D-l Lower Coal	17.5	-	-	1,750	USGS	
9S 40E 13CAAA	Stock	3,500	108	D-l Upper Coal	63.4	-	-	2,400	USGS	
9S 40E 13DCCD	Stock	3,520	75	D-l Overburden	31.2	-	-	925	USGS	
9S 40E 21CACD	Domestic	3,554	110	D-l Overburden	-	-	-	5,010	MBMG	yes
9S 40E 21CCDB	Unused	3,642	200	D-l Overburden	131.6	-	-	-	MBMG	
9S 40E 21CDAC	Unused	3,565	280	D-l Coal	123	-	-	2,700	MBMG	
9S 40E 21CDBB	Domestic	3,578	-	Unknown	-	-	-	-	MBMG	
9S 40E 21CDBD	Commerc'l.	3,574	227	D-l Coal	117	5	73	1,570	MBMG	yes
9S 40E 21DDBA	Stock	3,502	171	Sandstone	26	20	39	4,500	MBMG	
9S 40E 22DAAD	Stock	3,455	269	D-l Coal	40.7	5	-	2,500	USGS	yes
9S 40E 22DADA	Domestic	3,460	170	D-l Coal	41	-	-	2,340	MBMG	yes
9S 40E 24ABBB	Stock	3,520	140	D-l Upper Coal	82	5	48	-	USGS	
9S 40E 26BADD	Stock	3,490	40	Above mineable beds	15	36	15	2,200	MBMG	

Table VII-3.– Example of chemical analyses of waters from wells in the Decker area southeastern Montana. (From Van Voast and Hodges, 1975, table 3.)

[Concentrations in milligrams per liter; analyses by Montana Bureau of Mines and Geology water laboratory, Butte, MT.
Collecting agency: MBMG, Montana Bureau of Mines and Geology; USGS, U. S. Geological Survey.
Aquifer: Interpretation by MBMG. Coded Sources— Al, Alluvium; D-l 0, D-l Overburden; D-l C, D-l Coal; D-l Cl, D-l Clinker; D-2 C, D-2 Coal; Sub D-2, Unspecified aquifers below the mineable beds.]

Location	Well depth (feet)	Date of collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Hydroxide (OH)	Alkalinity as $CaCO_3$	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (calculated)	Hardness as $CaCO_3$: Carbonate	Hardness as $CaCO_3$: Noncarbonate	Sodium adsorption ratio	Specific Conductance (microsiemens per centimeter at 25°C)	pH (laboratory)	Temperature (°C.)	Collecting agency	Aquifer
8S.39E.12ACB$_1$	141	07-18-74	12.0	0.00	0.01	31	23	261	7.5	426	9	0	381	367	5.3	2.2	1.5	1,146.0	173	0	8.6	1,419	8.46	12.5	USGS	Sub D-2
8S.39E.12ACB$_2$	370	07-18-74	9.3	.00	.00	7.8	3.6	460	4.3	455	33	0	482	553	6.5	4.0	5.6	1,541.5	34	0	34.3	2,041	8.74	12.0	USGS	Sub D-2
8S.39E.13BBC	348	07-29-74	15.4	.00	.12	156	198	542	13.8	859	0	0	705	1,523	15.3	.8	58.6	3,382.5	705	507	6.8	3,690	7.44	10.0	USGS	D-1&D-2C
8S.39E.14CBBD	-	10-13-73	14.2	.05	.04	89	70	112	7.5	507	0	0	416	327	6.5	.3	1.5	1,135.1	416	97	2.2	1,190	7.88	12.0	USGS	unknown
8S.40E.11CAA	14	07-17-74	21.3	.00	.00	85	57	36	8.1	420	0	0	344	176	6.8	1.0	1.3	812.1	344	102	.7	920	7.64	13.5	USGS	Al
8S.40E.33ACDB	-	10-11-73	13.2	.03	.05	130	72	178	12.4	347	0	0	285	703	5.7	.3	6.0	1,468.6	285	336	3.1	1,610	7.74	10.5	USGS	D-2 C
8S.40E.34BDAA	53	10-11-73	27.8	.02	.02	40	65	75	8.9	198	0	0	163	347	4.4	.5	5.5	773.0	163	210	1.7	927	7.76	12.0	USGS	D-1 Cl
8S.41E.21CABC	99	10-17-73	32.6	.00	.00	24	32	60	5.6	215	0	0	176	142	7.4	1.8	5.9	526.3	176	17	1.9	638	8.21	15.0	USGS	D-1 Cl
9S.39E.14BDAD	185+	10-17-73	8.8	.00	.00	2.6	0.8	354	4.0	870	28	0	808	10	3.5	2.8	4.4	1,289.4	10	0	48.7	1,370	8.82	14.0	USGS	D-1&D-2C
9S.40E.03ACAB	200	05-02-75	9.1	.01	.00	2	0.6	350	3.2	933	0	0	765	1	3.9	4	.3	1,306.7	7	0	55.8	1,340	8.03	12.0	MBMG	Sub D-2
9S.40E.10DDBA	160	11-17-71	4.0	.04	.00	5.7	0.4	443	6.6	1,190	0	0	976	4	7.1	3.6	0.1	1,666.0	16	0	48.5	1,714	8.09	10.5	MBMG	D-2 C
9S.40E.17ACAC	180	07-14-72	9.0	4.00	.02	3.8	1.6	500	4.1	953	18	0	843	273	5.1	2.9	6.4	1,870.0	16	0	54.4	1,870	8.69	12.0	MBMG	D-1 C
9S.40E.21CACD	110	10-14-72	8.6	.02	.03	31	13	1,355	9.4	996	19	0	1,701	1,320	16.4	.4	32.0	4,801.4	132	0	51.3	5,060	8.40	15.0	MBMG	D-1 O
9S.40E.21CDBD	227	07-14-72	9.0	.09	.00	6	0.4	450	3.7	1,139	23	0	1,012	8	16.2	2.6	.0	1,658.8	17	0	47.8	1,660	8.52	13.0	MBMG	D-1 C
9S.40E.22DAAD	169	10-18-73	9.4	.00	.01	17.7	22	710	7.8	1,578	51	0	1,466	275	35.0	.9	8.8	2,716.4	135	0	26.7	2,840	8.43	10.0	USGS	D-1 C
9S.40E.22DADA	170	08-17-72	7.6	.00	.00	5.9	8.4	616	5.4	1,416	127	0	1,586	8	13.2	1.9	10.0	2,219.4	50	0	38.2	2,340	9.10	10.0	MBMG	D-1 C
9S.40E.29CCAD	153	07-27-72	8.0	.00	.00	3.2	1.6	455	3.7	985	102	0	1,147	22	14.4	2.2	.0	1,596.2	14	0	52.2	1,740	9.50	10.9	MBMG	D-1 C
9S.41E.09ACBC	29	10-14-73	27.0	.01	.01	86	185	350	11.5	626	0	0	514	1,152	11.0	.3	7.5	2,457.2	514	447	4.9	2,620	7.88	10.5	USGS	Al

Table VII-4.– Types of information needed for a spring-inventory

1. Location of spring on a planimetric map, such as necessary for the proposed mine-permit application, or on a U.S. Geological Survey 7½-minute topographic map.
2. Spring owner's name and address.
3. Use of spring water (stock, domestic, unused).
4. Quantity of spring water used, and time distribution of useage.
   Does it stop flowing? what month? or, Is it perennial?
5. Spring discharge measurement and date of measurement; range of discharge by month over the year.
6. Chemical analyses and date of water sampling; specific conductance measurement and date of measurement.
7. Type of spring (perched, contact, fracture).
8. Aquifer designation (for example, Dakota sandstone, Ogallala Formation, Quaternary alluvium)

Table VII-5 – Records of springs and mine discharges in Clarion River and Redbank Creek Basins, Northwestern Pennsylvania.
(From Buckwalter and others, 1979, table 2.)

[Spring or mine-discharge number: AR, Armstrong County; CR, Clarion County; CF, Clearfield County; EK, Elk County; JE, Jefferson County; SP, spring; MD, mine discharge.
Location: Lat.-long., latitude and longitude in degrees and minutes of the southeast corner of a one-minute quadrangle within which the? spring or mine discharge is located.
Use: H, household; P, public supply; R, recreation — swimming; S, stock; U, unused. Altitude of land surface: Estimated from topographic maps feet above sea level; ft, feet. Discharge: gal/min (gallons per minute).
Temperature: ˚C, degrees Celsius.
Hardness: gr/gal, grains per gallon; (conversion factor - 17.1 milligrams per liter for each grain per gallon) Specific conductance: umho/cm, micromhos per centimeter at 25˚C.
Iron dissolved: mg/L (milligrams per liter)
Aquifer: QAL, Alluvium; QCL, Colluviurn; PCG, Glenshaw Formation of the Conemaugh Group; PA, Allegheny Group; PP, Pottsville Group; ML, Lower Mississippian Series; DO, Oswayo Formation.]

Spring or mine-discharge number	Location latitude-longitude	Owner or name	Use	Altitude of land surface (ft)	Aquifer	Yield Discharge (gal/min)	Yield date	Temperature (°C)	Hardness (gr/gal)	Specific conductance (umho/cm)	pH	Iron dissolved (mg/L)
AR-SP- 2	4059-7920	Seneca Trail	P	1,220	PA	6	4-14-72	8.3	17	558	5.7	0.04
CR-SP- 1	4105-7940	(unknown)	H	950	PA	2	-	-	-	-	-	-
2	4118-7923	Huefner	P	1,300	QAL	43	4- 5-72	7.5	1	50	5.1	0
3	4119-7914	Mars Gas Co.	P	1,300	ML	53	4- 5-72	8.5	1	95	4.9	0
6	4113-7923	Lions Club	U	1,150	ML	8	4-25-72	9.8	21	610	4.2	.09
9	4111-7914	Lemonade	U	1,565	QCL	247	1-26-72	9.8	24	1,240	3.6	.50
33	4115-7921	State Game Land	U	1,360	PP	2	7- 2-73	21.0	290	7,000	3.0	141
34	4115-7922	do.	U	1,290	PP	10	7- 2-73	15.3	34	1,350	3.6	4.3
35	4116-7922	do.	U	1,370	PP	15	7-14-73	10.2	69	2,950	3.7	5.0
36	4119-7921	Lutz, Winfield	S	1,580	PA	4	3-13-75	6.7	-	135	3.9	.29
MD- 1	4104-7903	(unknown)	-	1,240	PA	<11	4-10-73	-	-	-	3.4	1.0
2	4104-7930	do.	-	1,235	PA	144	2-21-75	10.5	21	850	5.0	29
7	4105-7930	do.	-	1,250	PA	800	2-21-75	11.0	31	1,000	3.3	15
8	4102-7917	do.	-	1,280	PA	14	4-27-73	-	-	2,400	5.7	52
9	4105-7916	do.	-	1,390	PA	-	-	-	-	8,000	1.8	2,100
CF-SP- 1	4111-7942	Treasure Lake	U	1,850	PP	285	5-16-73	12.8	1	50	4.5	.26
2	4111-7942	do.	U	1,865	PP	124	5-16-73	7.0	1	40	6.7	.10
3	4111-7942	do.	U	1,875	PP	36	5-16-73	7.0	1	40	7.4	.10
EK-SP- 2	4131-7837	Bendigo State Pk.	R	1,740	PP	27	8-30-74	10.0	1	60	6.4	.03
JE-SP- 1	4105-7852	Reynoldsville Bor.	P	1,410	PA	100	10-11-29	7.2	2	-	-	.18
3	4108-7910	Carrier Homesite	U	1,430	PA	64	6- 5-73	-	-	-	-	-
MD- 1	4107-7857	(unknown)	U	1,800	PA	40	2- 6- 74	-	17	620	-	4.4

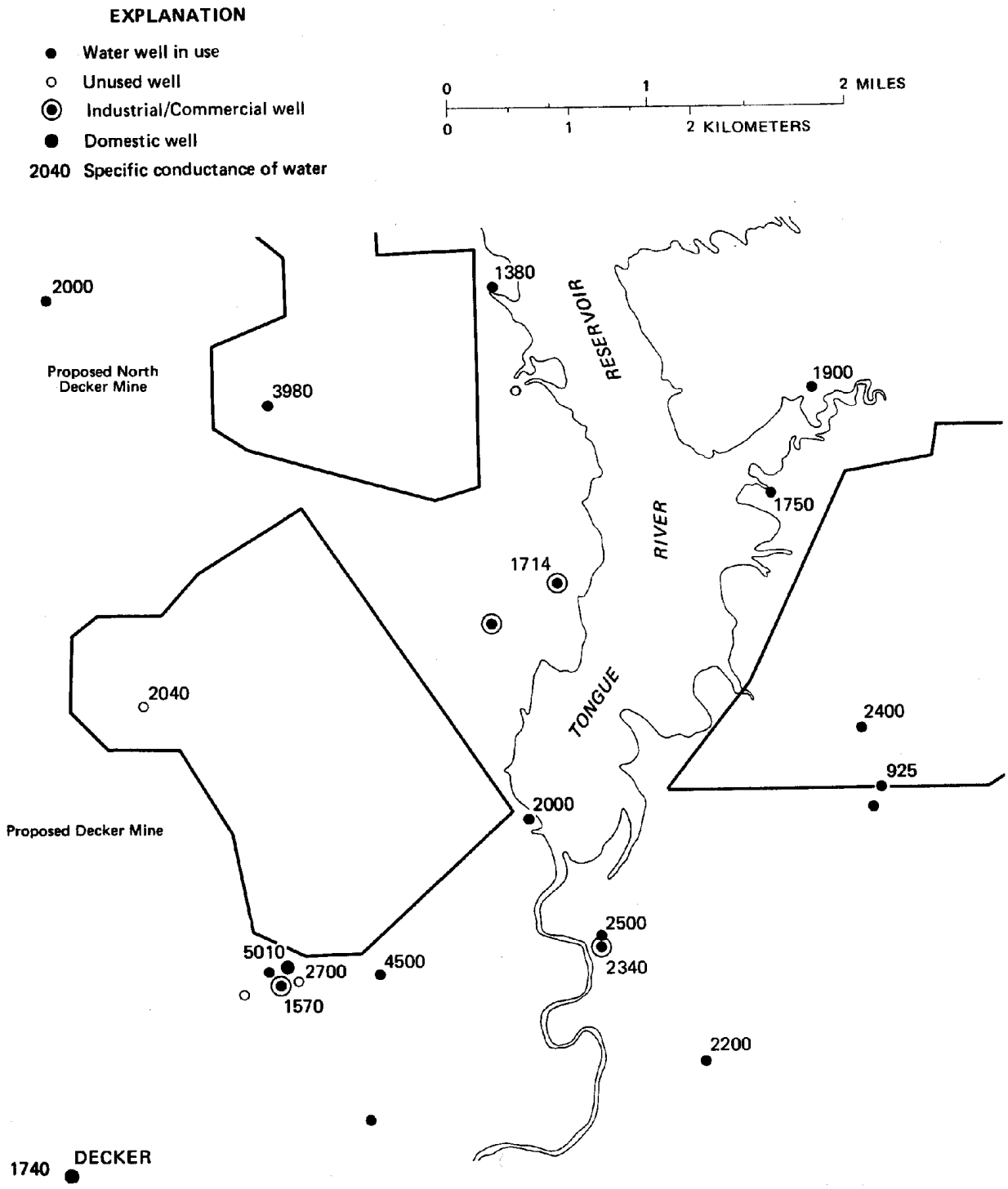


Figure VII-1.— Example map showing inventory of ground-water uses in permit area. (Modified from U.S. Geological Survey and. Montana Department of State Lands, 1977, fig. 43)

VIII. WELL DRILLING, COMPLETION, AND DEVELOPMENT; DRILLER'S LOGS

Pertinent 30CFR[1] sections:

Description of geology.
Ground-water information.
Cross sections, maps, and plans.

The geologic and hydrologic settings of the permit and adjacent areas, and the feasibility of mining them, are determined from the exploratory program (described in chapter XVI). The principal products from this program are geologic cross sections and potentiometric maps (described in chapter IX) based on data from drill holes and core borings. The maps and cross sections define:

(1) occurrence and areal extent of the coal reserves,
(2) aquifers above and below the coal seams,
(3) confining beds between the aquifers and the coal seams, and
(4) lithologic description of the overburden material to determine the acid-generating potential of the waste spoils by the acid-base accounting method.

During the drilling of the exploratory holes, the cores and cuttings are examined, recorded, and compiled on driller's logs, which are used to develop the cross section. Whenever practical, the water levels are measured during the drilling-rig "down time". Depending on the type of drilling method used, caution must be used in measuring water levels during this "down time". For example, if drilling mud is used, as in the rotary method, water-level measurements in mud-filled holes are not reliable. In cable-tool drilling, air rotary, and other methods that do not use drilling mud, measurements of water levels during rig "down time", may be more reliable. However, the length of "down time" should be considered, especially in materials of low permeability. The disturbance caused by removal of earth material and water during drilling, may require many hours for the water to return to levels that are representative of the aquifer.

Cross sections.—The most important features of the cross section (See example in fig. VIII-1) are the locations of the logs, the land-surface elevations of the: logs, the depth of the drill holes, the lithologic descriptions in the logs, and the depth to the final water level. Interpretation of the cross section indicates the geologic structure and the associated areal extent, variation of dip, and thickness of the coal seams. A planimetric or topographic map should accompany the cross section to show the location of the drill holes and core borings, the line of the cross section, the location of surface-water features, and the permit and adjacent areas.

Potentiometric maps.—If the water levels are representative of an aquifer, a potentiometric map should be drawn. If the water levels are indicative of a multiple-^aqiiifer system, additional water-level information may be needed before potentiometric maps can be drawn. The information from the map and cross sections aids in the definition of the occurrence, flow, and quality of ground water. Geohydrologic data may be compiled into a colunnar section such as the example in figure VIII-2, which is representative of the geohydrologic conditions of the permit area.

[1]CFR= Code of Federal Regulations

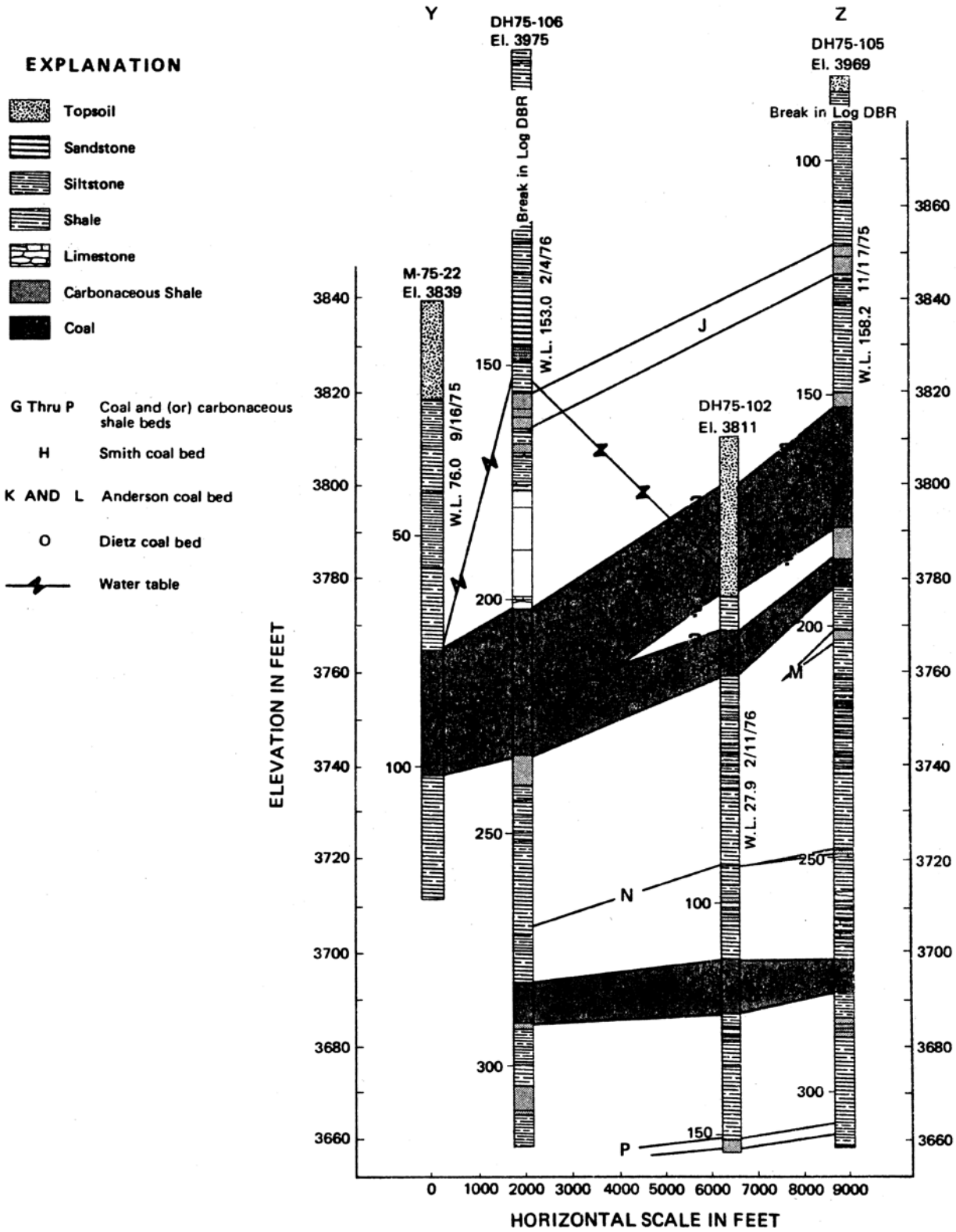
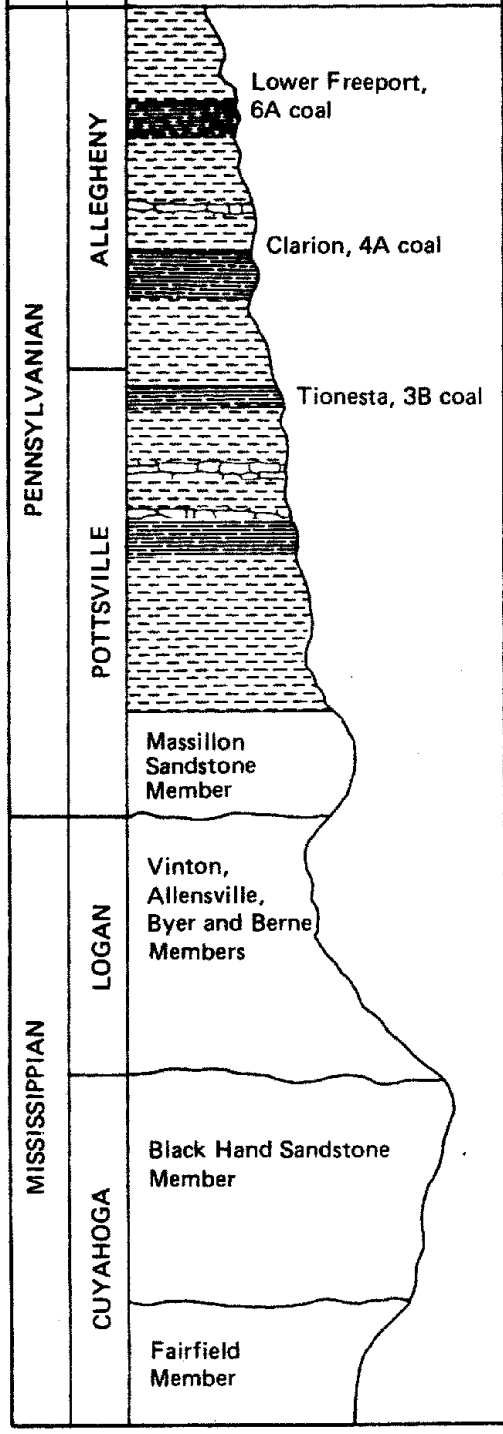


Figure VIII-1.— Example of geologic section derived from driller's logs. (Modified from U.S. Department of Interior, 1977b, p. 26)



SYSTEM	FORMATION	LITHOLOGY AND WEATHERING PROFILE	THICKNESS, IN FEET	AQUIFER GROUP	DESCRIPTION
PENNSYLVANIAN	ALLEGHENY		40 - 80	First	Thin soil, shale, sandstone
PENNSYLVANIAN	ALLEGHENY / POTTSVILLE		60 - 350	Second	Shale, chiefly with sandstone, thin limestone, iron stone, and coal
PENNSYLVANIAN	POTTSVILLE		10 - 60	Second	Fine grained sandstone
MISSISSIPPIAN	LOGAN		100 - 140	Confining bed	Shale, chiefly with interbedded sandstone and siltstone
MISSISSIPPIAN	CUYAHOGA		60 - 200	Third	Sandstone, coarse grained, cross bedded
MISSISSIPPIAN	CUYAHOGA			Confining bed	Shale

Figure VIII-2.— Example of columnar section of consolidated rocks showing arbitrary divisions into aquifer groups.
(Members follow the usage of the Ohio Geological Survey.)
(Modified from Norris, 1981, p. 28)

After the coal setting has been defined, the drilled or cored holes can be converted into wells, provided aquifers were penetrated. These wells could be used for water supply, water-level and water-quality monitoring, and aquifer testing to determine aquifer characteristics (as described in chapter X). Water-level montitoring and aquifer test information are necessary in the prediction and detection of potential hydrologic impacts due to mining (See chapter XIII).

The basis for selection of holes to be converted into wells includes ground-water availability, ease of access to well site for routine measuring, and site location relative to neighboring ground-water users, including adjacent active mining operations. The conversion of these exploratory holes to observation wells involves entails determination of the aquifer(s) to be monitored, well completion, including construction and development.

Well completion, construction, and development are important in aquifer testing and ground-water monitoring (See chapter XIV). If the wells are not in contact with the aquifer(s) and are not capable of responding to the variations in ground-water flow, the measured data will be of little value.

Well completion includes all activities after the drilling or coring of the hole, including construction and development. Well completion also includes the setting of perforated casing, or screening, at the center of the saturated thickness, and sealing off, by cement or clay grout, the space between the non-perforated casing and the drill-hole surface and the other aquifer groups not tested and monitored.

Well construction involves the selection of casing type (steel, plastic, or fiberglass); length of casing, both perforated and nonperforated; depths for setting the perforated casing; and casing diameter (2-, 4-, or 6-inch). The larger the casing diameter, the better the accessibility for testing and monitoring of water levels and quality.

Typical well construction designs are shown in figure VIII-3. In unconsolidated deposits, well completion within the top half of the saturated thickness is sufficient for monitoring purposes. However, the depth of monitoring wells is flexible, depending upon the proximity of the well to the mining operation. If the exploratory hole is to be converted to a large capacity water supply well, the full thickness of water-bearing material should be screened off. In bedrock aquifers, the well-completion screens are at the same depth as the water-bearing zones. If the bedrock is capable of maintaining an open hole, and if one aquifer is to be monitored, only surface casing needs to be cemented off.

Well development includes any and all operations necessary to remove the mud cake lining the drilled hole, and the mud and fines forced into the fractures and joints of the bedrock units. The mud and fines retard the ground-water flow into the drilled/cored hole. If the drill rig is used over the hole, the water can be overpumped to cause maximum water pressure on the mud and fines. Water can also be made to surge back and forth through the screen, gravel pack, and aquifer by means of surge blocks. Other development schemes include compressed air, hydraulic jetting, shooting of dynamite, and use of acids and polyphos-phates. Additional information on well completion, construction, and development can be found in references - Johnson Division, Inc., 1975, and U.S. Department of Interior, 1981a.

Well development is completed when the pumped water is clear and when successive periodic pH and specific conductance measurements (chapter XII) give identical results.

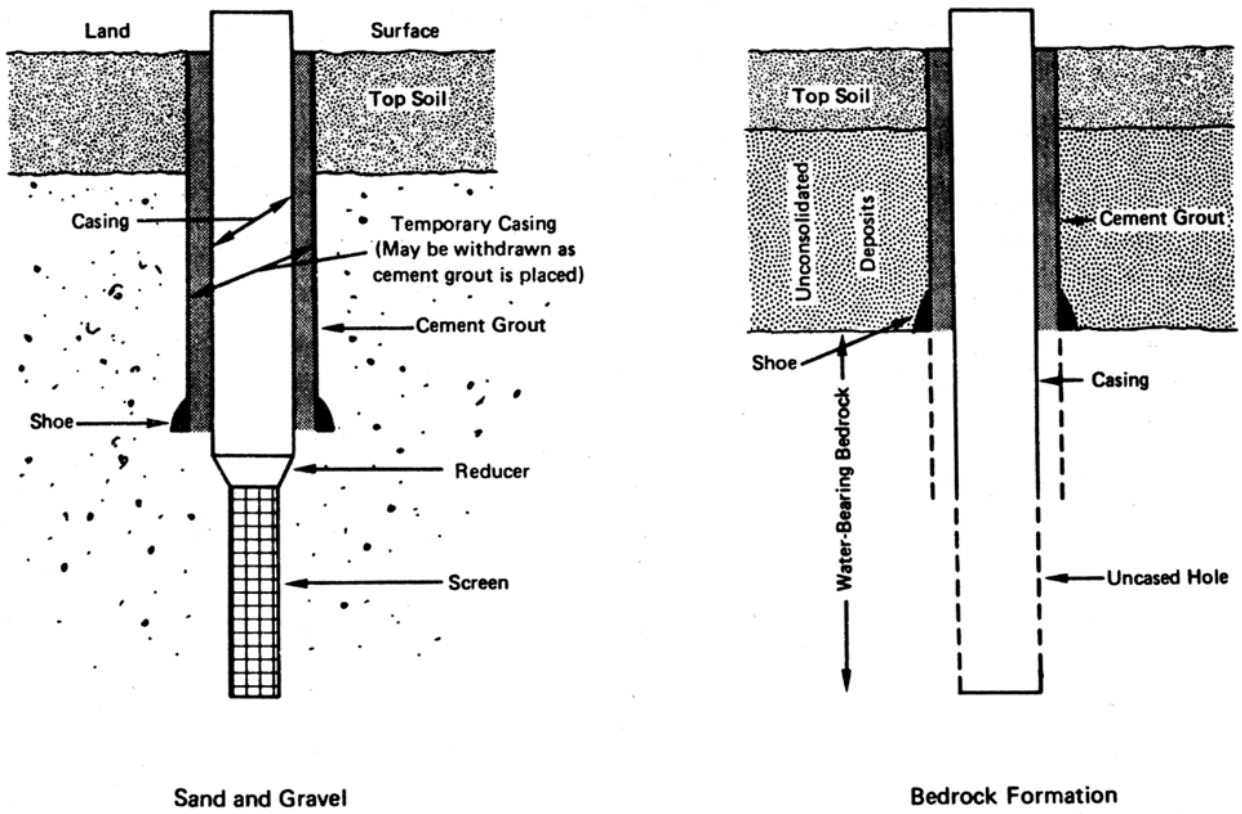


Figure VIII-3.— Typical well-construction designs.
(Modified from U.S. Department of Interior, 1981a, chapt. XI)

IX. WATER LEVELS IN WELLS AND WATER-LEVEL (POTENTIOMETRIC-SURFACE) MAPS

Pertinent 30CFR[1] Sections:

Description of hydrology and geology.
Ground-water information.
Cross sections, maps, and plans.
Hydrologic balance.

The definition of an aquifer system(s) and the direction of ground-water flow within these aquifers in the permit area and the vicinity involves the compilation and interpretation of water-level data. The most important indicators of ground water and of ground-water flow are water-level measurements in wells and the locations of springs. During well inventory (chapter VII) and during the test-drilling program (chapter XVI), water levels are measured and compiled together with veil depths and names of aquifers penetrated. Some exploratory wells and water-supply wells obtain water from more than one aquifer; water levels in these wells represent a composite potentiometric head of all aquifers penetrated and should not be included in the potentiometric map representing a single aquifer.

Water levels in wells may be determined with several measuring devices: weighted and chalked steel tape, electric cable, air line, sonic, and pressure transducers. The first three methods, described below, are the most common and are illustrated in figure IX-1.

Tape. — The tape is lowered into the well until the lower part intersects water. The wetted length of the tape is subtracted from the "held" length of the tape to determine the depth to water.

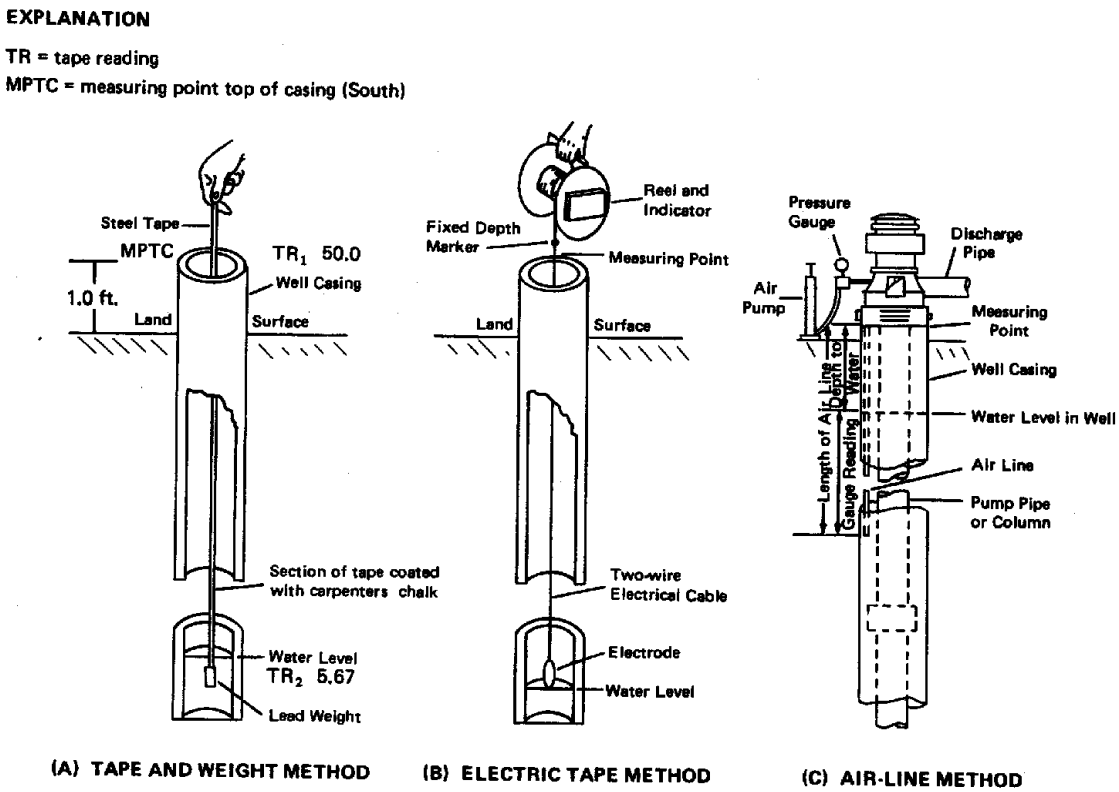
Electric cable. — This method consists of two parallel wires, insulated from each other, which close a circuit when they touch the water. This contact causes an anmeter needle to deflect. The insulated line is marked at 5-foot intervals, so that the depth to water can be determined with a carpenter's tape.

Air line. — This method is generally used only in wells on which pumps are installed. This method involves the installation of a small-diameter air line from the top of the well to about 10 ft below the lowest anticipated position of the water during the pumping test. Air is pumped into the air-line; and the pressure reading is subtracted from the air-line length to determine the depth to water.

A record of a water level measurement includes:

(1) The date and time of measurement.
(2) The intersection of the weighted steel tape with the water level in the well.
(3) The reading at the "held" part of the tape at the measuring point (MP) at a selected compass direction, such as, at an access hole, at the top of casing for an open hole, or at a hole in the pump base; for example, hole in pump base north side.
(4) The depth to water below the MP.
(5) The distance of the MP above or below the land surface elevation (LSE).
(6) Any other observations that might indicate the water level may be non static, such as the influence of a nearby well pumping, reported recent pumping of the observation well, or the sound of water cascading into the well, as from a fracture.

[1]CFR = Code of Federal Regulations



(a) Tape & Weight Method - Graduated steel tape lowered to belcw water level; wetted tape (TR2) subtracted from held tape at top of casing	(b) Electric Tape Method - Graduated electrical cable lowered until electrode contacts water surface; depth to water recorded at measuring point.	(c) Air-Line Method - Air pressure pumped into air line; pressure gage shows the height of water above end of air line, which is converted depth to water level.

Figure XI-1.— Three types of water-level measurement devices. (Modified from Heath, 1983, p. 72)

The water-level record shown in figure IX-2 indicates that on July 15, 1982, at 8:30 in the morning, I.M.User held the 50.0-ft mark at the top of the casing (south side), and chalked part of the tape was wetted to the 5.67-ft mark. The depth to water below the measuring point is 50.0 ft - 5.67 ft = 44.33 ft. Since the MP is 1.0 ft above land surface, the depth to water below the land surface is 44.33 ft - 1.0 ft = 43.33 ft. The LSE can be estimated from a 7½-minute topographic map or could be determined from surveying. For this well, the LSE is 3,456 ft. Therefore, the water level in this aquifer at well 3 was 3,413 ft on July 15, 1982. The other water-level measurements and remarks indicate the effects of nearby pumping.

If the waller level does not fluctuate with time, the well is probably plugged. A sinple test can be done to determine whether the well is responsive to the variations in hydrostatic head of the aquifer. A slug of good-quality water could be; poured into the casing to raise the water level. Should the water level decline within several hours, the well is probably not plugged. If the water level does not decline, the well is plugged and should not be measured further, unless steps are taken to open it.

WATER LEVEL MEASUREMENTS (fields)

COAL STRIP-MINE PERMIT APPLICATION

Measured by

Location of Project A-B-C South Forty Mine
Description of Measuring Point (MP). Top of Casing (South) 1.0 ft. above LS
Land Surface Elevation (LSE) - 3456 ft. (USGS 7½' Baden Quad.)

DATE	HOUR	WELL	TAPE READING AT MEAS PT	TAPE READING AT WAT LEV	DEPTH TO WATER MP BELOW	DEPTH TO WATER LS BELOW	REMARKS
1982			TR_1	TR_2			
7-15	0830	No. 3	50.0	5.67	44.33	43.33	irrigation well
							¼ mi. N. pumping
8-13	1630	No. 3	50.0	10.15	39.85	38.85	rain, no pumping
9-10	1415	No. 3	60.0	none	dry	dry	irrigation wells
							to North and South
							pumping
10-21	0915	No. 3	40.0	1.31	38.69	37.69	no pumping
11-30	1110	No.3	40.0	4.55	35.45	34.45	no pumping

Figure IX-2.— Typical water-level measurement form.
(In part from U.S. Department of Interior, 1981a, fig, 7-3)

A series of successive water levels plotted against time on a graph is called a hydrograph. The examples in figure IX-3 illustrate the natural fluctuation of ground-water levels in an observation well in eastern Kentucky. The monthly hydrograph for the 1974 water year illustrates the seasonal variation in depth to water and the direct response of the aquifer to precipitation. The 5-year hydrograph (1970-74) reflects natural water-level fluctuations. Most offices of the U.S. Geological Survey, State Geological Surveys, State Department of Natural Resources, or State Engineer's Offices, maintain recording observation-well programs.

Water levels fluctuate naturally in response to recharge to the aquifer, from streams and precipitation, and to discharge from the aquifer to streams, springs, wells, and evapotranspiration. The depth to water is dependent on many factors such as typographic position of the well, season, and hydraulic properties of the aquifer. Water levels are generally low in late summer or early fall because of the high evapotranspiration and the lack of recharge. Water levels are generally high in the spring because of recharge from snowmelt water and rain before the plants leaf out. Installation of strip-chart recorders on the well head enables continuous monitoring of water levels.

The directions of ground-water flow in a permit area are determined from a potentiometric map, which is a contour map depicting lines of equal ground-water elevations. This is done by compiling concurrent water-level measurements that have beer converted to potentiometric "heads" or elevations above a common datum and plotting them on a well-location planimetric map and drawing contours to connect the points of equal water levels. The flow moves downgradient at right angles to these contours. The water levels used for these maps are measured within a short period of time, generally a week; thus the potentiometric map is representative of the ground-water flow conditions for that particular time only. An example of a water-level compilation from which a potentiometric map could be drawn is presented in table IX-1 which gives the well number, the land-surface elevation, the aquifer designation, the premining water-level measurement and date, and the calculated potentiometric heads. A potenticmetric map drawn fran these data is illustrated in figure TX-4.

Water level changes through time may be presented in three ways — data tabulation, hydrograph, and water-level-change map. The sample data compilation table in IX-1 includes the measured depth to water below land surface at a Montana mine on June 4th, 1975, and the calculated water-level change from the premining water-level conditions. The 4-year hydrographs in figure IX-5 show the water-level declines due to dewatering in the same area. Figure TX-6 is a water-level-change map of two aquifers in the same area showing declines that resulted iron surface mining during a 3-year period.

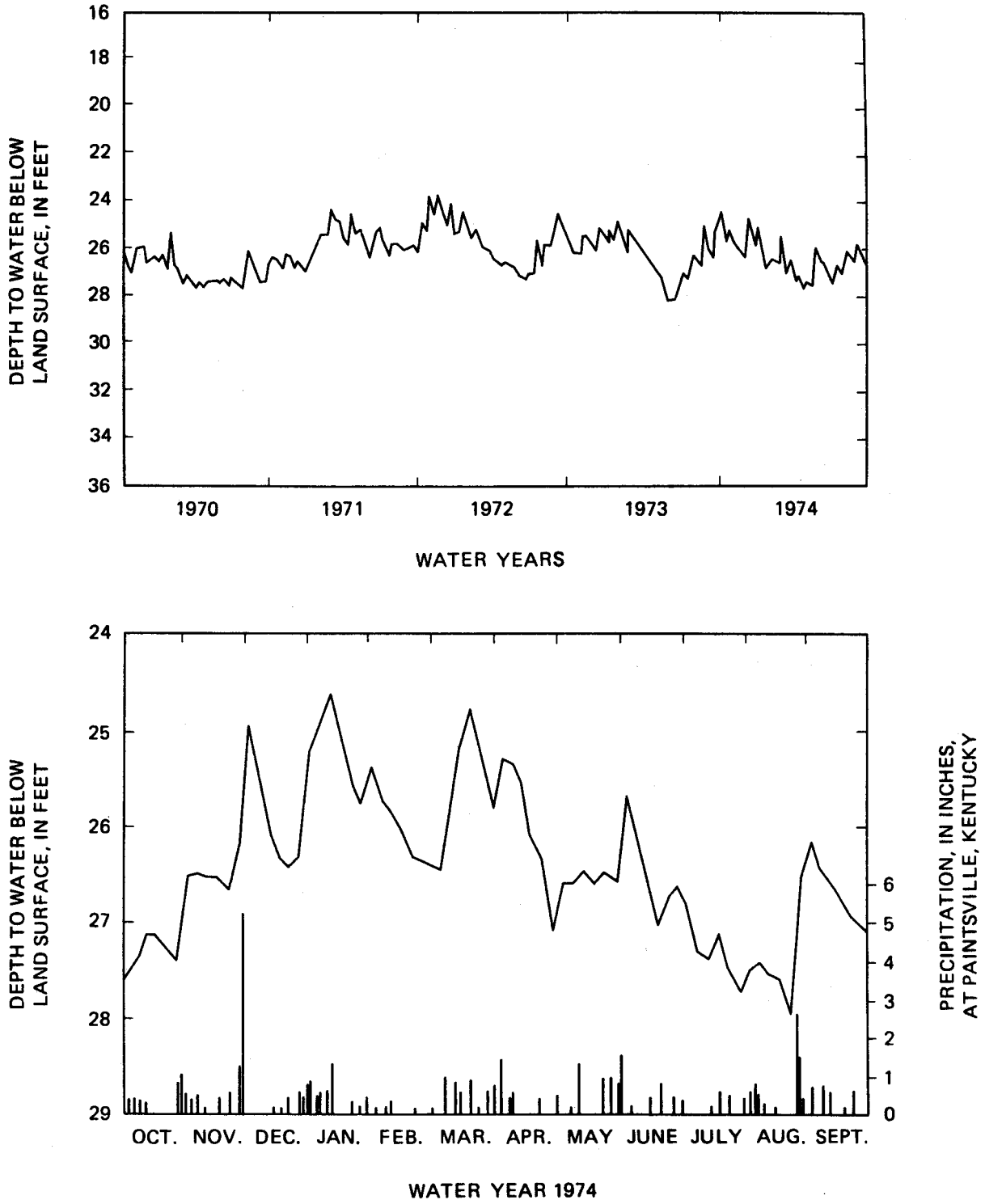


Figure IX-3.— Example of 5-year (long-term) hydrograph (above) and monthly hydrograph (below) for an observation well in eastern Kentucky, (From Kiesler and others, 1983, p. 57)

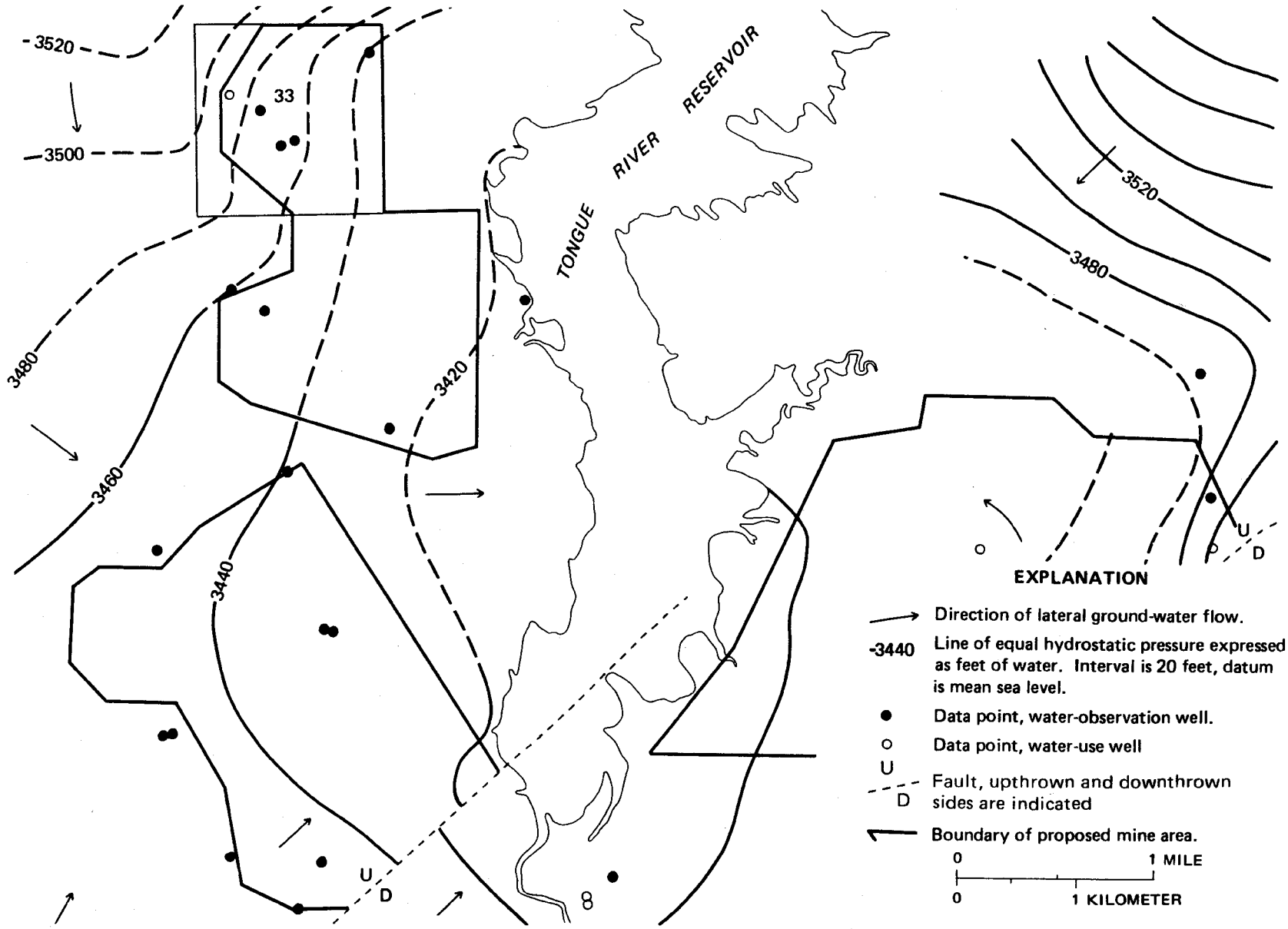


Figure IX-4.— Example of potentiometric map of D-1 coal aquifer in the Decker, Montana area, before mining, based on data such as in table IX-1. (From VanVoast and Hedges, 1975, pl. 4)

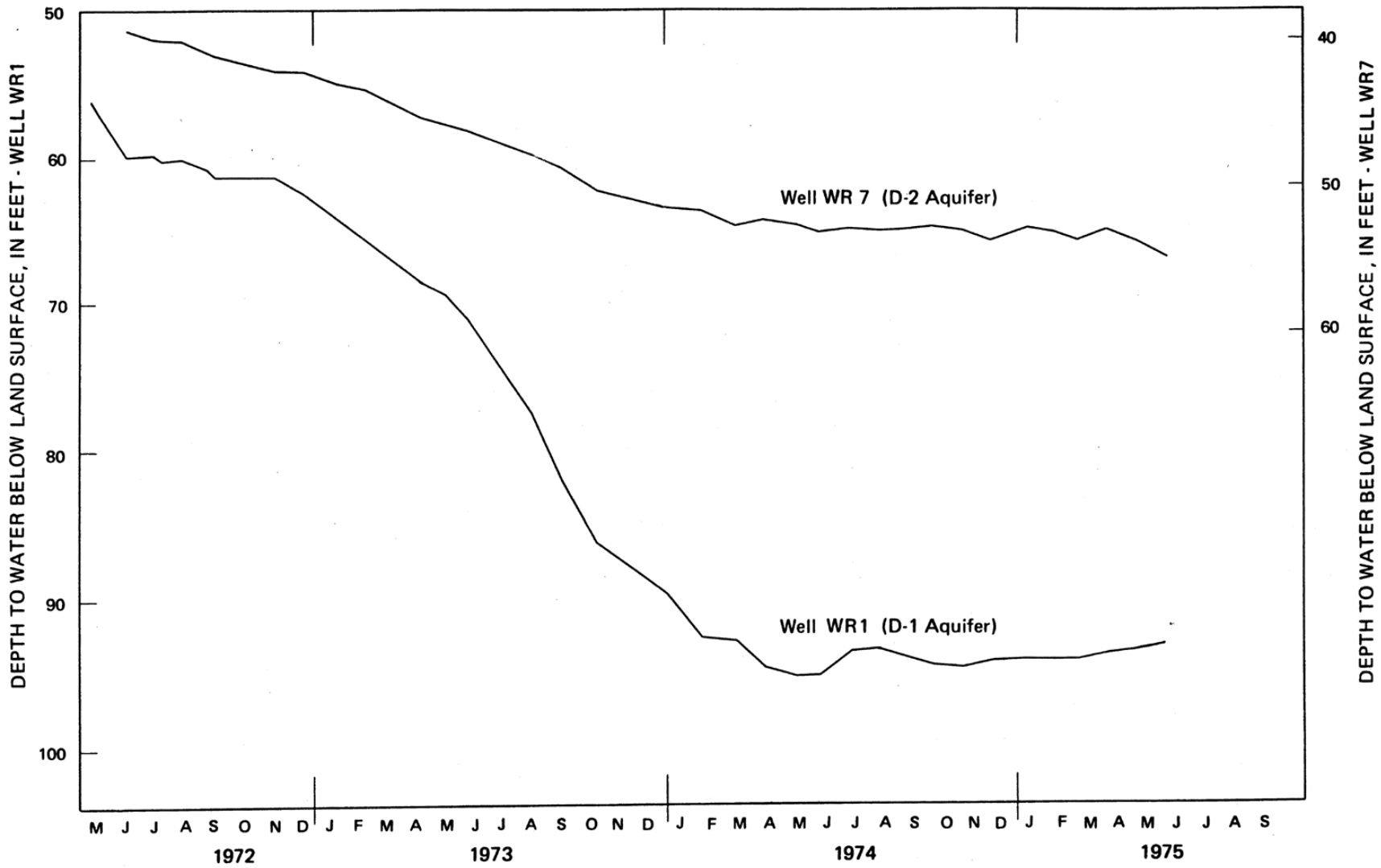


Figure IX-5.— Four-year hydrographs of observation wells near Decker, Montana, (Mine area is shown in figs. IX-4 and DC-6.) (Mining started in spring of 1972.) (Modified from VanVoast and Hedges, 1975, pl. 10)

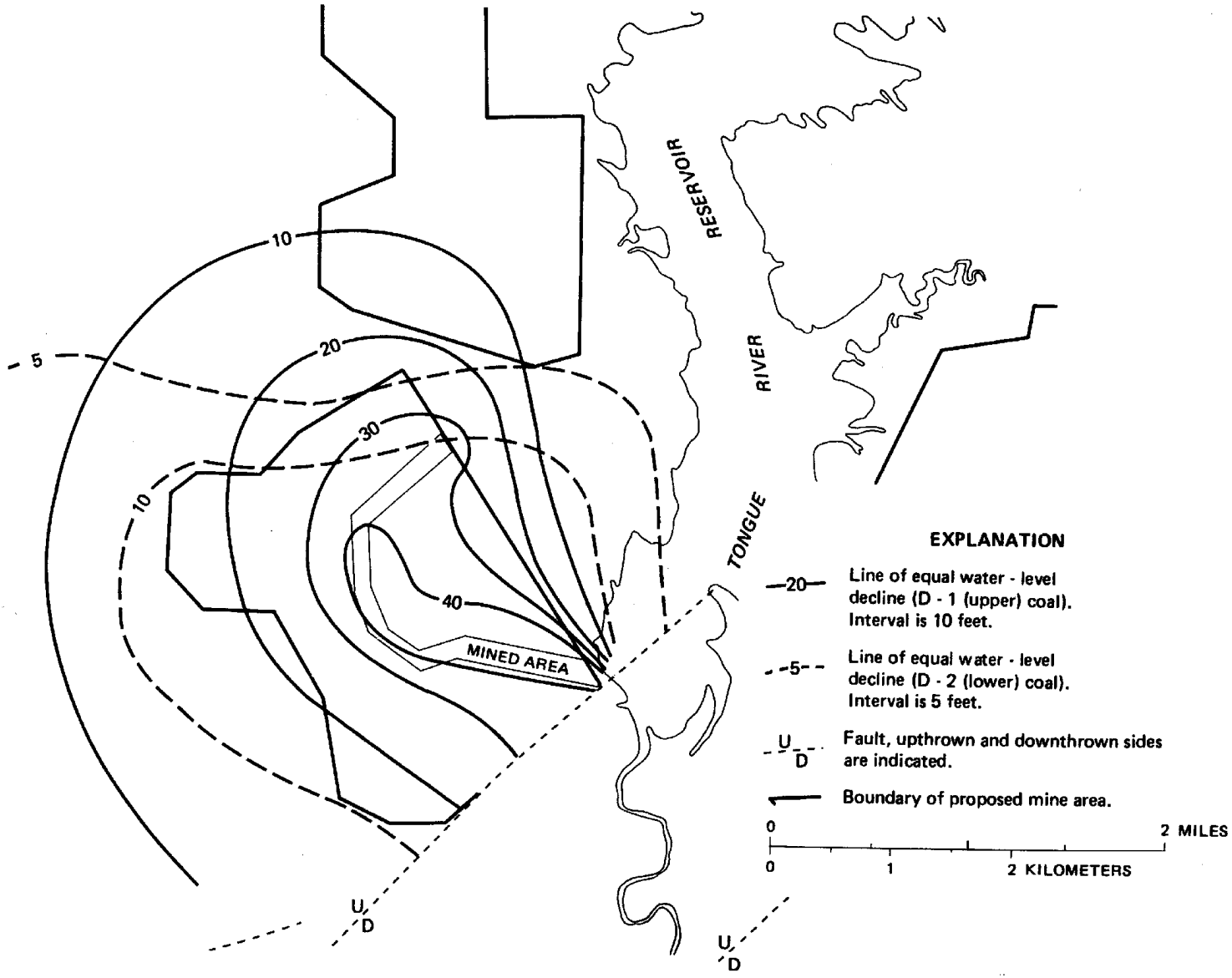


Figure IX-6.— Example of water-level change map in two aquifers near Decker, Montana after 3 years of surface mining.
(Modified from VanVoast and Hedges, 1975, pl. 9)

Table IX-1– Example of water-level data compilation for observation wells.
(From Van Voast & Hedges, 1975, table 5.)
[ft,feet]

Well number	Land surface elevation	Aquifer	Initial measurement: depth to water (ft below land surface)	Initial measurement: Date	Premining potentiometric surface elevation (ft above sea level)	June 4, 1975 depth to water (ft below land surface)	Water level decline (ft)
WR 1	3,498	D-1 Coal	56.12	8/10/70	3,442	93.12	-37.00
WR 3	3,612	D-1 Coal	159.23	11/24/70	3,453	180.57	-21.34
WR 4	3,585	D-1 Coal	134.51	3/30/71	3,450	156.87	-22.36
WR 6	3,499	D-1 Coal	55.97	6/12/71	3,443	92.57	-36.60
WR 7	3,498	D-2 Coal	39.24	6/21/72	3,459	54.58	-15.34
WR 8	3,537	D-1 Coal	90.41	9/30/72	3,447	111.29	-20.88
WR 9	3,537	D-2 Coal	67.64	9/30/72	3,469	80.48	-12.84
WR 10	3,537	D-1 Coal	92.46	9/26/72	3,445	111.95	-19.49
WR 11	3,575	D-1 Coal	128.25	9/26/72	3,447	146.94	-18.69
WR 12	3,586	D-1 Coal	138.99	9/26/72	3,447	158.77	-19.78
WR 13	3,592	D-2 Coal	152.20	9/26/72	3,440	156.50	- 4.30
WR 14	3,598	D-1 Coal	157.60	9/26/72	3,440	179.40	-21.80
WR 15	3,685	D-1 & 2 Coal	236.39	6/04/74	3,449	239.01	- 2.62
WR 16	3,640	D-1 & 2 Coal	184.00	6/04/74	3,456	188.20	- 4.20
WR 17	3,570	D-1 & 2 Coal	112.86	6/04/74	3,457	114.98	- 2.12

X. AQUIFER CHARACTERISTICS AND AQUIFER TESTING

Pertinent 30 CFR[1] Sections:

Description of hydrology and geology.

Ground-water information.

1. Aquifer Characteristics

The quantity and rate of ground-water discharge into a surface coal-mining excavation depend upon the hydraulic properties of the ground-water flow system near the excavation. The hydraulic properties include hydraulic conductivity (K), also called permeability, transmissivity (T), and storativity (S), which is the storage coefficient for confined aquifers and specific yield for water-table aquifers. Definitions of these properties are included in the glossary (chapter XVIII).

For steady-state ground-water flow conditions, the quantity of discharge (Q) is

$$Q = K\,I\,A \qquad \text{(x-1.0-1)}$$

where: K = hydraulic conductivity of the aquifer,

I = hydraulic gradient, and,

A = cross-sectional area of the aquifer perpendicular to the flow direction through which the ground water flows.

1.1 Saturated Thickness

The saturated area (A) of an aquifer is the product of the width and depth of the water-bearing material. The flow of ground water is commonly expressed in units related to 1 foot of width of cross section and the saturated thickness of the aquifer. This thickness, often expressed algebraically as b or m, is the distance between the water table and the bedrock surface for water-table aquifers, and for confined aquifers, as the distance between the confining beds above and below the aquifer. The vertical section in figure X-1.1-1 illustrates local variations in the saturated thickness of an unconsolidated water-table aquifer and a confined sandstone aquifer beneath it. The saturated thickness of the alluvial (water-table) deposits varies form zero, at the contact with the bedrock, to 115 ft. The sandstone thickness ranges from 100 ft at the south edge to 60 ft at the north edge.

[1]CFR= Code of Federal Regulations

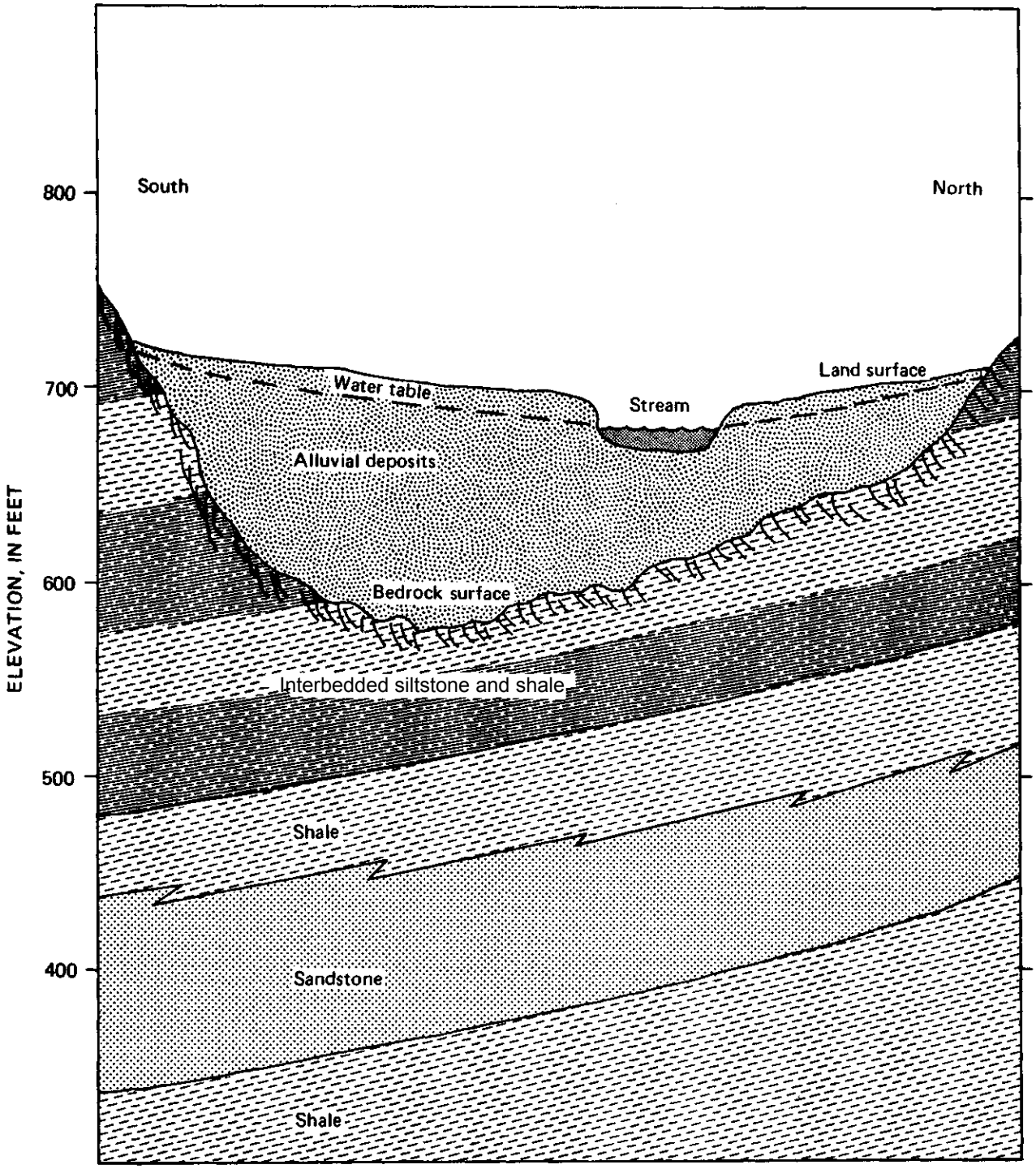


Figure X-l.1-1.— Local variations in saturated thickness (b) of unconsolidatd water-table aquifer and confined sandstone aquifer.

1.2 Hydraulic Conductivity and Transmissivity

The typical hydraulic conductivity (K) values for various geologic materials is summarized in figure X-l.2-1. For example, K for shale ranges from about 0.0000001 to 0.005 ft/d and, for sandstone, from less than 0.0001 ft/d (unfractured) to about 1 ft/d (semiconsolidated). The K values for fractured bedrock may be many orders of magnitude greater than for unfractured bedrock.

A more convenient means of calculating the steady-state volume of ground-water flow (Q) is by using transmissivity (T), which is equivalent to K multiplied by the saturated thickness (b) of the aquifer. For this case,

$$Q = T\ I\ W \qquad \text{(X-l.2-1)}$$

where W is the width of the ground-water flow cross section.

The geologic material having the greatest water-bearing capability is saturated unconsolidated alluvial sand and gravel. The hydraulic-conductivity values for unconsolidated deposits can range from about 0.0000001 to more than 100,000 ft/d. Table X-l.2-1 lists some representative hydraulic-conductivity values for specific grain-sized alluvial materials.

The units for hydraulic conductivity are feet per day. K does not represent ground-water flow velocity but is a constant of proportionality in the equation for determining ground-water discharge, Q. The K dimensions are rate per area, in $(ft^3/d)/ft^2$ (cubic feet per day per square foot), which reduces to ft/d (feet per day).

Transmissivity (T) of unconsolidated alluvial deposits can be estimated by multiplying the "handbook values" (such as in table X-l.2-1) for K.of each described material by the saturated thickness (b) of that material. As illustrated in table X-l.2-2, transmissivity at the driller's log location is the sum of these products for the saturated thicknesses, b_1, b_2, b_3, ... b_n:

$$T = \text{sum of } K_m \bullet b_m = K_1\ b_1 + K_2\ b_2 + K_3\ b_3 + ... + K_n\ b_n. \qquad \text{(X-l.2-2)}$$

The quantity of ground-water discharge into a mine excavation from an aquifer can be estimated from information given on a potentiometric map of the coal aquifer, aquifer -test results, and equation X-l.2-1. For example, the hydraulic gradient (I) for the two aquifers in the Decker mine area can be determined from the potentiometric maps of the permit and adjacent area (fig IX-4 for the clinker aquifer and fig X-l.2-2 for the D-2 aquifer). The discharge into the initial surface-mine cut is calculated as follows:

Given: 1. The two aquifers, Clinker (CD and D-2 Goal (D-2), to be excavated in surface mining

2. Potentiometric maps for both aquifers -
figure IX-4 for D-l Coal bed aquifer combined with Clinker
(also pl. 4 of VanVoast and Hedges, 1975)
and figure X-l.2-2 for D-2 Coal bed aquifer
(also pl. 5 of VanVoast & Hedges, 1975)

3. Average hydraulic gradient (I):=
$^{I}Cl = 40/4827 = 0.0083$; $^{I}D\text{-}2 = 20/4224 = 0.0047$

4. Saturated thickness (b)
$^{b}Cl = 20$ ft; $^{b}D\text{-}2 = 15$ ft

5. Average hydraulic conductibity (K)
$^{K}Cl = 125$ ft/d; $^{K}D\text{-}2 = 3$ ft/d;

6. Discharge Formulas: Q= TIW and T=Kb

Find the average ground-water discharge per foot of width of coal aquifer that would discharge into the surface-mine excavation.

Solution:

$^{Q}Cl = 125 \times 20 \times 0.0083 = 20.7$ ft^3/d per foot of width

$^{Q}D\text{-}2 = 3 \times 15 \times 0.0047 = 0.21$ ft^3/d per foot of width

Total discharge (^{Q}T) $= {}^{Q}Cl + {}^{Q}D\text{-}2$

$= 20.7 + 0.21$

$= 20.9$ ft^3/d per foot of width of aquifer

The hydraulic-conductivity values presented in figure X-1.2-1 and table X-1.2-1 are not necessarily applicable to all permit areas. Published hydraulic-conductivity values for similar material vary by orders of magnitude. Hydraulic conductivity and transmissivity of bedrock aquifers cannot be accurately estimated, because of local variations in primary permeability and secondary permeability (fracturing). These values vary both horizontally and vertically, depending on geologic conditions.

The aquifer properties in the permit areas can be determined by aquifer testing as described in chapter X-2. Some of the published transmissivity values obtained during variious hydrologic investigations are giben in table X-2.4-1. Reference (21) also lists ranges of transmissivity for selected ground-water regions of the United States.

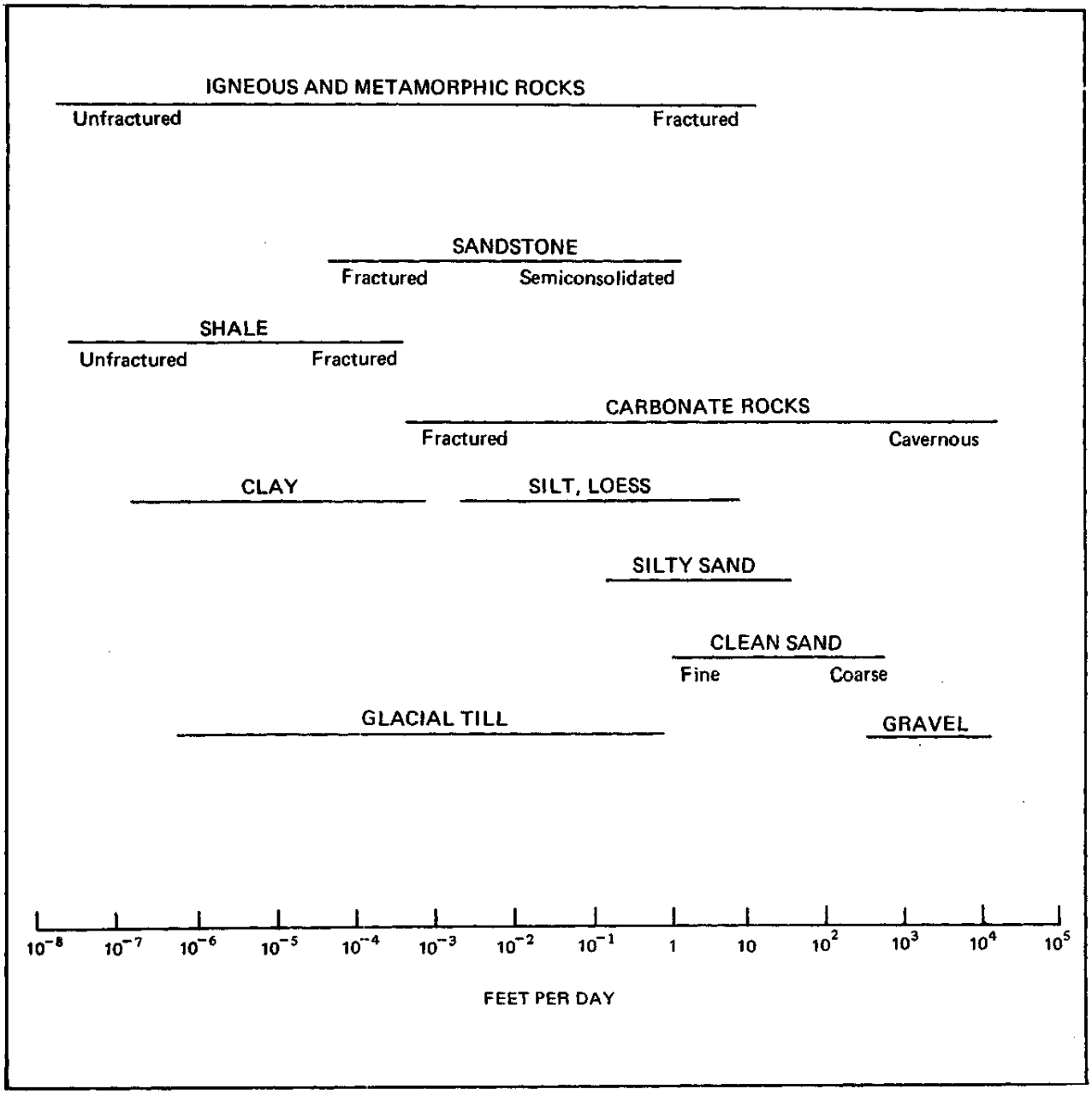


Figure X-l.2-1.— Range of hydraulic-conductivity values of selected aquifer materials. (Modified from Heath, 1983, p. 13)

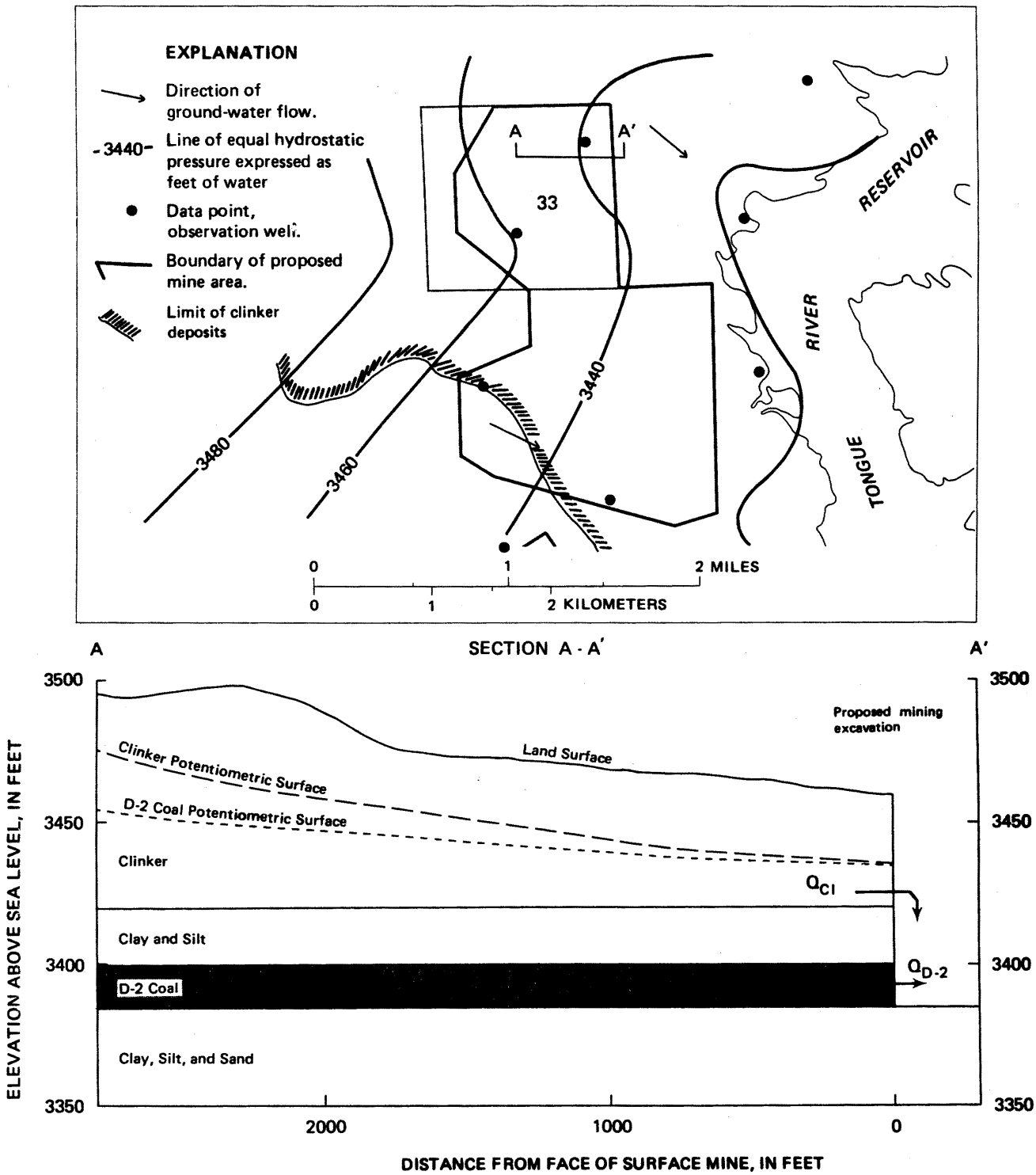


Figure X-1.2-2.— Potentiometric map of D-2 coal aquifer, near Decker, Montana, before mining began (above), and geologic section showing potentiometric surface profiles (below).
(Modified from VanVoast and Hedges, 1975, pls. 5, 11)

Table X-l.2-1.– Average hydraulic conductivity values of alluvial materials (From Lohman, 1972, table 17.) [ft/d, feet per day]

Alluvial Material	Hydraulic Conductivity (ft/d)
GRAVEL:	
Coarse	1,000
Medium	950
Fine	900
SAND:	
Gravel to very coarse	800
Very coarse	700
Very coarse to coarse	500
Coarse	250
Coarse to medium.	100
Medium	50
Medium to fine	30
Fine	15
Fine to very fine.	5
Very fine	3
CLAY:	1

Table X-l.2-2. Example of transmissivity calculation from driller's log of a well in an alluvial aquifer.
[ft, feet; ft^2/d, square feet per day; ft/mi, feet per mile; gal/d, gallons per day]

Material (from driller's log)	Thickness (b) (ft)	Bottom depth (ft)	Hydraulic conductivity(K) (ft/d)	Transmissivity (T) (T = Kb) ft^2/d
Top soil	1	1		-
Clay	5	6		-
Fine sand	4	10		-
----------(Water level at 10 feet)----------				
Medium sand	5	15	50	250
Medium to coarse sand	25	40	100	2,500
Clay	20	60	1	20
Sand and gravel	10	70	800	8,000
Coarse gravel	15	85	1,000	15,000
Shale (bedrock)	5	90	-	-

T = sum of $K_m \bullet b_m$ = 25,770 ft^2/d
rounded to 26,000 ft^2/d

Ground-water discharge(Q) per foot of aquifer width at this location, initially, with T = 26,000 ft^2/d and I = 40 ft/mi would be from equation X-1.2-1

$Q=T\ I\ W \times 7.48= 26{,}000 \times {}^{40}/_{5280} \times 1 = 1500$ gal/d 5280

1.3 Storativity and Specific Yield

Storativity (S) indicates the capability of an aquifer to store or release water as head changes. Storativity is usually determined through analysis of data from multiple-well aquifer tests. However, rough approximations of specific yield for most types of aquifer material can be obtained from table X-l.3-1, and storativity of a confined aquifer can be calculated from the range of b values given in table X-l.3-2. The applicability of storativity to confined aquifers is increased by converting it to specific storage (Ss), which represents storativity per foot of confined aquifer thickness (b), or S/b. Table X-l.3-2 uses an Ss value of 0.000001 (or 10^{-6}) per foot of aquifer thickness.

Additional information on storage coefficients, storativity, and specific yields can be found in bibliographic references listed in chapter XVII; these include Barrett and others, 1980; Ferris and others, 1962; Freeze and Cherry, 1979; Heath, 1983; Johnson Division, 1975; McWhorter and Sunada, 1977; and U. S. Department of Interior, 198la.

TABLE X-l.3-1. Average specific yield for unconsolidated water-table aquifers (From Johnson, 1967, p. D 70.)

Alluvial Material*	Average Specific Yield
Clay □	0.02
Silt □	.08
Sandy clay □	.07
Fine sand □	.21
Median sand □	.26
Coarse sand □	.27
Gravelly sand □	.25
Fine gravel □	.25
Medium gravel □	.23
Coarse gravel □	.22

* Generally ranges from 0.1 to 0.3 depending on the size and sorting of the alluvial material.

TABLE X-l.3-2. Method of estimating storage coefficient (S) for confined aquifers (From Lohman, 1972, p. 53.)

Thickness of Confined Aquifer (b, in feet)	Storage Coefficient (S)
1	0.000001
10	.00001
100	.0001
1000	.001

Example of application: a confined aquifer with a saturated thickness(b) of 300 feet, S equals approximately 0.0003

1.4 Effect of Hydraulic Properties on Drawdown

The relationship between drawdown and time (t), distance (r), transmissivity (T), and storativity (S) under conditions of constant discharge are illustrated in figure X-l.4-1. The general pattern is that the smaller the T and S values, the larger the drawdown values near to the point of discharge and the larger the volume of aquifer affecter through time. Dewatering an excavation where T and S are small will affect a larger aquifer volume than in an area where T and S are large. The change in drawdown with distance from a well pumping from a confined aquifer after 1 year at several pumping rates with a constant T = 20 ft^2/d and S = $5X10^{-5}$ are depicted in figure X-l.4-2. The drawdowns for the same pumping rates at a single location over a period of several years are plotted in fig X-l.4-3.

An application of the information presented in figure X-l.4-2 for the stated T and S values is as follows: Consider a well pumping at a constant rate of 26 gal/min for 365 days; the drawdown in a homogeneous confined isotropic aquifer would be 50 ft at a distance of 1 mi or 95 feet at a distance of 1/4 mi.

An application of the information presented in figure X-l.4-3 for the same hydrologic conditions is as follows: For a well pumping at a constant rate of 26 gal/min, the drawdown at a distance of 1,000 feet will be 40 ft after 10 days, 90 ft after 100 days, and 135 ft after 1,000 days.

Transmissivity is locally variable; some published values for selected consolidated formations are presented in figure X-l.4-4 and table X-l.4-1. For example, transmissivity of Pennsylvanian rocks, in the border area between Tennessee and Alabama, ranges from 50 to 13,000 ft^2/d. The major bedrock types are sandstone and shale, which are fractured to varying degrees, and the T value is related to the size, density, and extent of fractures. In contrast, the T value in the Mississippian carbonate rocks ranges from 100 to 27,000 ft^2/d and is related to the size and abundance of solution openings and fractures. The drawdown distributions in the aquifer units that are affected by mining operations will be irregular and parallel the irregular distribution of hydraulic properties.

Aquifers overlying and underlying coal seams can differ in hydraulic properties because of differences in lithology and fracturing. For example, a sandstone and conglomerate rock unit would have a much higher T value than an interbedded siltstone, shale, and sandstone rock unit. Hydraulic properties can also vary laterally within the same unit. These variations are related to local differences in saturated thickness, lithology (called facies changes), solution openings, and fracture density.

The difference between transmissivity of the aquifer unit overlying a coal bed and that of a aquifer below it can be determined through aquifer tests in each water-bearing formation and in each aquifer unit that might be affected by the mining operation.

The lateral variation of T within an aquifer unit can be determined through aquifer tests at several locations within and adjacent to the proposed permit area. A map showing the variation of T in an aquifer is shown in figure X-l.4-5, where T varies from zero at the outcrop to 300 ft^2/d. The transmissivities were determined at the data points. The contours represent interpolated estimates. The best method of predicting the hydrologic affects of dewatering is through computerized ground-water modeling. Transmissivity maps such as that in figure X-l.4-5 are essential for the development of a ground-water model of a proposed permit area.

Single-well aquifer tests can be performed in conjunction with the exploratory program for coal-resource-evaluation. If the results of these tests show a range of only 1 order of magnitude in hydraulic properties of the pertinent units, the system is sufficiently uniform that additional aquifer testing is not necessary. Also, if the aquifer thickness, confining-bed thickness, and fracture spacings are consistent among units, additional aquifer testing may not be necessary. However, if aerial photographs indicate the presence of structural features such as faults, fracture traces, or lineaments, which might affect the aquifer systems in the permit area, additional aquifer testing will probably be necessary. These structural features are generally saturated, extend to hundreds of feet, and can have a hydraulic conductivity thousands of times greater than that of the adjacent unfractured rock. These water-bearing features can be particularly troublesome in deep-mine operations because they may discharge large quantities of water into underground workings.

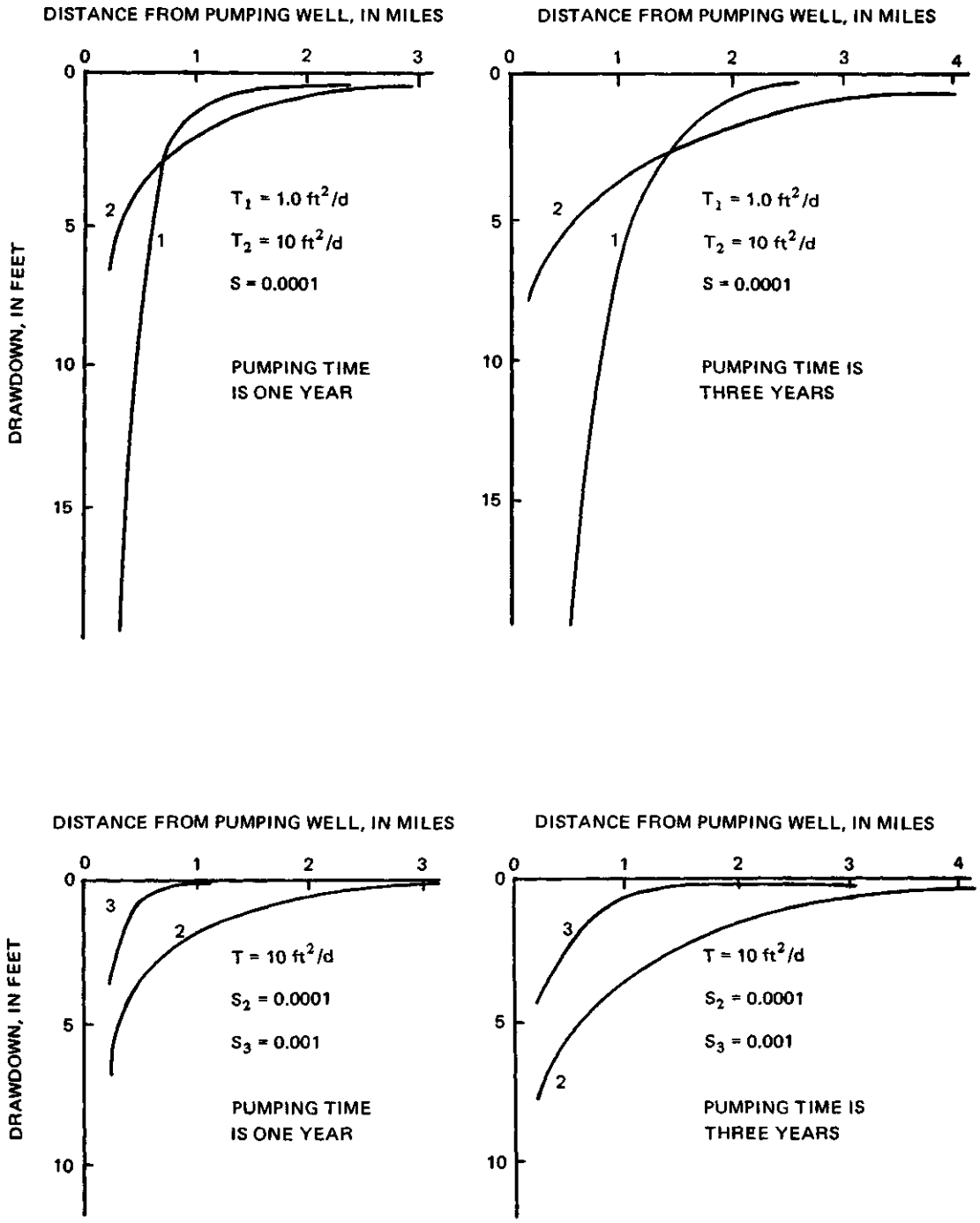


Figure X-l.4-1.— Influence of transmissivity (above) and storativity (below) on the distribution of drawdown for pooping periods of 1 year and 3 years. (Well discharge is 1 gallon per minute.)

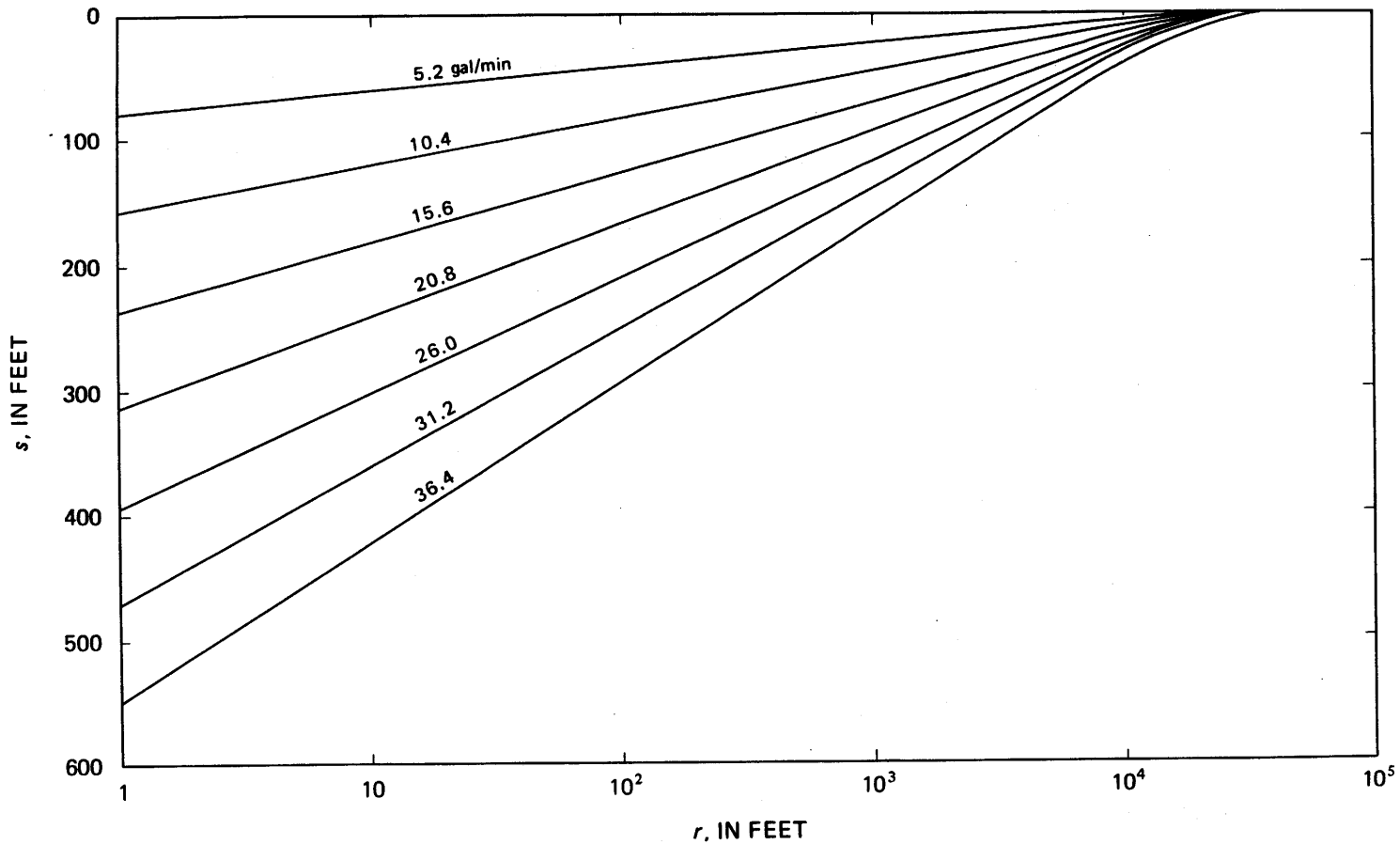


Figure X-l.4-2.— Family of curves showing drawdown produced at various distances from a well discharging at selected rates for 365 days from a confined aquifer for which transmissivity is 20 ft^2/day and storage coefficient is 0.00005. (From Lohman, 1972, p. 54)

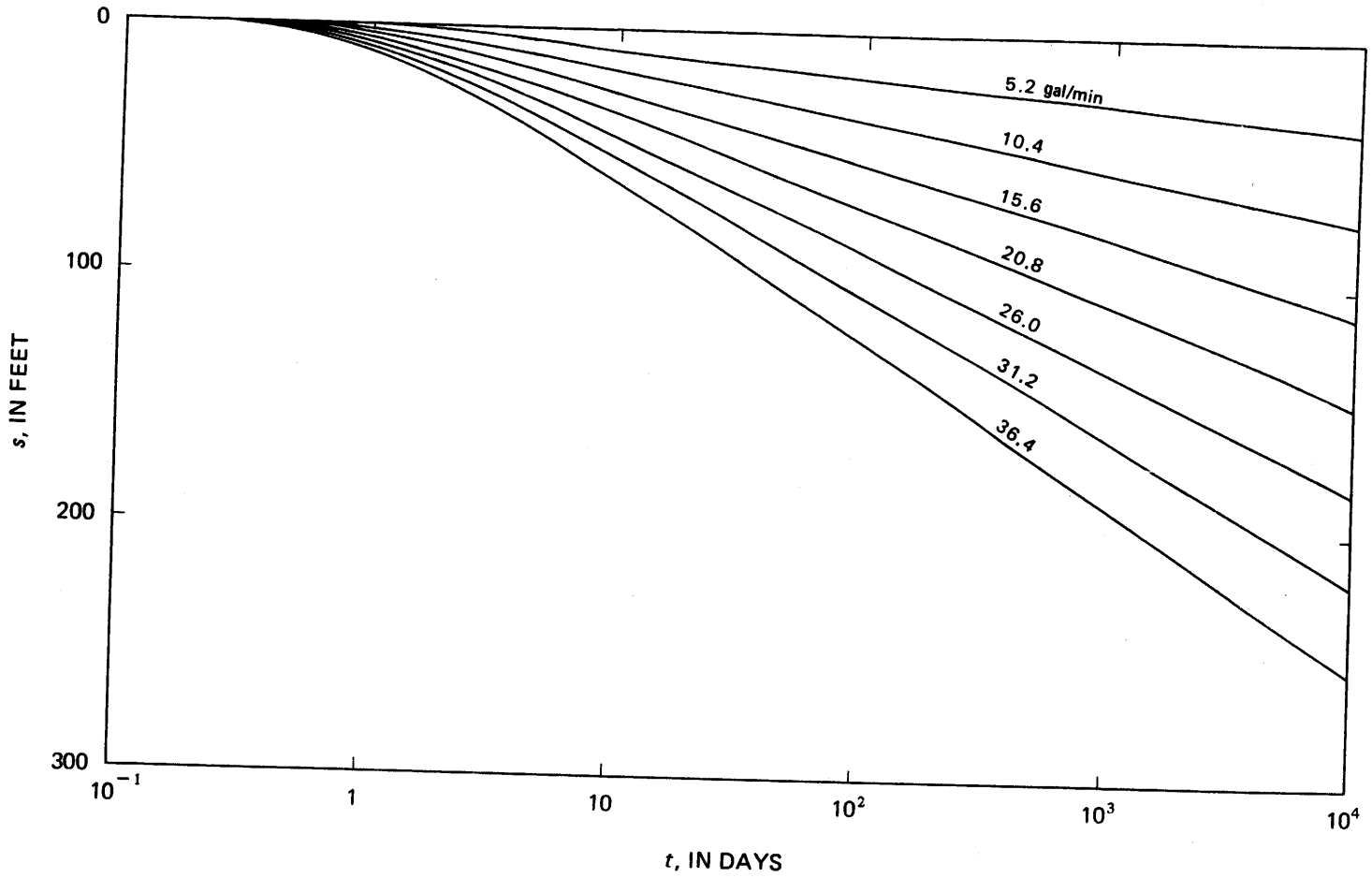


Figure X-l.4-3.— Family of curves showing drawdown produced throught time at a distances of 1000 ft from a well discharging at selected rates from a confined aquifer for which transmissivity is 20 ft^2/day and storage coefficient is 0.00005.
(From Lohman, 1972, p. 55)

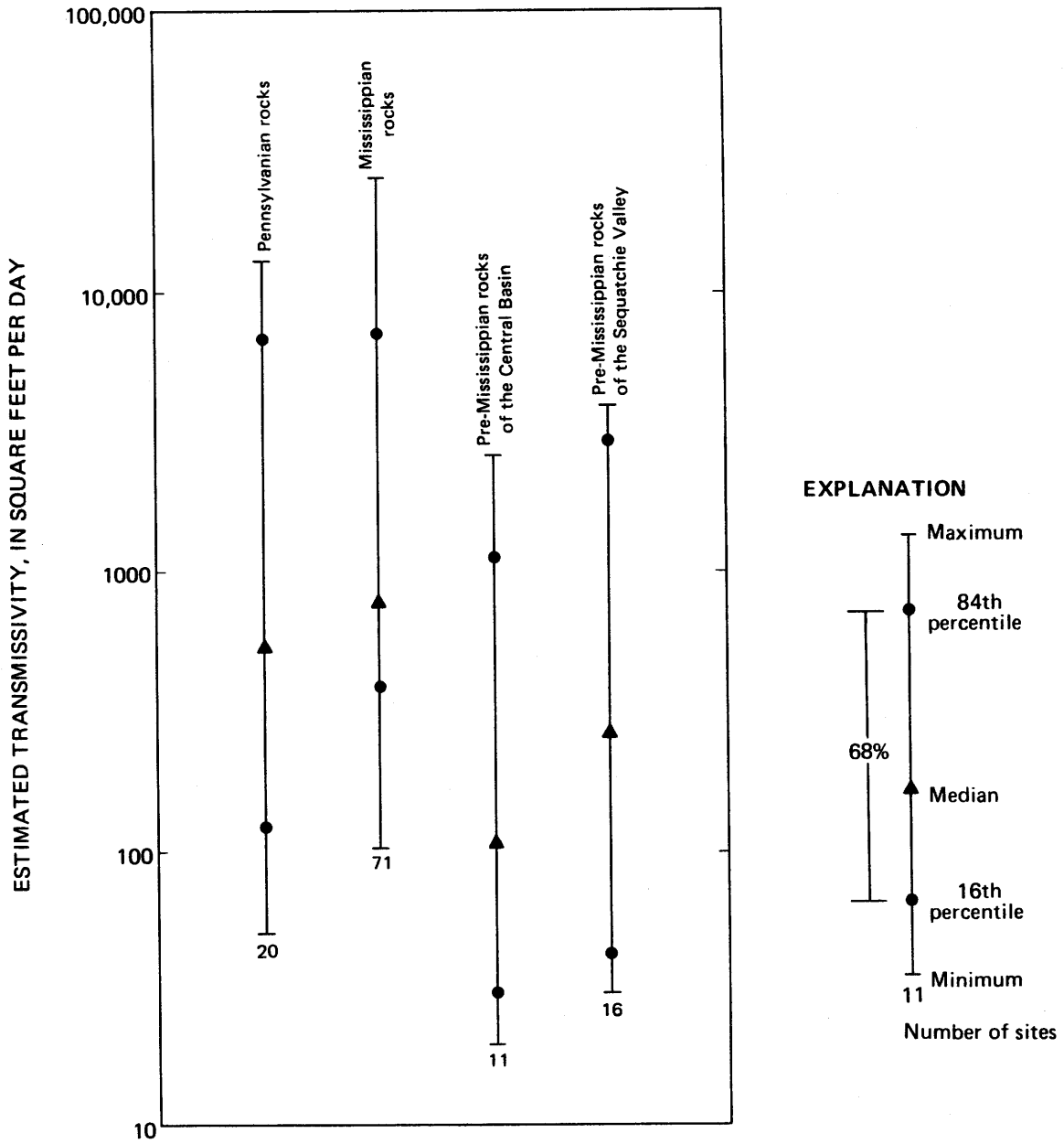
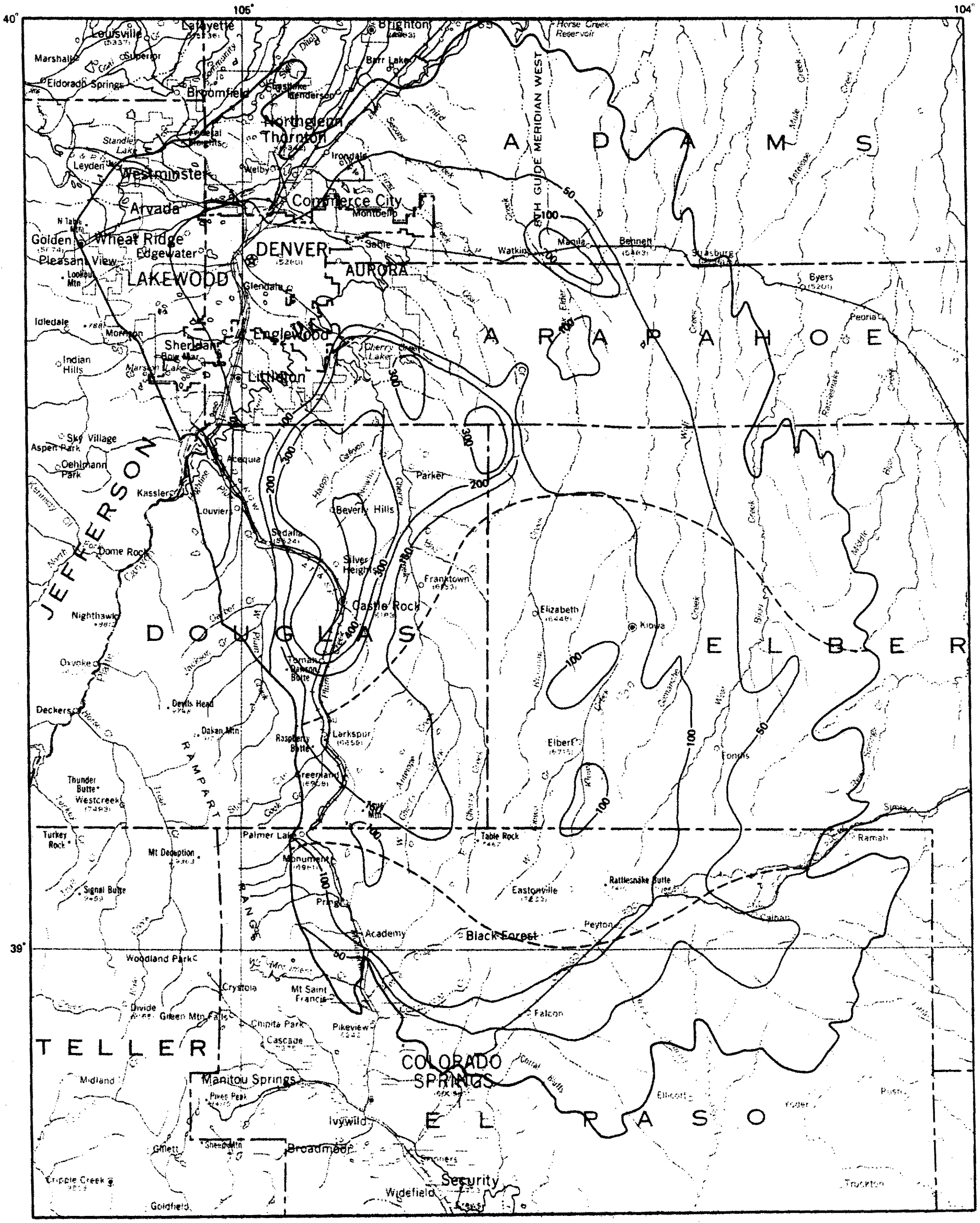


Figure X-1.4-4— Range of estimated tranmissivities of selected rock units in Eastern Coal Province, Tennessee and Alabama–Area 21. (From May and others, 1983, p. 63)



EXPLANATION

—100— LINE OF EQUAL TRANSMISSIVITY-Interval, in feet squared per day, is variable.

——— APPROXIMATE LIMIT OF THE DENVER AQUIFER (in Denver formation)

- - - - LIMIT OF AREA IN WHICH HYDRAULIC CONDUCTIVITY WAS ESTIMATED.

0 20 MILES

0 20 KILOMETERS

Figure X-1.4-5.— Example of a transmissivity map of the Denver Aquifer in eastern Colorado.
(from Robson, 1983, fig 9)

Table X 1.4-1. Published transmissivity values of aquifers in selected permit areas.

[Rock type abbreviations: c, coal; cong, conglomerate; Is, limestone; sh, shale; sit, siltstone; ss, sandstone (listed in order of decreasing significance); frac, fractured; sol. op., solution openings; mine sub., mine subsidence. Aquifer abbreviations: Fm., formation; Ss., sandstone; Mbr., member. Geologic age abbreviations: Miss., Mississippian; Quat., Quaternary; Pa., Pennsylvanian; Paleo.-Cret., Paleocene-Cretaceous]

Coal Province	State	Aquifer	Geologic Age	Rock type	Transmissivity (feet squared per day) Range min.	Range max.	Median or Mean	Method of Analysis	Source of Information
Eastern	MD	Conemaugh Fm.	Pa.	frac, slt, ss, sh, & c.	3.	550.	19.	slug test (Bouwer & Rice, 1976)	(1)
	TN & KY	(not defined)	Pa.	frac, ss, sh, slt, & c.	5.	13,000.		specific capacity	(2)
			Miss.	ls, slt, & sh. sol. op.	35.	7,000.			
	TN	(not defined)	Pa.	frac. ss, sh, slt, & c.	20.	2,000.		specific capacity	(3)
			Miss.	ls, slt, & sh. sol. op.	7.	8,000.			
	TN & GA	Crab Orchard Mtns. Fm. Gizzard Fm. Pennington Fm.	Pa.	frac. ss, sh, slt, & c.	20.	750.		specific capacity	(6)
			Miss.	ls sol. op.	30.	900.			
	TN & AL	Pottsville Fm.	Pa.	frac, ss, cong, sh, & c.	50.	13,000.	520.	specific capacity	(10)
			Miss.	ls sol. op.	20.	27,000.	800.		
	WV	Conemaugh Fm.	Pa.	frac, ss, slt, sh, & c. mine sub.	.13	41.	13.	slug test	(5)
Northern Great Plains	MT	'overburden'	Paleo-cene and Holo-cene		.008	44.	3.3	aquifer tests	(12) (13)
		(1)Anderson coal			3.2	120.	34.	aquifer tests	
		(2)Dietz 1 coal			16.	150.	(2 values)		
		(3)Dietz 2 coal			6.5	441.	40.		
		Combined aquifers (1), (2)&(3) beds			44.	84.	55.		
Rocky Mountain	UT	Ferron Ss. Mbr. Mancos Shale	Creta-ceous	ss	10.	800.	100	aquifer tests	(19)
	CO & NM	Alluvium	Quat.		0.16	570	92.9	aquifer tests	(20)
		Raton and Vermejo Formations	Paleo. - Cret.	c&carb.sh	0	38.0	9.26		
		Trinidad Ss.		ss	0	49.2	8.11		
				slt&sh	0	90.7	16.9		

1.5 References Cited for Aquifer Characteristics

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(2) Gaydos, M. W., and others, 1982a, Hydrology of area 17, Eastern Coal Province, Tennessee and Kentucky: U.S. Geological Survey Water Resources Investigations Open-File Report 81-1118; 77 p.

(3) _____, 1982b, Hydrology of area 19, Eastern Coal Province, Tennessee: U.S. Geological Survey Water Resources Investigations, Open-File Report 81-901; 75 p.

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(6) Hollyday, E. F., and others, 1983, Hydrology of area 20, Eastern Coal Province, Tennessee, Georgia, and Alabama: U. S. Geological Survey Water Resources Investigations, Open-File Report 82-440; 80 p.

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(16) Malmberg, G. T., and Downing, H. T., 1957, Geology and ground-water resources of Madison County, Alabama: Geological Survey of Alabama County Report 3, 225 p.

(17) McMaster, W. M., 1963, Geology and ground-water resources of the Athens area, Alabama: Geological Survey of Alabama Bulletin 71, 45 p.

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(20) Abbott, P. O., Geldon, A. L., Cain, D., Hall, A. P., and Edelmann, Patrick, 1983, Hydrology of Area 61, Northern Great Plains and Rocky Mountain Coal Provinces, Colorado and New Mexico: U. S. Geological Survey Water Resources Investigations, Open File Report 83-132, 99 p.

(21) Heath, R. C., 1984, Ground-Water Regions of the United States; U.S. Geological Survey Water Supply Paper 2242, 78 p.

2. Aquifer Testing

Pertinent 30CFR[1]- Sections:
Description of hydrology and geology.
Ground-water information.

2.1 Introduction and General Procedure

Quantification of changes in aquifer storage due to recharge and discharge requires reliable estimates of transmissivity, storativity, and apparent specific-yield values as well as knowledge of hydraulic boundary conditions. Solutions to mine-related hydrology problems, such as inflow and disturbance of the potentiometric surface through time and with distance, also require accurate values of these terms.

An aquifer test is a controlled field experiment to determine the hydraulic properties of water-bearing deposits and rocks. The procedure is to cause a stress on the aquifer and to measure the observed aquifer response; the hydraulic-property values are then obtained by matching the measured response to mathematically derived relationships (type curves) between flow and aquifer pressures. Aquifer testing by pumping consists of either discharging water from or injecting water into the aquifer, and observing the response by measuring water levels in nearby wells. An example of an aquifer-test layout, with map and cross section, is shown in figure X-2.1-1.

The procedures for aquifer test design, field observation and data analysis outlined herein are modified from the published literature (9), (10), (14), (15), and (17). Elementary analytical methods commonly applied to geologic and hydro-logic settings of coal mines in the United States are listed in table X-2.1-1; detailed descriptions of these methods are presented in the following sections. Consideration of hydrologic boundary conditions and tight formations also are presented. More complete discussion of the analytical techniques for a particular problem are given in (16) and (17).

The purpose of an aquifer test design is to yield reliable values of hydraulic coefficients; therefore, the design phase is probably the most important aspect. The cost of an aquifer test ranges from a few hundred dollars for the least complicated type to thousands of dollars for a more detailed or sophisticated test. The cost depends on the number and distribution of observation wells, the duration of the test, and the manpower and equipment allocated to the field test. To increase the probability of success and to avoid unnecessary costs and waste effort, the tests should be designed carefully and followed by careful and complete data collection.

[1]CFR= Code of Federal Regulations

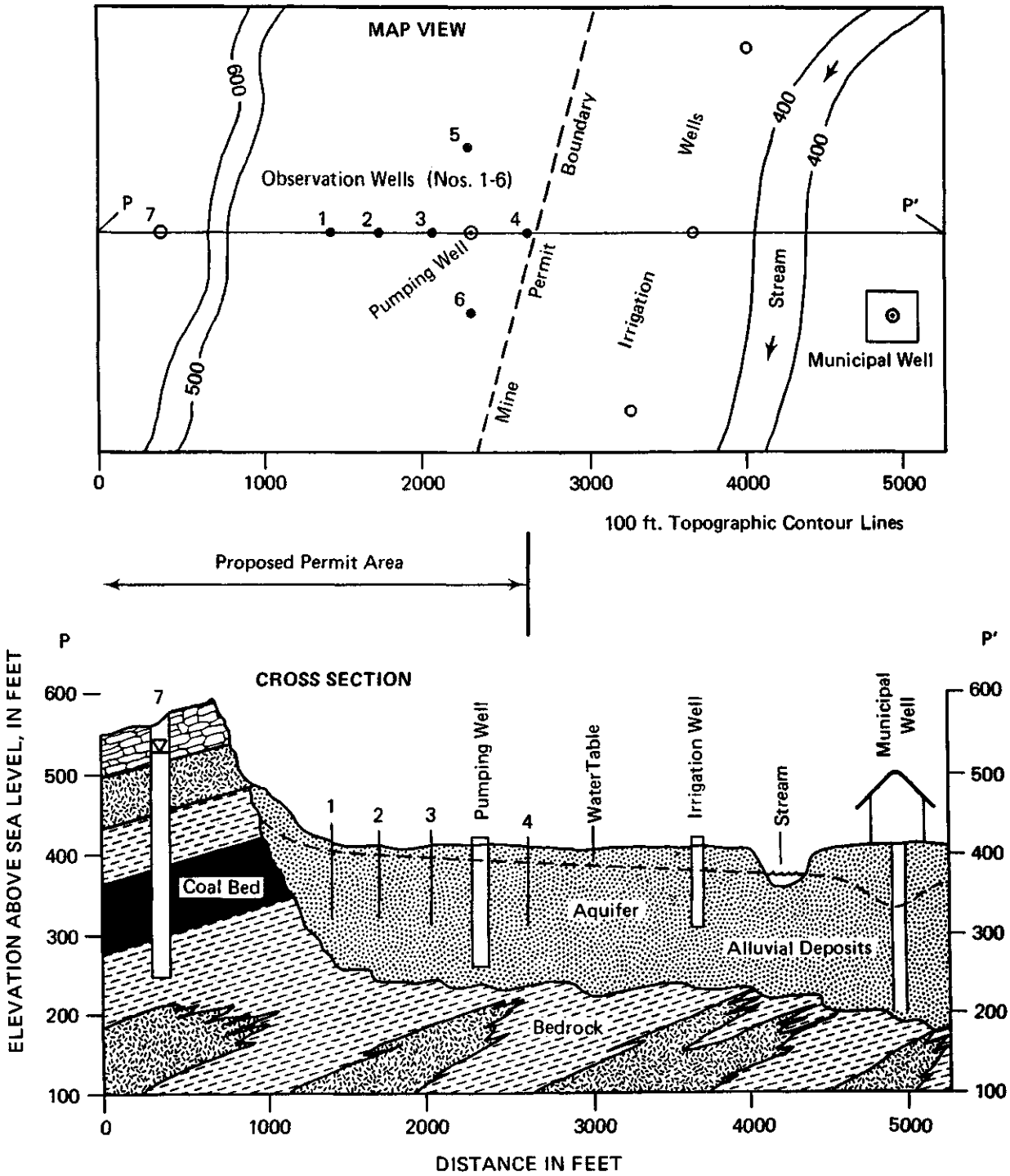


Figure X-2.1-1.— Example of an aquifer-test layout.

Information desirable in the design phase includes:

1. Knowledge of the geologic and hydrologic setting of the aquifer system in sufficient detail that the conditions controlling ground-water flow can be defined. For example, the following should be known: aquifer thickness and extent, basic lithologic composition, type of aquifer (confined or water table), approximate order of magnitude of transmissivity and storage coefficients, and magnitude of stress to be imposed on the aquifer.
2. Response (drawdown) curves, based on imposed stress and known boundary conditions, if available.
3. Type of equipment available and whether it will produce an adequate set of measurements. Some examples of equipment are devices for measuring well discharge, drawdown in observation wells, and field temperature and specific conductance.

After the geologic and hydrologic settings (item 1 above) have been evaluated, the next step is to locate and evaluate available wells in the area at which tests are proposed. The cost of testing may be reduced by using production and abandoned wells rather than installing new wells. Use of available wells is contingent upon knowing well depths, locations of intake screens, and aquifer (s) penetrated. Unfortunately, few such wells are suitable for aquifer-test purposes, and most are poorly equipped for water-level observation.

Some criteria for test-site evaluation are as follows:

Pumped Well

1. The pumped well must have a pump and discharge-control equipment. If the discharge is not controlled carefully at a constant value, the test results will be unreliable and thus unusable.
2. The water discharged must be conducted away from this well and not spilled on the ground where it could recharge the aquifer during the test. This is particularly important in testing shallow unconfined aquifers or deeper aquifers in fractured formations.
3. The wellhead and discharge lines should be accessible for installing discharge-regulating and monitoring equipment.
4. Measurement of depth to water in the pumped well before, during, and after pumping must be possible.
5. The diameter, depth, and position of all intervals open to the aquifer in the pumped well, as well as the total depth, should be known.

Observation Well

1. All observation wells must be completely developed, that is, interactive with the aquifer. Abandoned wells may tend to become clogged; consequently, they should be pumped or bailed for complete development.
2. Depth, diameter, screened or open interval, and land-surface elevation should be known for each observation well.
3. Distance from the pumped well to each of the observation wells must be determined.

Aquifer

1. Depth to, thickness of, and boundary conditions of the aquifer should be determined.
2. The aquifer and any discontinuities caused by changes in lithology or by incised streams and lakes should be mapped.
3. Hydraulic properties of the aquifer and adjacent rocks must be estimated. Estimates of transmissivity and storativity may be obtained from reports on aquifers in geologic and hydrologic settings similar to that of the mine-permit area. Estimates based on general lithology and relative degree of confinement are available in references (5), (9), and (16).

Site evaluation serves not only to determine the location and configuration of wells in the area, but to plan well installations specifically for the aquifer test. Estimating the radius of influence from the pumping well as a function of time can be determined from estimates of transmissivity and storativity based upon the Theis method of analysis (20). If only one observation well is to be installed, this procedure could be used to establish the distance from the control well within which the drawdown would be sufficient for analysis. Examples of response curves showing the relationship between drawdown and transmissivity, storativity, and distance from pumped well are depicted in figure X-l.4-1; the use of such curves for pretest evaluation and the uncertainties associated with water-table flow and partial penetration of the wells is discussed in (15).

Table X 2.1-1 - Selected aquifer test methods.

[T = transmissivity, K = hydraulic conductivity, S = storage coefficient, storativity, or apparent specific yield (S) is determined only for multi-well tests, or, under certain circumstances.]

Type of Test	Analytical method	Hydraulic Characteristics Determined	Remarks
Drawdown	Theis (1935) (curve match)	T, K, S	Multiwell: Used to determine hydraulic values averaged over a relatively large volume of aquifer; gives best reliability but is relatively expensive and requires at least two wells (preferably more), a pump, and a power source. Useful to detect uncertain boundary conditions, leakage or directional permeability. Does not work well in tight, K, formations.
	Cooper-Jacob (1946) (straight-line)	T, K, S	Multiwell: Same remarks as Theis method insofar as limiting assumptions are met, and u is less than 0.01 (See table X-2.3-2). Boundary effects may cause serious errors and must be recognized.
Recovery	Theis (1935) (straight line)	T, K, S	Multiwell: Same remarks as Theis method insofar as limiting assumptions are met. Boundary effects may cause serious errors. Single well only: Ccmmonly useful for determining T in recovering pumped well at small additional cost. Method is not recommended for determining S in tight aquifers where well-bore storage effects are evident
Slug	Cooper and others (1967) (curve match)	T, K, (S)	Single well only: Simple and inexpensive method used to estimate coefficients in a small volume of a confined aquifer. The S determination is rather insensitive to type-curve matching and is not recommended. Works well in tight aquifers. This method accounts for aquifer and well-bore storage.
	Bouwer and Rice(1976) (straight line)	T, K	Single well only: Same remarks as for Cooper and others (1967) method except that it is applied to water-table aquifers and accounts only for well-bore storage. Can also be used for partially penetrating or perforated wells
Flowing Well	Jacob and Lohman (1952)	T, K, S	Single well only: Constant drawdown and variable discharge for flowing well; artesian well must be shut-in until head is static; period of testing ranges from 2 to 4 hours; radius of well must be known to determine S.

2.2 Field Observations

The hydrologic data required for analysis are listed below with the precision in measurement generally considered acceptable in parentheses. (See ref. 15):

1. pumped well discharge (± 10 percent),
2. depth to water below measuring point (± 0.01 ft),
3. distance from pumping well to each observation well (± 0.5 ft),
4. synchronous time (±1 percent of time since pumping started),
5. descriptions of measuring points,
6. elevations of measuring points (±0.01 ft),
7. vertical distance between measuring point and land surface (±0.1 ft),
8. measured depths of all wells (±1 percent),
9. depth and length of screened intervals of all wells (± 0.1 ft),
10. diameter, casing type, screen type, and method of construction,
11. location of all wells in plan, relative to land-survey net or by latitude and longitude, on 7½ minute U.S. Geological Survey topographic map.
12. specific conductance of discharge.

The observations needed to define boundary conditions and measure aquifer response are decided in the next phase of the aquifer test. For example, the type of geologic and hydrologic setting roughly indicates the response of the aquifer to pumping, which in turn allows the timing of water-level measurements to be estimated. Adequate attention to aquifer test design, aids the efficient allocation of the observer's time and will provide the most useful information.

Items 1 through 4, above, are documented specifically in the testing process. Some of these items are recorded on well-schedule and water-level forms, which become part of the permanent records. An example of a form for recording water-level and discharge data is shown in figure X-2.2-1. Specific conductance measurements can be recorded in the "remarks" column. An example of a drawdown and recovery curve in which the symbols and critical points are explained is shown in figure X-2.2-2.

Lithology of the aquifers and construction features of the pumping well and observation wells are generally determined by interviewing the well owners and well drillers. Field measurements of well depths and casing diameters afford a rough check on the accuracy of information obtained by the interviews. Detailed lithologic logs should be made and construction features noted during drilling of all wells installed for the test. Geophysical logs such as resistivity, self-potential, gamma, caliper, temperature, and neutron logs provide more detailed information on subsurface conditions. Accurate positioning of observation wells and pumped wells is especially important in a test of a heterogeneous or anisotropic aquifer. Position of the test site with respect to a regional land-survey net or by latitude and longitude must also be noted so that the regulatory authority can use the data to interpret the regional characteristics of the aquifer.

County: _____ Observation well no. : _____
Location: _____ Pumped well no. : _____
Average Discharge (Q): _____
Distance between observation well and control well (r): _____ ft. (r^2 = _____)

		Drawdown data				Recovery data						
Date	Hour	t (min)	Depth to water (ft)	s (ft)	Q (gpm)	t' (min)	Ratio t/t'	Drawdown from extended pumping curve* (ft)	Depth to water (ft)	s' (ft)	Δs (ft)	Remarks

*number determined from graphical plot of drawdown (s vs. t) data extended to the end of the test.

EXPLANATION
t = Time since pumping began.
t' = Time since pump was shut off; start of recovery period.
S = Drawdown; difference between static water level and pumping water level.
S' = Residual drawdown; difference between static water level and recovering water level.
Δs = (s - s'), calculated recovery
Q = pumping well discharge, in gallons per minute.

Figure X-2.2-1.— Example of an aquifer-test from for drawdown and recovery. (Modified for Stallman, 1971, fig.3)

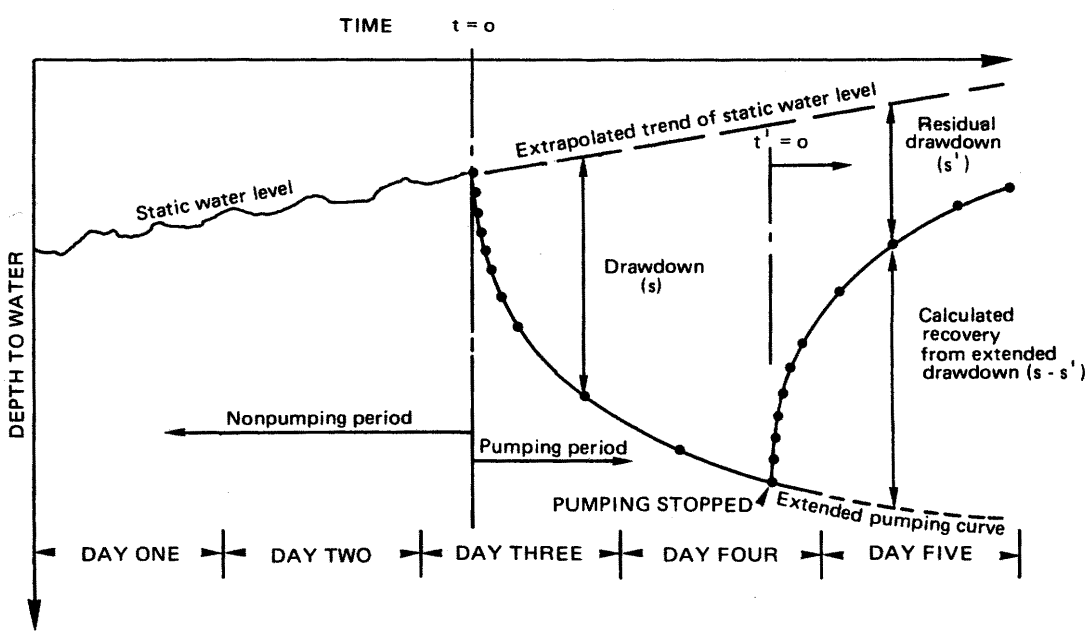


Figure X-2.2-2. Example of hydrograph of water levels in observation well before, during and after pumping test.
(Modified for Johnson Division , 1975, figs. 95 and 97; and Stallman, 1971, fig.4)

Most "type curves" indicate the change in potentiometric head, recharge, or drawdown during pumping. However, the changes in observed water level during the test may also include the effects of tides, recharge, and atmospheric pressure changes. Also, because flow in most aquifers is nonsteady; the trend of the static water level with time should be determined before testing so that drawdown measurements can be adjusted during the test. Drawdowns can be determined accurately only if background water-level trends are known or the drawdown due to pumping is large compared to other effects.

General rules regarding the length of time for aquifer tests are:
1. the minimum length of an aquifer test should be 24 hours for a confined aquifer and 3 days for a water-table aquifer (8);
2. period of pretest water-level measurements should be at least twice the length of the aquifer test. Longer aquifer test times are desirable, considering the application of the hydraulic properties to, and the drawdown effects of, long-range water-use estimates.

Water levels in many confined-aquifer wells fluctuate in response to changes in atmospheric or barometric pressure; that is, increases in atmospheric pressure cause a greater depth to water, while decreases in atmospheric pressure cause a lesser depth to water. The 6-day hydrographs in figure X-2.2-3 illustrate this relationship for two artesian wells. Changes of a foot or more in barometric pressure can cause fluctuations of a foot or more in the potentiometric surface at these wells within a few days (2).

If water-level responses to pumping in a confined aquifer test are relatively small, drawdown measurements should be corrected to remove the barometric effects before comparison with type curves. The correction procedure entails:
1. measuring the water-level variations caused by barometric pressure changes (as shown in fig. X-2.2-3) before the aquifer test;
2. determining the barometric efficiency(BE) of the well;
3. measuring barometric pressure during the aquifer-test period;
4. correcting the measured drawdowns (before applying the type-curves) accordingly by applying the barometric efficiency. The barometric efficiency of an aquifer may be expressed as shown below (6), (17), (18)

$$BE = s_w/s_b \qquad \text{(X-2.2-1)}$$

where:

s_w = the net change in water level observed in a well tapping the aquifer, in feet or centimeters, and

s_b = the corresponding net change in atmospheric pressure, in ft (or cm).

For example, a well having a 0.50 barometric efficiency would have a water-level rise of 0.05 ft for each decrease of 0.10 ft in barometric pressure. Thus, for each decrease of 0.10 ft in barometric pressure since the start of the aquifer test, the measured water levels, or drawdowns, would have to be decreased by 0.05 ft to account for the atmospheric-pressure changes.

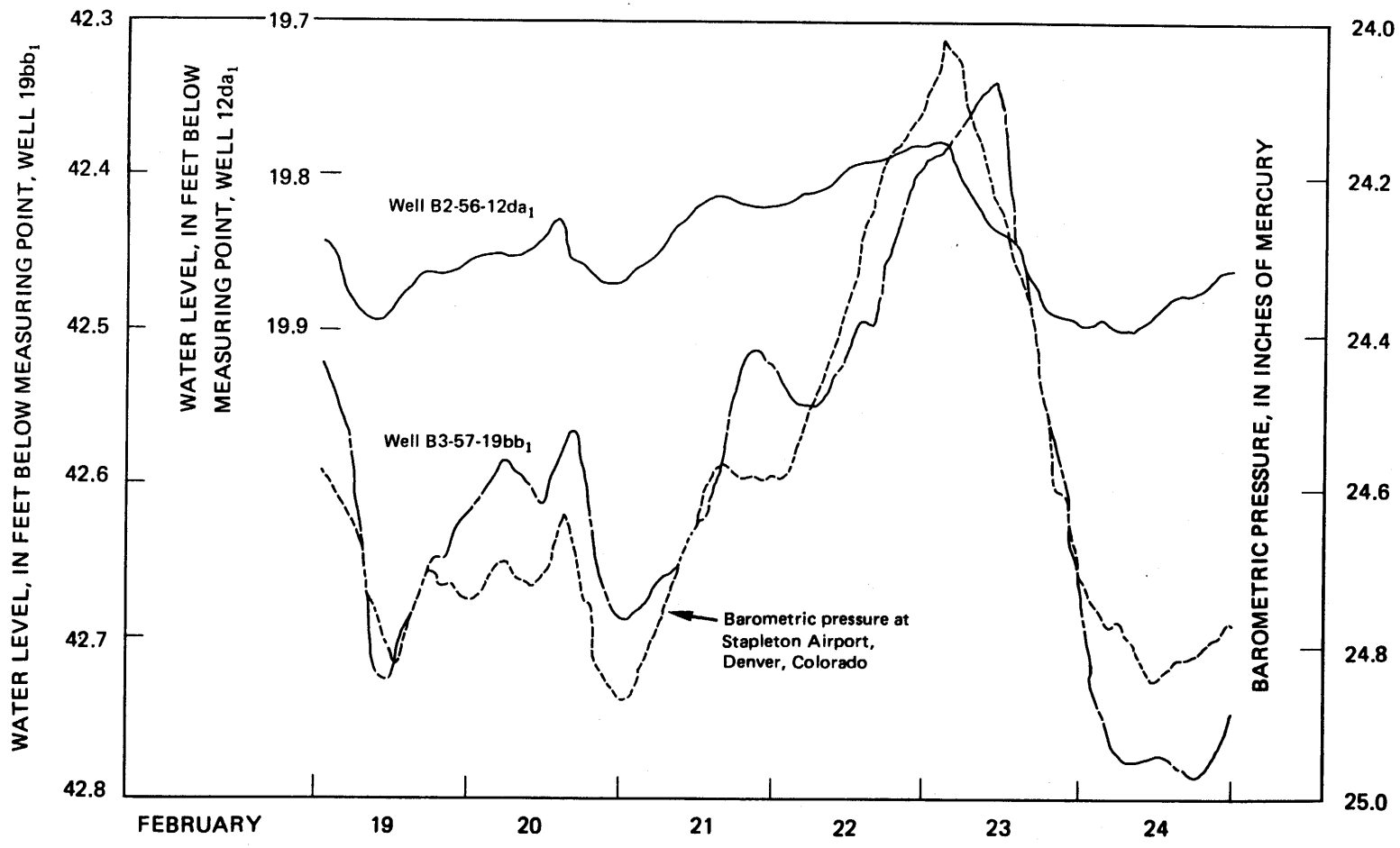


Figure X-2.2-3.— Water-level fluctuations caused by changes in barometric pressure. (Modified from U.S. Department of Interior, 1968, fig. E:1a-2)

Water levels in wells also are affected by other background factors such as the operation of nearby wells, recharge, earth and ocean tides, and pulse of force on the aquifer by trains and earthquakes. Measurements of water levels before the aquifer test will identify the extent to which such factors affect the water levels. Drawdown effects due to nearby pumping wells ordinarily can be removed from the data if the pumping times and discharge rates of these wells before and during the test are known.

Depth to water in all wells should be measured with sufficient frequency that each logarithmic cycle of time on the data plots contains at least 10 data points spread through the cycle. Thus, after t = 0, depth to water should be measured in each well at t = 1, 1.2, 1.5, 2, 2.5, 3, 4, 5, 6, 7, and 8 minutes, approximately, and all succeeding decimal multiples (10, 12, 15, 20, 25, 30, 40, 50, 60, 70, 80, 100; and 120, 150, 200, 250, 300, 400, 500, 600, etc. minutes) of these numbers until the end of the test (15). If the test design indicates that measureable drawdown is not expected at a given observation well for several hours after the test starts, the early measurements may, of course, not be necessary.

Discharge from the pumping well can be measured in several ways:
1. at wells with open discharge pipes— by the trajectory method, Hoff-meter method, and volumetrically with a tank and stopwatch method.
2. at wells with closed discharge pipes— by Pitot-tube and clamp-on ultrasonic flowmeter methods (29).
3. inline discharge measurements— by flow-rate pass-through meters and total-flow meters.
4. ditch or canal measurement— Hoff-meter, Price type M or pygmy current meters, weirs, or flumes.
The discharge is maintained at a constant rate by means of a gate-control valve. The discharge must be conducted away from the area of the pumped well.

For tests in which discharge is to be held constant throughout the test, the discharge should be measured periodically and adjusted as needed. Pumps powered by electric motors produce the most constant discharge. This discharge rate should not be allowed to vary more than $\pm$ 10 percent or it will produce aberrations in drawdowns that are difficult to analyze (15). Maintaining discharge at $\pm$ 10 percent is difficult in aquifers with low transmissivity that require flow rates less than 5 gal/min. Furthermore, discharge from tight formations must be checked and adjusted frequently, because the drawdowns are large.

2.3 General Approach to Aquifer- Test Analyses

Aquifer-test analyses involve the graphical transformation of field data into estimates of the hydraulic properties of the aquifer. These analyses include Thies, Jacob, recovery, and slug-test methods. Interpretation of aquifer tests requires a simplified concept off the aquifer, its boundaries, and the stress imposed on the aquifer. This reduction of a complex field setting to a quantifiable simplified aquifer representation is important in the determination of hydraulic coefficients. The objective is to closely simulate the observed effects of the stress imposed on the aquifer during the test.

The following examples of the use of type-curve methods apply to aquifer tests in relatively simple hydrologic settings. Analysis of more complex problems in the literature - (6), (8), (9), (3jO), (14), (15), (16), (17), (18), (22) - usually involves similar curve-matching techniques however.

The type-curve method devised by C. V. Theis (20) calculates values for two terms—transmissivity (T), and storativity (S)—in the equations:

$$s = \frac{Q\,W(u)}{4\pi T} \qquad \text{X-2.3-1}$$

and

$$u = \frac{r^2 S}{4\,T^{t}} \qquad \text{X-2.3-2}$$

where:

s = drawdown in response to the pumping
Q = pumping rate
T = transmissivity
S = storativity or storage coefficient
r = distance from the pumping well,
t = time since pumping began

In this procedure, r and t combine with T and S to define a dimensionless variable, u, and corresponding dimensionless response function W(u). Type-curve methods use W(u) in relation to u or 1/u. This; manual uses W(u) in relation to 1/u. A table of W(u) values for a range of u values is presented in table X-2.3-1; the graph of this relationship is shown in figure X-2.3-1.

Briefly, the method consists of plotting a function curve or type-curve, such as (1/u, W(u)) on logarithmic paper (figure. X-2.3-1) and plotting the time versus drawdown (t,s) data on a second sheet of logarithmic paper, having the same scales. If the two sheets are superimposed and matched with coordinate axes parallel, as shown in figure X-2.3-2, the respective coordinate axes will be related by the constant factors:

$$\frac{s}{W(u)} = CL \qquad \text{and} \qquad \frac{t}{(1/u)} = C_2$$

The values of these two constants are:

$$C_1 = \frac{Q}{4nT} \quad \text{and} \quad C_2 = \frac{R^2 s}{4T}$$

Thus, a common match point for the two curves may be chosen, and the four coordinate points W(u), 1/u, s, and t recorded for the common match point. T and S can be obtained from the following equations:

$$T = \frac{QW(u)}{4\,n\,s} \qquad \text{X-2.3-3}$$

and

$$S = \frac{4Tut}{r^2} \qquad \text{X-2.3-4}$$

where W(u), 1/u, s, and t are the match-point values.

The methods of analysis described below are used for tests in confined aquifers with fully penetrating wells, as shown in figure X-2.3-3; symbols used in these computations are listed and defined in table X-2.3-2. Water-table aquifers(fig. X-2.3-3) are analyzed by the same Methods. If drawdowns observed in thin water-table aquifers are adjusted by subtracting $s^2/2b$, equations based on the assumption of negligible dewatering and radial flow can be used (7). Where the dewatering is significant, the data plot used is s - ($s^2/2b$) and time which is matched to the 'type curves' of artesian flow. The value of S is obtained as follows (15):

$$S = \frac{(b-s)S'}{b} \qquad \text{X-2.3-5}$$

where:

s = the appropriate drawdown at the geometric mean radius of all observation wells at the end of pumping,
b = the original saturated thickness of the aquifer, and
S' = the apparent storage coefficient

Jacob's correction, $s^2/2b$, is most applicable to data from observation wells fully penetrating the aquifer but may also be used for observation wells open within the bottom two-thirds of the aquifer. Moreover, the correction is applicable only after the data begin to follow the artesian response curve (11) and does not apply if effects of partial penetration are significant.

The rate of drawdown with respect to time at any point within the cone of depression is needed for the Theis, Jacob, recovery, and slug test methods. The shape and position of the cone of depression with respect to distance at some time during the aquifer test is required for the distance-drawdown method. Certain assumptions must be considered for all methods presented. The following assumptions are common to all methods (6), (14), (15):

1. The aquifer is homogeneous and isotropic.
2. The aquifer has uniform thickness.
3. The aquifer is horizontal and infinite in areal extent.
4. The well is open to the aquifer throughout the aquifer thickness.
5. Flow to the well is laminar and uniform along the length open to the well.
6. The aquifer is bounded by relatively impermeable confining layers.
7. Water is released from storage instantaneously with a decline in head.
8. The well has a reasonably small diameter.
9. Hydraulic potential at the pumped well is the only cause of flow in the aquifer system during testing.

Even though all these assumptions are rarely satisfied in any particular aquifer test, the methods are still adequate for estimating the hydraulic properties of aquifers.

In addition to these common assumptions, each analytical method entails other assunptions. Some conditions that affect the theoretical aquifer response such as vertical boundary conditions, finite well diameter, and fractured rock permeability are briefly mentioned in the Practical Considerations chapter 2.7. Treatment of leaky aquifers, confining beds with storage, anisotrqpy, and partial penetration of wells, all of which are common factors to be dealt with in real aquifer tests, are not treated in this manual, but references on these conditions include (9), (14), (16), and (17).

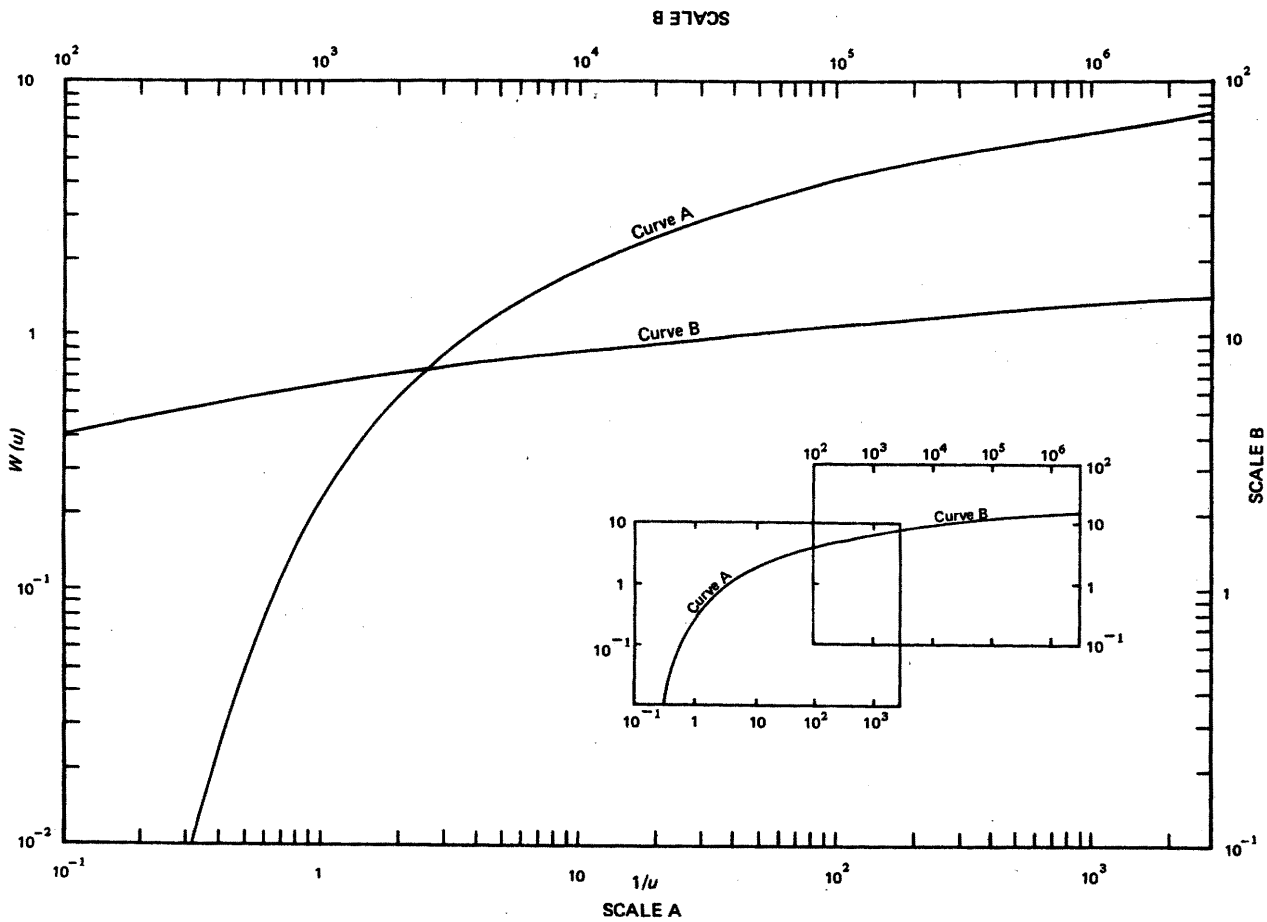


Figure X-2.3-1.— Type curve of dimensionless drawdown (W(u)) in relation to dimensionless time (1/u) for constant discharge from an artesian well (Theis curve). (Insert shows range of fields for curve A and curve B.) (Table X-2.3-1 presents W(u) versus 1/u.) (From Reed, 1980, pl. 1)

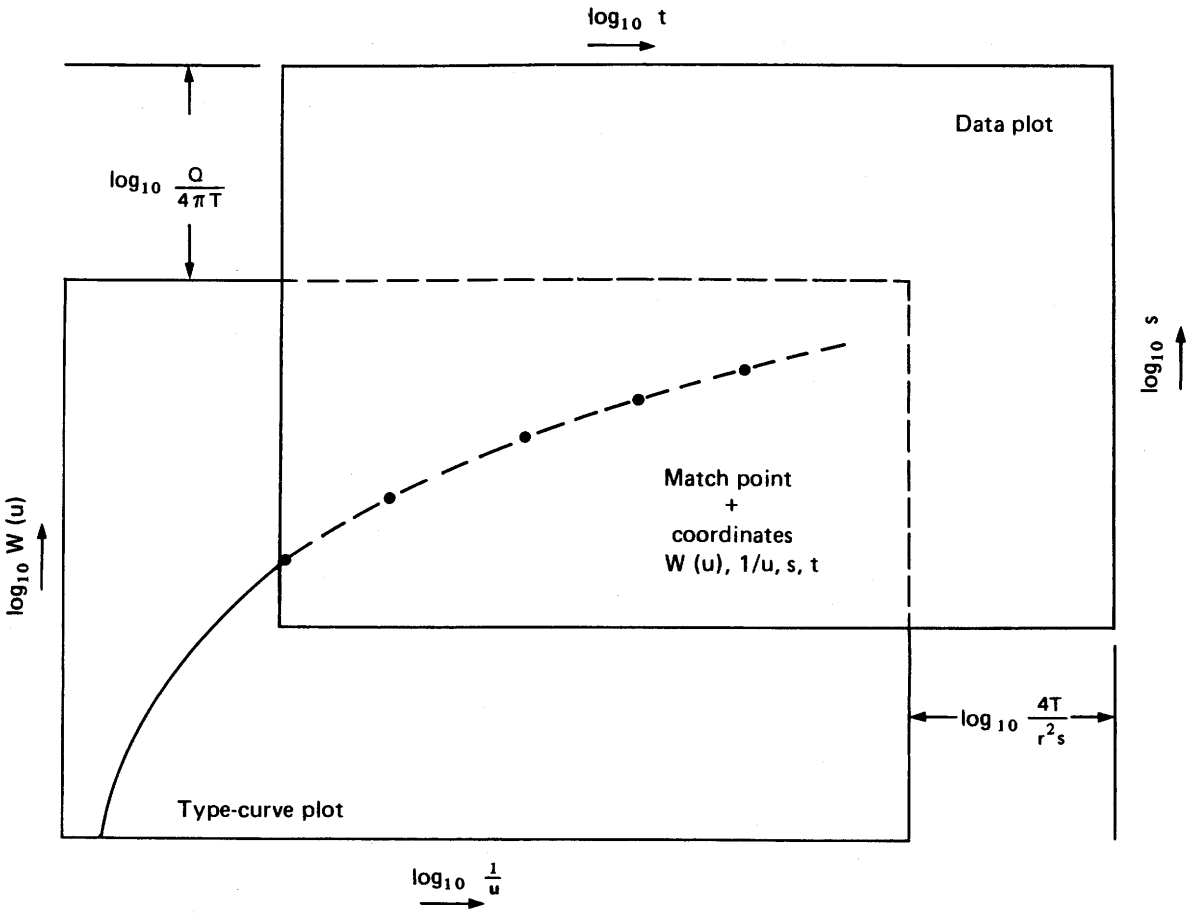


Figure X-2.3-2.— Superposition of W(u) versus l/u type curve onto B versus t data plot. (From Reed, 1980, fig. 0.1 and Stallman, 1971, fig. 1)

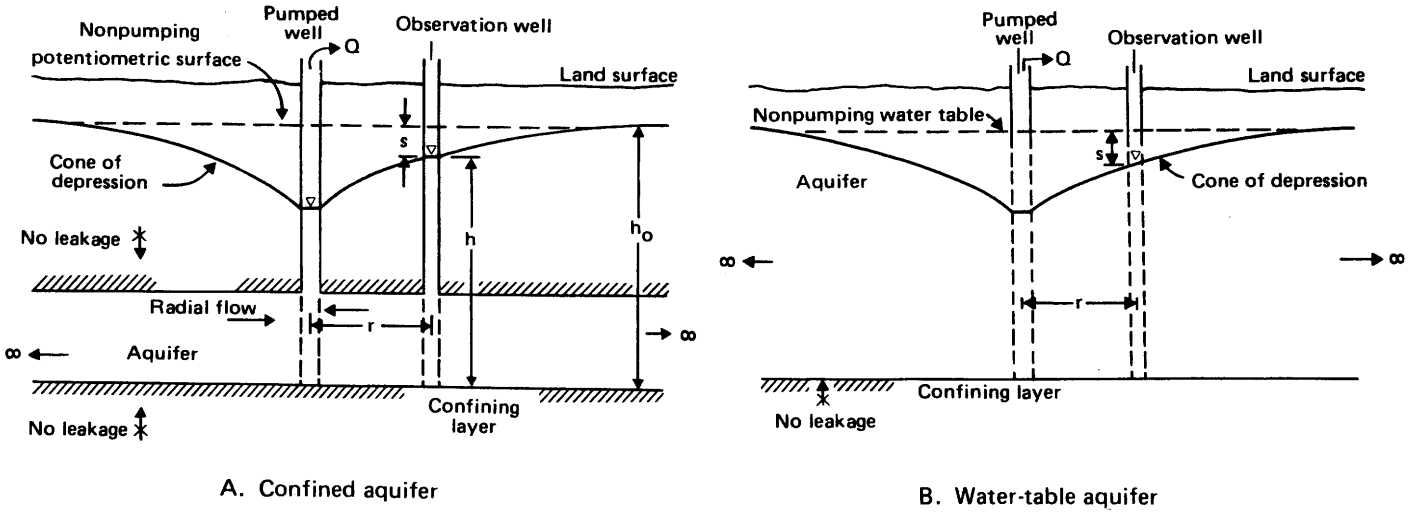


Figure X-2.3-3.— Drawdown conditions for aquifer tests with fully penetrating wells. (Modified from Walton, 1970, figs. 3.1 and 3.4)

Table X-2.3-1– Selected values of W(u) for values of 1/u.
(Modified from Heath, 1983, p. 35.)

Multiplication factor for 1/u	1/u value													
	10	7.69	5.88	5.00	4.00	3.33	2.86	2.5	2.22	2.00	1.67	1.43	1.25	1.11
$\times 10^{-1}$	0.219	0.135	0.075	0.049	0.025	0.013	0.007	0.004	0.002	0.001	0.000	0.000	0.000	0.000
$\times 1$	1.82	1.59	1.36	1.22	1.04	.91	.79	.70	.63	.56	.45	.37	.31	.26
$\times 10^{1}$	4.04	3.78	3.51	3.35	3.14	2.96	2.81	2.68	2.57	2.47	2.30	2.15	2.03	1.92
$\times 10^{2}$	6.33	6.07	5.80	5.64	5.42	5.23	5.08	4.95	4.83	4.73	4.54	4.39	4.26	4.14
$\times 10^{3}$	8.63	8.37	8.10	7.94	7.72	7.53	7.38	7.25	7.13	7.02	6.84	6.69	6.55	6.44
$\times 10^{4}$	10.94	10.67	10.41	10.24	10.02	9.84	9.68	9.55	9.43	9.33	9.14	8.99	8.86	8.74
$\times 10^{5}$	13.24	12.98	12.71	12.55	12.32	12.14	11.99	11.85	11.73	11.63	11.45	11.29	11.16	11.04
$\times 10^{6}$	15.54	15.28	15.01	14.85	14.62	14.44	14.29	14.15	14.04	13.93	13.75	13.60	13.46	13.34
$\times 10^{7}$	17.84	17.58	17.31	17.15	16.93	16.74	16.59	16.46	16.34	16.23	16.05	15.90	15.76	15.65
$\times 10^{8}$	20.15	19.88	19.62	19.45	19.23	19.05	18.89	18.76	18.64	18.54	18.35	18.20	18.07	17.95
$\times 10^{9}$	22.45	22.19	21.92	21.76	21.53	21.35	21.20	21.06	20.94	20.84	20.66	20.50	20.37	20.25
$\times 10^{10}$	24.75	24.49	24.22	24.06	23.83	23.65	23.50	23.36	23.25	23.14	22.96	22.81	22.67	22.55
$\times 10^{11}$	27.05	26.79	26.52	26.36	26.14	25.96	25.80	25.67	25.55	25.44	25.26	25.11	24.97	24.86
$\times 10^{12}$	29.36	20.09	28.83	28.66	28.44	28.26	28.10	27.97	27.85	27.75	27.56	27.41	27.28	27.16
$\times 10^{13}$	31.66	31.40	31.13	30.97	30.74	30.56	30.41	30.27	30.15	30.05	29.87	29.71	29.58	29.46
$\times 10^{14}$	33.96	33.70	33.43	33.27	33.05	32.86	32.71	32.58	32.46	32.35	32.17	32.02	31.88	31.76

Examples: When $1/u = 3.33 \times 10^{-1} = 0.333$, $W(u) = 0.013$; when $1/u = 10 \times 10^{-1} = 1$, $W(u) = 0.219$.

Table X 2.3-2.3-2 –Terms used in aquifer testing.

Symbol	Definition	Units of Measure
b	Thickness of saturated part of the aquifer.	Feet.
K	Hydraulic conductivity of aquifer for horizontal flow.	Feet per day.
L	Length of open hole or screen open to aquifer.	Feet.
π	pi = 3.14159	Dimensionless.
Q	Discharge from a well.	Gallons per minute.
r	Distance from pumping well to observation point.	Feet.
r_c	Radius of casing	Feet.
r_w	Radial distance from the well center and the undisturbed aquifer, which includes the sand and gravel envelope.	Feet.
s	Change in head, or drawdown	Length.
Δs	Change in drawdown over one log cycle of t or $\frac{t}{t}$, (for straight-line solutions)	Length.
s_w	Constant drawdown (for flowing-well analysis)	Feet.
S	Storage coefficient of the aquifer(storativity).	Dimensionless.
S'	Apparent storage coefficient, observed in aquifers dewatered significantly in proportion to saturated thickness.	Dimensionless.
Sya	apparent specific yield	Dimensionless.
t	Time since pumping began.	Minutes.
t'	Time since pumping ceased, for recovery test analysis.	Minutes.
t_o	time when drawdown is zero (from extension of straight line solutions)	Minutes.
T	Transmissivity of aquifer.	Feet squared per day.
u	$\frac{r^2 s}{4Tt}$	Dimensionless.
W(u)	Theis Well function of variable (u)	Dimensionless.
y	recovery drawdown (Bouwer and Rice method)	Feet.
y_0	recovery drawdown when time is zero.	Feet.
y_t	recovery drawdown at any time, t.	Feet.

2.4 Pumping Test Methods and Analyses

Three cornmon pumping test methods used on nonflowing wells are the Theis method, Jacob straight-line method, and the recovery method. Hydrologists commonly apply all three test methods to verify results. The general procedure for each method is outlined below; assumptions beyond those mentioned earlier are included. Some data used for the examples are from Barrett and others, 1980. Metric units have been converted to inch-pound units for consistency. Aquifer-test geometry, terms, and symbols used in the sample analyses are depicted in figure X-2.3-3 and defined in table X-2.3-2.

Theis Analysis

Additional assumption:

1. Well discharge, Q, is constant starting at t = 0.

Procedure:

1. Plot s (drawdowns) against t/r^2 , such as shown in figure X-2.4-1 on transparent log-log paper[1/] having the same scale as the Theis-type curve (9) (14).
2. Superimpose this field plot over the type curve. Move the field plot over the type curve, keeping both axes parallel, until a best fit is made between the two curves.
3. Select any arbitrary match point and record the values of W(u) and 1/u from the type curve and the corresponding values of t/r^2 and s (figure X-2.4-1).
4. Insert these values of W(u), 1/u, t/r^2 , and s into equations X-2.3-3 and X-2.3-4 to determine T and S:

$$T = \frac{Q\ W(u)}{4\ \pi\ s} \qquad \text{X-2.3-3}$$

and

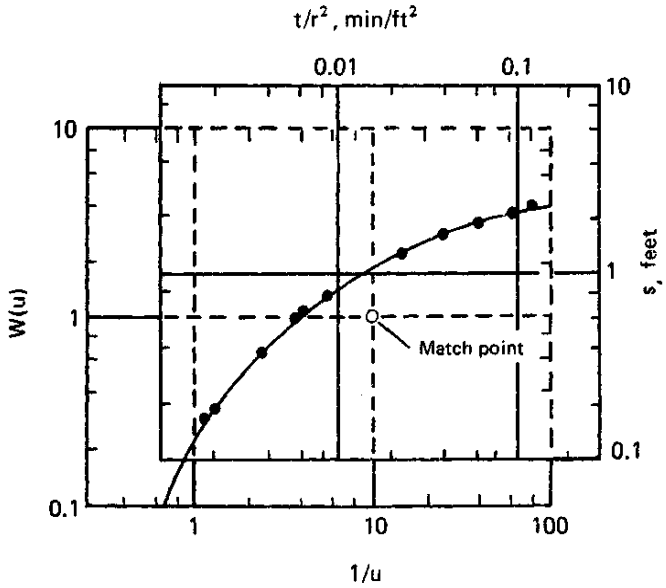
$$S = 4\ T\ u\ \frac{t}{r^2} \qquad \text{X-2.3-4}$$

Note that the field plot could be s versus t for only one observation well. For such plots, the radius can be accounted for in the formula used to compute storage coefficient. Also, the Theis analysis can be used to determine transmissivity in the pumped well.

[1/] 'K & E' - # 467323 - (Keuffel & Esser Co.) 2 cycles by 3 cycles.

(a) pumping test data.
[r, distance;
Q, discharge;
s, drawdown;
t, time;
ft, feet;
gal/min, gallons per minute;
ft^2, square feet.]

r = 65.6ft, Q = 494 gal/min



t/r^2 (min/ft^2)	s (ft)
0.00105	0.08
.00174	.16
.00197	.18
.00372	.36
.00557	.56
.00615	.59
.00837	.72
.0149	.98
.0226	1.21
.0376	1.48
.0600	1.74
.0948	2.03
.113	2.10
.119	2.13

(b) Curve matching of Theis curve to drawdown data.

(c) Calculation for Theis drawdown method.

Match point coordinates:

from fig. X-2.4-l(b), the match point coordinates:

$W(u) = 1.0,\ 1/u = 10,\ s = 0.60,\ t/r^2 = 0.015$

$$T = \frac{Q\,W(u)}{4\,\pi\,s} = \frac{(494\ \text{gal/min})\ (1.0)\ (1440\ \text{min/d})}{4\,\pi\ (0.60\ \text{ft})(7.48\ \text{gal/ft3})}$$

$$= 12{,}600\ \text{ft}^2$$

$$S_{ya} = \frac{4T\,t}{r^2\ (l/u)} = \frac{4\ (12{,}600\ \text{ft}^2/\text{d})\ (0.015\ \text{min/ft}^2)}{(10)\ (1440\ \text{min/d})}$$

$$= 0.053$$

Figure X-2.4-1— Example of data and calculations for Theis analytical method, (From Barrett and others, 1980, p. 79)

Jacob Straight-Line Method (Cooper-Jacob Method, 1946)

Additional assumptions:

1. Well discharge, Q, is constant starting at t = 0.
2. Test must be conducted for a time sufficiently long to satisfy the condition:

$$\frac{r^2 S}{4Tt} \text{ is less than } 0.01$$

where: S = storage coefficient or apparent specific yield.

Procedure:

1. Plot drawdown on the vertical axis against time on the horizontal (logarithmic) axis of semilog paper[1/] (see figure X-2.4-2).
2. Eventually, the data should plot as a straight line. From the line, determine the change in drawdown over one log cycle.
3. Insert the change of drawdown over one log cycle (As) into the following equation to determine T:

$$T = 2.30 \frac{Q}{4 \pi \Delta s} \qquad \text{X-2.4-1}$$

4. Extrapolate the straight segment of the data plot to the horizontal axis where: s = 0. Determine the time (t_o) where the line intersects the horizontal axis.
5. Insert to into the following equation to determine S:

$$S = 2.25 \frac{Tt_o}{r^2} \qquad \text{X-2.4-2}$$

6. Determine the time for which the data meets assumption 2 above by inserting the T and S values into

$$t = \frac{r^2 S}{4Tu} \qquad \text{X-2.4-3}$$

where: u = 0.01. Drawdown data collected at times less than this value of t should not be used in the straight-line plot.

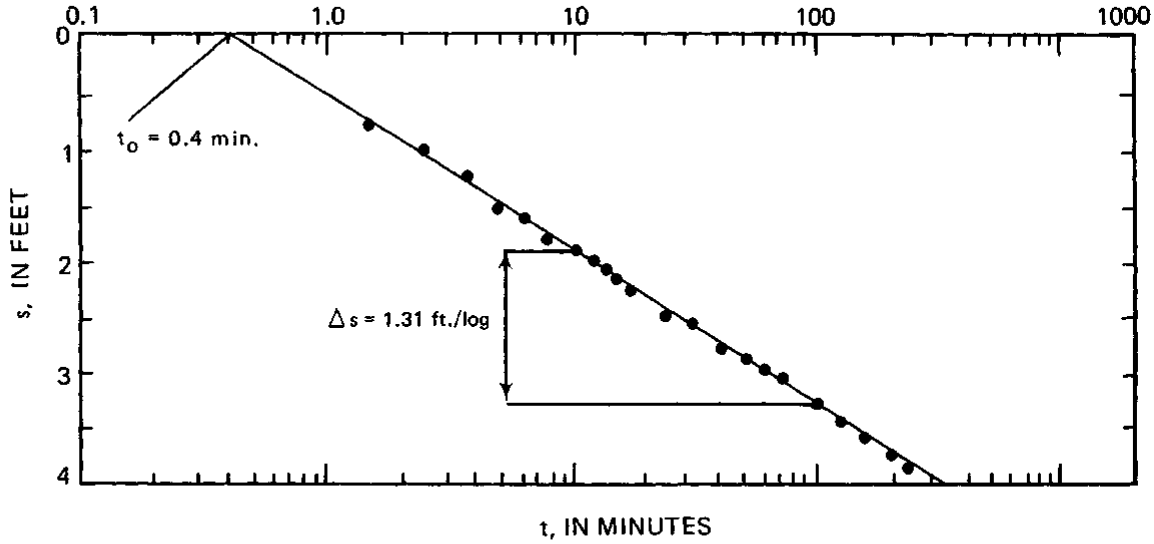
This method carmonly is used to analyze drawdown data from the pumped well. When so used, the restriction that u must be less than 0.01 is usually met. However, well-bore storage is expected to be a significant source of error in very tight aquifers. Treatment of the well storage problem is discussed in chapter X-2.6.

The coefficient of storage (storativity) from the drawdown response of a pumped well cannot be determined (6).

[1/] 'K&E'- # 466212 - 5 cyclesx70 divisions.

(a) pumping test data.
[r, distance;
Q, discharge;
s, drawdown;
t, time;
ft, feet;
gal/min, gallons per minute;
ft^2, square feet.]

r = 200 ft.
Q = 487 gal/min



t (min)	s (ft)
1	0.66
2	.98
3	1.21
4	1.36
5	1.48
6	1.59
8	1.74
10	1.87
12	1.97
14	2.08
18	2.20
24	2.36
30	2.49
40	2.66
50	2.79
60	2.87
80	3.03
100	3.17
120	3.28
150	3.43
180	3.51
210	3.61
240	3.67

(b) Example of Cooper-Jacob method applied to drawdown data.

(c) Calculation for Jacob drawdown method.

from fig. X-2.4-2(b), As = 1.31 ft/log cycle; t_o = 0.4 min

$$T = \frac{2.30\ Q}{4\pi\Delta s} = \frac{2.30\ (487 gal/min)\ 1440\ min/d}{4\ \pi\ (1.31)\ (7.48\ gal/ft^3)} = 13{,}100\ ft^2/d$$

$$S = \frac{2.25\ T\ t_o}{r^2} = \frac{2.25\ (13{,}100)\ (0.4)}{(200)^2\ (1440\ min/d)} = 0.00020$$

for this method to be valid, $u \leq 0.01$ or

$$t = \frac{r^2}{4}\ \frac{S}{T\ u} = \frac{(200)^2\ (0.0002)\ (1440)}{(13{,}100)\ (0.01)} = 22\ min$$

Therefore, only the data points for time greater than 22 minutes should be used to determine hydraulic coefficients by this method.

Figure X 2.4-2.— Example of data and calculations for Cooper-Jacob analytical method.
(Modified from Barrett and others, 1980, p. 80)

Theis Recovery Method

Additional assumptions:

1. Well discharge, Q, is constant starting t = 0. The pump is shut off some time later, tr = 0.
2. Same assumption 2 as for Jacob Straight-line Method.

Procedure:

1. For each time that drawdown was measured during recovery, compute the ratio of time since pumping started, t, over time since pump was turned off tr. (See fig. X-2.4-3).
2. Plot residual drawdown on the vertical axis against t/tr on the horizontal axis of semilog paper. Residual drawdown is the difference between the observed water level and the non-pumping, static water level trend extrapolated from the prepumping period.
3. The data should fall on a straight line after a long time over which the change in drawdown over one log cycle (Δs) can be computed, (See fig. X-2.4-3).
4. Determine T from equation X-2.4-1:

$$T = 2.30 \frac{Q}{4 \pi \Delta s} \qquad \text{X-2.4-1}$$

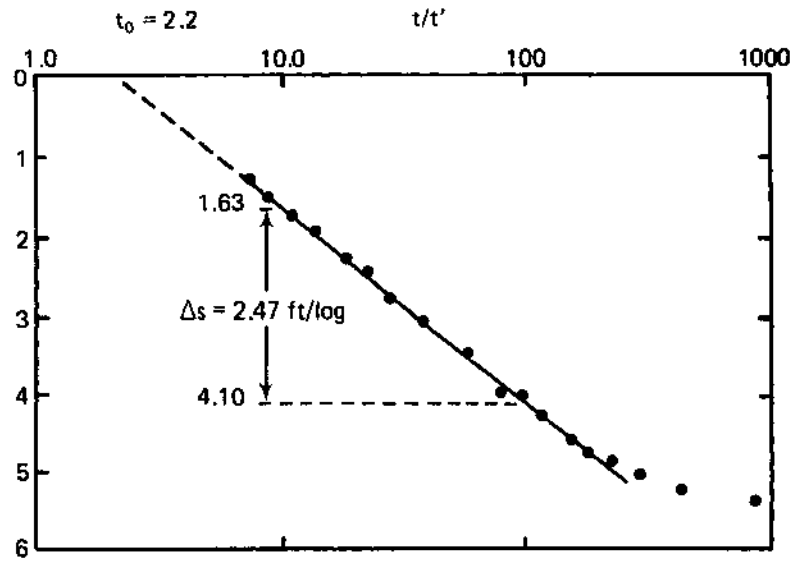
5. To determine the storage coefficient, or apparent specific yield, extrapolate the straight-line segment of the data plot to the horizontal axis, and determine to at the intersection of the straight line and the horizontal axis.
6. Insert the value of t_o into the equation X-2.4-2:

$$S = 2.25 \frac{Tt_o}{r^2} \qquad \text{X-2.4-2}$$

The precautions concerning the use of the Jacob straight-line method in the pumping well data analysis hold true for the recovery method.

(a) recovery test data.
[r, distance; Q, discharge;
s, drawdown; t, time;
t_p, pumping time;
tr, time since pump turned off;
t_o, time from graph when drawdown is zero,
ft, feet;
gal/min, gallons per minute.]

r = 15.1 ft;
Q = 473 gal/min;
t_p = 443 min



(b) Example of data plot for Theis recovery method.

tr (min)	t/tr	s (ft)
0.5	887.	5.38
1.0	444.	5.23
1.5	296.	5.03
2.0	223.	4.89
2.5	178.	4.74
3.0	149.	4.59
4.0	112.	4.28
4.5	99.4	4.05
5.5	81.5	3.94
8.0	56.4	3.48
12.	37.9	3.05
16.	28.7	2.77
21.	22.1	2.48
26.	18.0	2.30
36.	13.3	1.94
46.	10.6	1.71
56.	8.91	1.48
71.	7.24	1.26

(c) Calculations for Theis recovery method.

from fig. X-2.4-3(b) Δs = 2.47 ft/log cycle
and at s = 0 ft t/tr = 2.2

$$T = \frac{2.30\ Q}{4\ \pi\ \Delta s} = \frac{2.30\ (473)\ (1440\ \text{min/d})}{4\ \pi (2.47)\ (7.48\ \text{gal/ft}^3)}$$

$$T = 6{,}750\ \text{ft}^2/\text{d}$$

$$S = \frac{2.25\ T\ t_o}{r^2} = \frac{2.25\ (6{,}750)\ (2.2)}{(15.1)^2 (1{,}440\ \text{min/d})}$$

$$= 0.10$$

Figure X-2.4-3.— Example of data and calculations for Theis recovery method. (Modified from Barrett and others, 1980, p. 81)

2.5 Slug-Test Method

Slug test methods are single-well tests used to determine the aquifer transmissivity of the rock material near well-bore. The basic assumptions for these methods are that (1) a known volume, V, is injected into, or removed from, the water-filled portion of the well instantaneously, at t = 0, and (2) the well is of finite diameter and fully penetrates the aquifer.

The method of Cooper and others (1967) is for application to non-leaky confined aquifers. Storage coefficient (storativity) can also be determined by this method, but with questionable reliability because of the similarity of shapes of the type curves. The determination of transmissivity, however, is insensitive to the choice of the correct curve (4).

The Bouwer and Rice method (1976) can be used to determine hydraulic conductivity of water-table aquifers with completely or partially penetrating wells, and completely or partially perforated screens. The example presented is for a fully penetrating well that is partially perforated. In addition to the assumptions mentioned above delayed yield of ground water from the unsaturated zone is ignored. Therefore, the slug volume need only be removed from the well for this water-table aquifer analysis.

Both methods provide estimates of hydraulic coefficients of aquifer material close to the well bore which commonly is altered by fracturing and (or) infiltration of drilling mud. Therefore, knowledge of near-borehole conditions, such as from drillers logs and downhole geophysical logs, is needed before values of transmissivity can be accepted as representative of the aquifer characteristics at the well site. The slug-test method has applicability when wells are not flowing or a pump is not available. The slug-test method, when applied to completely developed wells, can nonetheless provide reasonable estimates of hydraulic properties. Slug tests are most suitable for aquifers having low transmissivity, less than 7,000 ft^2/d (9).

Cooper and Others (1967) Method

Procedure:

1. Plot the ratio H/HQ on the vertical axis and time(t) on the logarithmic axis of semilog paper. (See fig. X-2.5-1). where:
   - H = head inside the well at some time, t, after injection or removal of the slug, above or below the initial head. (See figure X-2.5-1).
   - H_o = head inside the well above or below initial head at instant of slug injection or removal.
   - r_c = radius of casing in interval over which level fluctuates. rw = radius of well screen or open hole.

   For a known slug volume, V: $H_o = \frac{V}{\pi r_c^2}$ X-2.5-1

2. Superimpose the field plot onto the suitable type curve of H/HQ versus Tt/r_c^2 (9), (14). Keeping axes parallel, adjust the field plot until a best fit is achieved (fig. X-2.5-2).

3. Select an arbitrary match point and record the value of t (from the field plot) which correlates to Tt/r_c^2 the type curve.

4. Compute T from these values of t and Tt/r_c^2 in the equation

$$T = \frac{(Tt/r_c^2)}{t} r_c^2 \qquad \text{X-2.5-2}$$

5. Compute S by inserting oc (type-curve designation), into the following equation:

$$S = oc \frac{t_c^2}{r_w^2} \qquad \text{X-2.5-3}$$

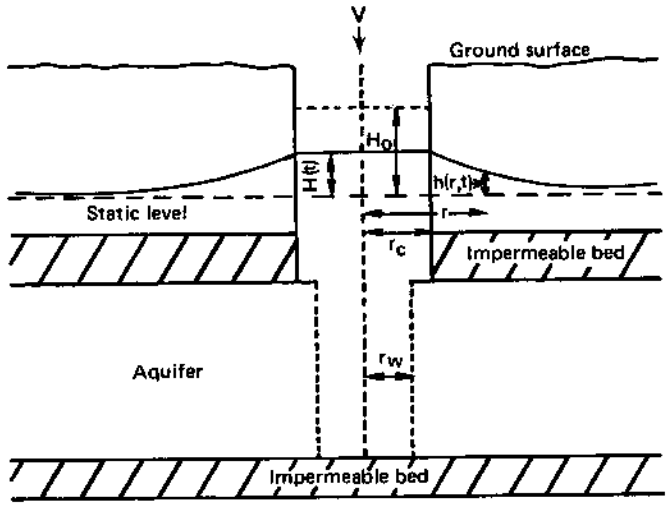


Figure X-2.5-1.— Cross section through a well in which a known volume is instantaneously injected.
(Modified from Reed, 1980, fig. 9.1)

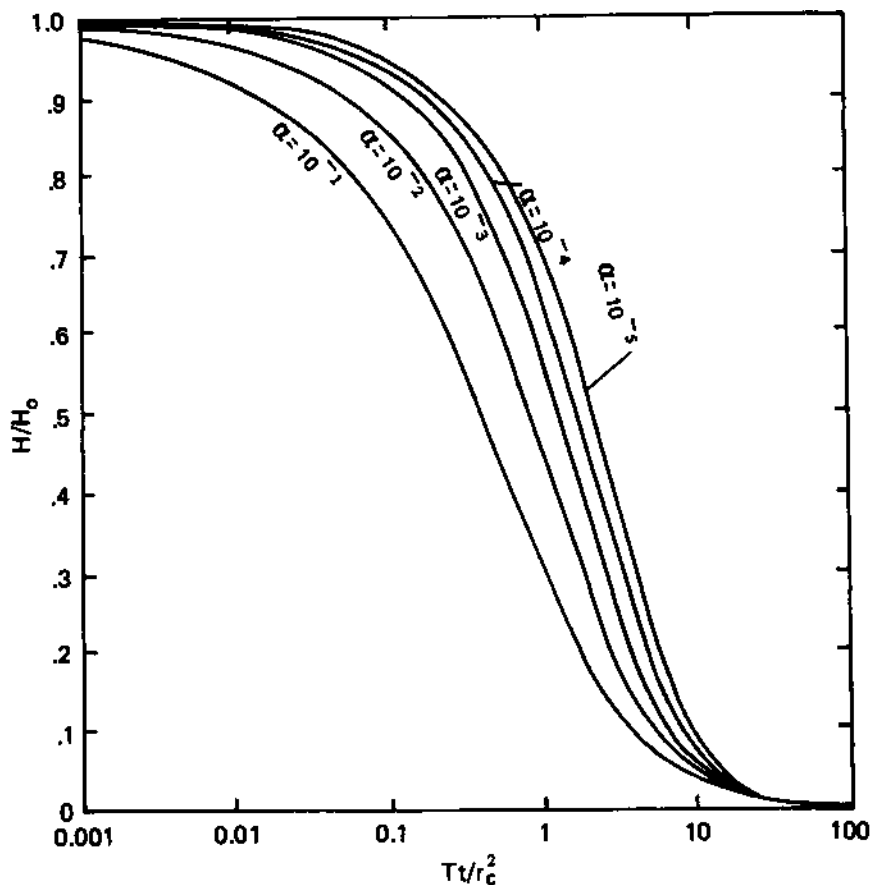
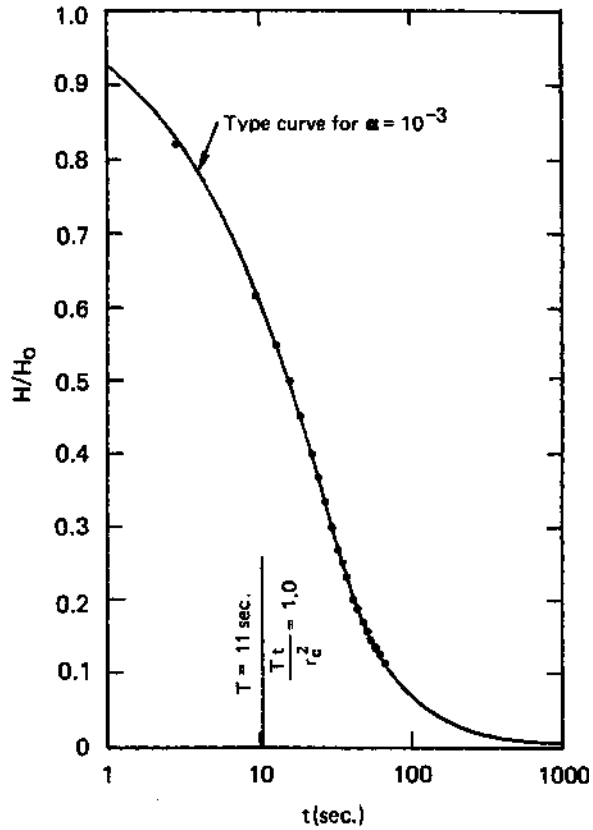


Figure X-2.5-2.— Type curves for instantaneous charge in well of finite diameter, for H/H_o versus Tt/r_c^2 for five values of *a*.
(From Lohman, 1972, pl. 2; and Cooper and others, 1967, table 1)

(a) Rise of water level in Dawsonville well after instantaneous withdrawal of weighted float.
[H, head at some time, t, after injection or removal of 'slug';
H_0, head above or below initial head at instant of 'slug'; (Ho=0.560m.)
m, meters; t, time]
(From Cooper, Bredehoeft, and Papadopulus, 1967, table 3)

t (sec)	Head above datum (m)	H (m	$\frac{H}{H_o}$
-1	0.896	—	——
0	.336	0.5	1.000
3	.439	.45	.816
6	.504	.39	.700
9	.551	.34	.616
12	.588	.30	.550
15	.616	.28	.500
18	.644	.25	.450
21	.672	.22	.400
24	.691	.20	.366
27	.709	.18	.334
30	.728	.16	.300
33	.747	.14	.266
36	.756	.14	.250
39	.765	.13	.234
42	.784	.11	.200
45	.788	.10	.193
48	.803	.09	.166
51	.807	.08	.159
54	.814	.08	.146
57	.821	.07	.134
60	.825	.07	.127
63	.831	.06	.116



(b) Curve matching of data from fig. X-2.5-3(a) and type curve $a = 10^{-3}$ from fig. X-2.5-2.

(c) Calculations for Cooper and others slug test method.

$r_w = r_c = 0.25$ ft

from fig. X-2.5-3(b) t = 11 sec.

and $Tt/r_c^2 = 1.0$

$$T = \frac{(1.0)\, r_c^2}{t} = \frac{(1.0)\,(0.25)^2}{11}$$

$= 0.0057\ ft^2/sec$

$= 490\ ft^2/d$

Figure X 2.5-3. Example of data and calculations for Cooper and others slug test method. (Modified from Cooper and others, 1967, p. 268)

Bouwer and Rice Method (1976)

Geometry and symbols used in this method are presented in figure X-2.5-3; a sample data set and plot of the data are included.

Procedure:

1. Plot recovery, y_t, on the logarithmic axis against time, t, on the arithmetic axis of semilog paper. (See fig. X-2.5-4).
2. Extrapolate the best-fitted straight line to intersect the t = 0 axis and determine y_o. For tests in which water-level change occurs within the casing having radius r_c, the value of y_o can be compared to the volume, V, removed from the well by:

$$y_o = \frac{V}{\pi r_c^2} \qquad \text{X-2.5-4}$$

3. From the straight-line plot, select an arbitrary time, t, and note the corresponding value of y_t Insert these values and y_o from above into the following expression:

$$\frac{1}{t} \ln \left| \frac{y_o}{y_t} \right| \qquad \text{X-2.5-5}$$

This expression is a constant for any value t and corresponding y_t from the straight-line plot.

4. Determine the coefficient C (figure X2.5-5) corresponding to the value of $\frac{LK}{r_w}$ derived from the well construction data
   where: L = the length of open hole or screen open to aquifer, and
   r_w = the radial distance between the undisturbed aquifer and the well center of which includes sand and (or) gravel envelopes, (See fig. X-2.5-3).
5. Solve the following equation for the natural logarithm of the ratio R_e/r_w where R_e is the effective radius of influence due to head loss y_t:

$$\ln \left| \frac{R_e}{r_w} \right| = \left| \frac{1.1}{\ln \left| \frac{H}{r_w} \right|} + \frac{C}{\frac{L}{r_w}} \right|^{-1} \qquad \text{X-2.5-6}$$

This equation is used for the case in which D = H. For partial penetration of (H less than D), use the following equation:

$$\ln \left| \frac{R_e}{r_w} \right| = \left| \frac{1.1}{\ln \left| \frac{H}{r_w} \right|} + \left| \frac{A + B \ln \left| \frac{D - H}{r_w} \right|}{\frac{L}{r_w}} \right| \right|^{-1} \qquad \text{X-2.5-7}$$

with an upper limit of $\ln \left| \frac{D-H}{r_w} \right| = 6$; and, where coefficients A, B, and C are obtained from figure X-2.5-5.

6. Substitute values from steps 3 and 5 along with casing radius, r_c, and screen length, L, into the following equation to determine hydraulic conductivity, K:

$$K = \frac{r_c^2 \ln}{2L} \left| \frac{R_e}{r_w} \right| \bullet \frac{1}{t} \ln \left| \frac{y_o}{y_t} \right| \qquad \text{X-2.5-8}$$

7. If needed, an approximation of transmissivity would be T = L•K.

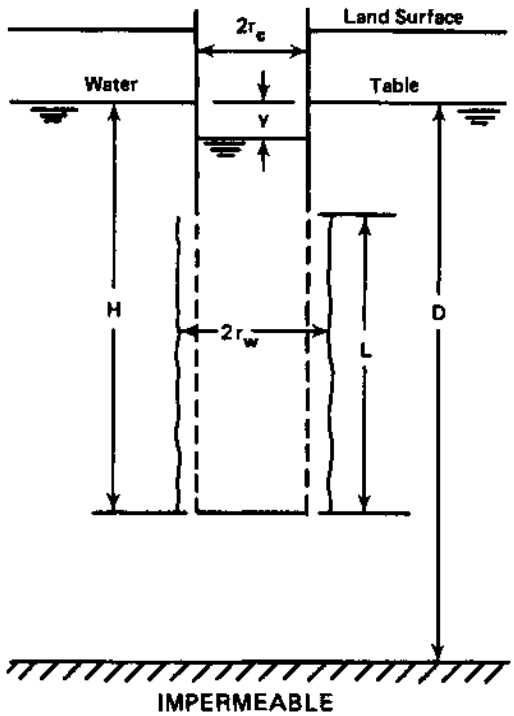


Figure X-2.5-4.— Geometry and symbols of a partially penetrating, partially perforated well in a water-table aquifer with gravel pack or developed zone around perforated section. (From Bouwer and Rice, 1976, fig. 1)

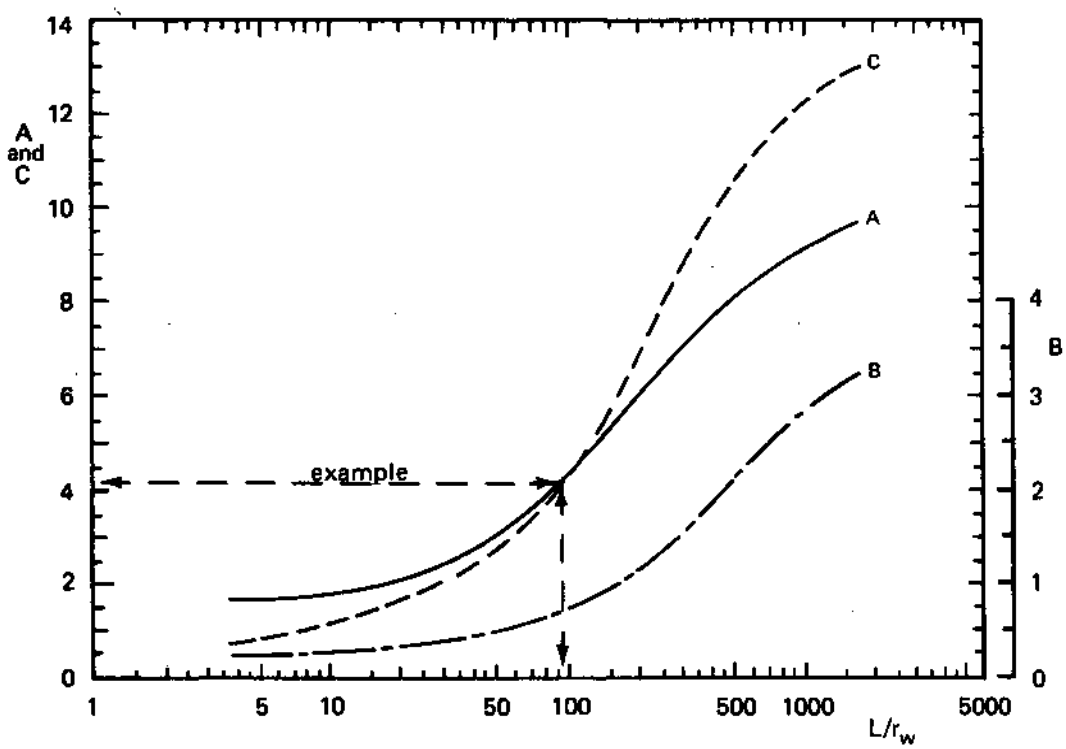
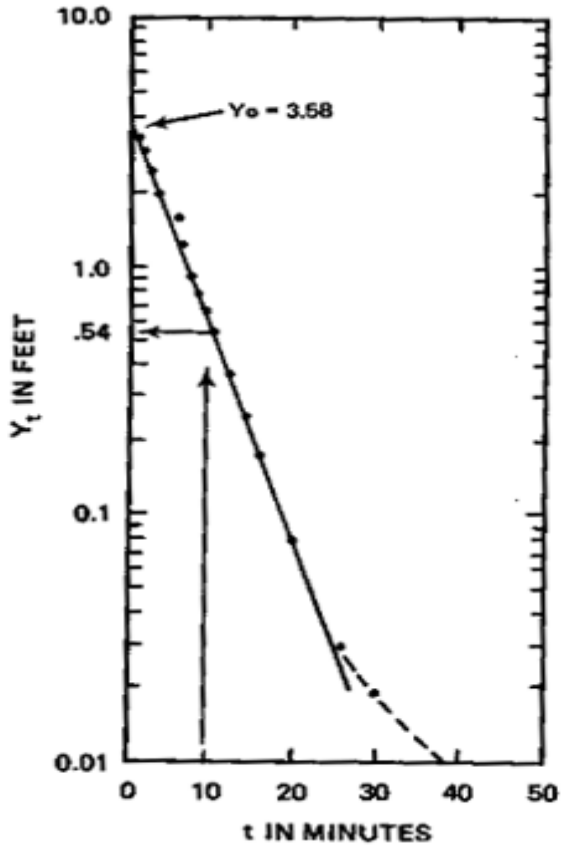


Figure X-2.5-5.— Curves relating coefficients A, B, and C, to L/r_w. (From Bouwer and Rice, 1976, fig. 3)

(a) Recover slug test data.
[r_c, radius of casing;
r_w, radius of well,
L, length of open hole;
H, distance between the water level and the bottom of the well; t, time; y_t, recovery distance of water level;
ft, feet; min., minute.]

2 r_c, = 0.42 ft; L=20 ft;
r_w,= 0.21 ft; H= 94.08 ft.

t (min.)	Y_t (ft)
0.5	3.27
1.0	2.94
2.0	2.44
3.0	2.01
4.0	1.68
5.0	1.39
6.0	1.24
7.0	0.96
8.0	0.81
9.0	0.68
10.0	0.56
12.0	0.38
14.0	0.26
16.0	0.18
18.0	0.12
20.0	0.08
25.0	0.05
26.0	0.03
30.0	0.02
40.0	0.01



b) Example of data plot for Bouwer and Rice slug test method.

c) Calculations for Bouwer and Rice method.

with $r_w = r_c = 0.21$ ft, L = 20 ft, and H = D = 94.08 ft
from fig. X-2.5-6(b), intercept at t = 0, y_o = 3.58 ft
and with t = 10 min, y_t = 0.54 ft

$$\frac{1}{t} \ln (y_o/y_t) = \frac{1}{10} \ln (3.58/0.54) = 0.19 \text{ min}^{-1}$$

L/ r_w = 20/0.21 = 95.2 and from fig. X-2.5-5, C = 4.25

$$\ln (R_e/r_w) = \left| \frac{1.1}{\ln H/r_w} + \frac{C}{L/r_w} \right|^{-1} = 4.45$$

$$K = r_c^2 \frac{\ln(Re/r_w)}{2L} \frac{1}{t} \ln(y_o/y_t) = 0.00093 \text{ ft/min} = 1.33 \text{ ft/d}$$

$$T = K\P b - 1.33 \times 20 = 27 \text{ ft}^2/\text{d}$$

Figure X 2.5-6. Example of data calculations for Bouwer and Rice slug test method. (Modified from. Burrett and others, 1980, fig. 22)

2.6 Aquifer Test with Constant Drawdown and Variable Discharge (Plowing Well)

Transmissivity and storativity can be determined on a naturally flowing (artesian) well after the well has been shut-in for a sufficient period of time that the artesian head is virtually static. During the test, the well is allowed to flow for 2 to 4 hours, and the discharge is measured at specific time intervals. The constant drawdown, s_w, in the discharging well is the difference between the static head and the head at the discharge point. The field data collected are the time and the instantaneous discharge measurements. (See table X-2.6-1). The assumptions for the aquifer test analyses are that the aquifer is homogeneous, isotropic, and extensive laterally, and that T and S are constant at all times and all places.

Procedure:

1. Reduce the field data to $\frac{s_w}{Q}$ and $\frac{t}{r_w^2}$ as shown in table X-2.6-1.

   where: s_w = constant drawdown in the discharging well.
   r_w = radius of discharging well,
   t = time since discharging began.
   Q = instantaneous discharge.
2. Plot $\frac{t}{r_w^2}$ on the logarithmic axis against $\frac{s_w}{Q}$ an the arithmetic axis of semilog paper as shown in figure X-2.6-1.
3. Interpolate best straight line for the data and determine the change of $\frac{s_w}{Q}$ for a log cycle of $\frac{t}{r_w^2}$.
4. Compute T from the respective values of step 3 into equations, from Lohnan, 1972, p. 23, equation 71:

$$T = \frac{2.30}{4\pi\,(s_w/Q)/\,\Delta \log_{10}(t/r^2)} \qquad \text{X-2.6-1}$$

5. Compute S in the data region of the straight-line plot from Lohrnan, 1972, equation 74:

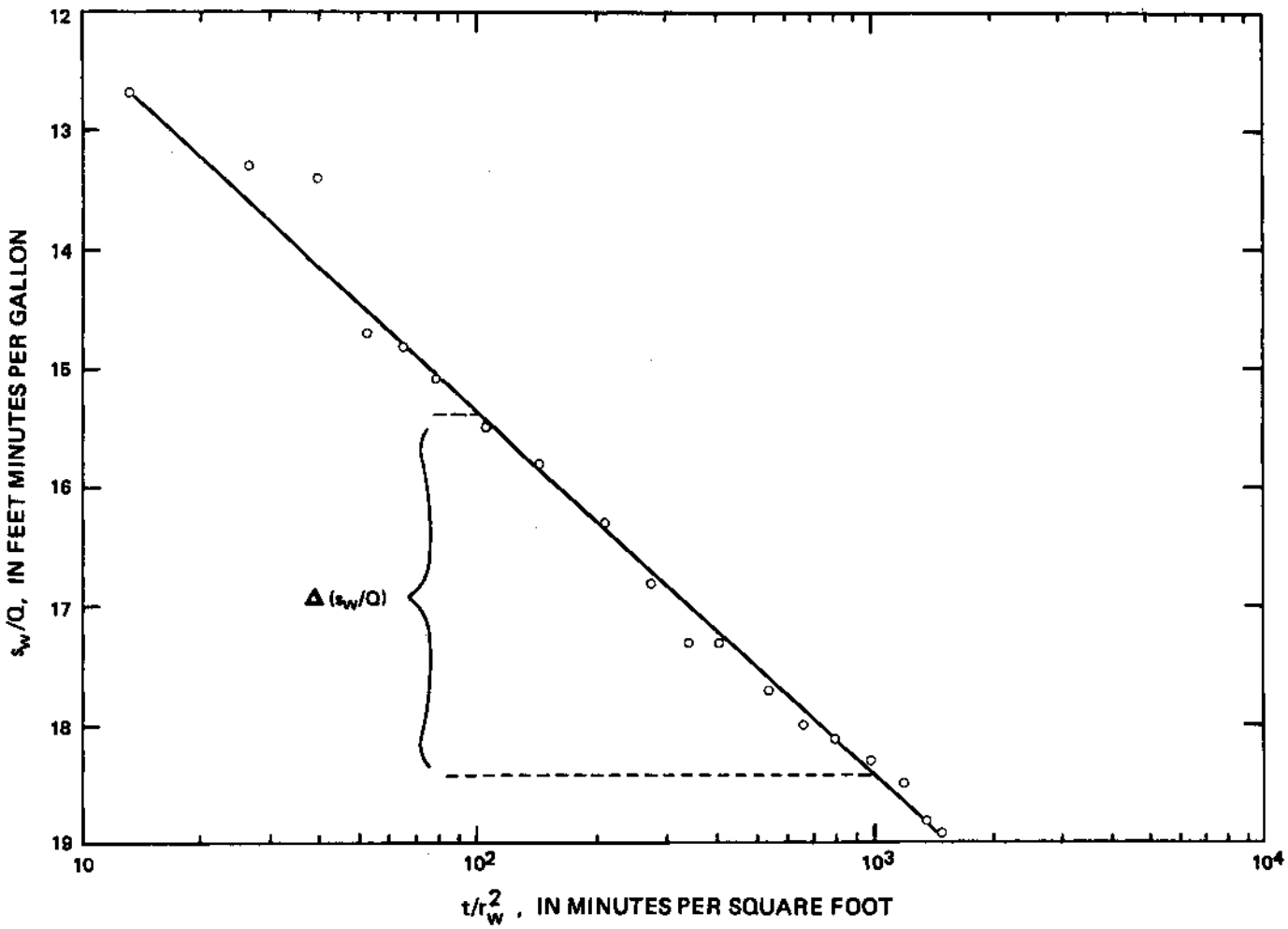
$$S = \frac{2.25\,T\,(t/r_w^2)}{\text{antilog}_{10}\left|\frac{s_w/Q}{\frac{s_w}{Q}}\right|} \qquad \text{X-2.6-2}$$

Table X 2.6-1.– Example of field data for flow test with constant drawdown and variable discharge.
(From Lohman, 1972, table 8; and Lohman, 1965, tables 6 & 7)

[gpm, gallons per minute; min, minute; ft/min, feet per minute; min/ft2, minute per square feet]
(Valve opened at 10:29 a.m.; s_w = 92.33 ft; r_w = 0.276 ft; Entrada Sandstone; well depth = 940 ft; depth of casing 936; ft; shut-in time about 12 hours.)

Time of observation	Rate of flow (gpm)	Flow interval (min)	Total flow during flow	Time since flow started	$\frac{s_w}{Q}$ (ft/min)	$\frac{t}{r_w^2}$ (min/ft^2)
10:30	7.28	1	7.28	1	12.7	13.1
10:31	6.94	1	6.94	2	13.3	26.3
10:32	6.88	1	6.88	3	13.4	39.4
10:33	6.28	1	6.28	4	14.7	52.6
10:34	6.22	1	6.22	5	14.8	65.7
10:35	6.22	1	6.22	6	15.1	78.8
10:37	5.95	2	11.90	8	15.5	105
10:40	5.85	3	17.55	11	15.8	145
10:45	5.66	5	28.30	16	16.3	210
10:50	5.50	5	27.50	21	16.8	276
10:55	5.34	5	26.70	26	17.3	342
11:00	5.34	5	26.70	31	17.3	407
11:10½	5.22	10.5	54.81	41.5	17.7	345
11:20	5.14	9.5	48.83	51	18.0	670
11:30	5.11	10	51.10	61	18.1	802
11:45	5.05	15	75.75	76	18.3	999
12: 00 (noon)	5.00	15	75.00	91	18.5	1,196
12:12	4.92	12	59.04	103	18.8	1,354
12:22	4.88	11	53.68	113	18.9	1,485
Total		114	*596.98			

* Weighted average discharge is 596.98 gallons per 114 minutes or 5.23 gpm.



(a) semilogarithmic plot of s_w/Q versus t/r_w^2 for flowing well with constant drawdown and variable discharge, data presented in table X-2.6-1.

(b) calculations

from semilog plot, $\frac{s_w}{Q} = 18.4$ $\frac{t}{r_w^2} = 1{,}000$, $\Delta \left|\frac{s_w}{Q}\right|$ - 18.40-15.38 = 3.02

$$\Delta \log_{10} \left|\frac{t}{r_w^2}\right| = 3 - 2 = 1$$

$$T = \frac{(2.30 \times 1{,}440 \text{ min/d})}{4(3.14159)\,(3.02 \text{ ft/gal/min})\,(7.48 \text{ gal/ft}^3)} = 11.7 \text{ ft}^2/\text{d}$$

$$S = \frac{(2.25 \times 11.7 \text{ ft}^2/\text{d})\,(1{,}000 \text{ min/ft}^2)}{\text{antilog}(18.4/3.02)(1{,}440 \text{ min/d})} = \frac{(2.25)(U.7)(1{,}000)}{(1{,}230{,}000)(1{,}440)} = 0.000015$$

Figure X-2.6-1.— Example of aquifer test analysis for a flowing well. (From Lohman, 1972, p. 25 and figure 17)

2.7 Practical Considerations

2.71 Boundary conditions

At every aquifer test site, the hydrologic boundary, conditions and hydraulic properties are unknown before testing. Thus, the problem analysis in the design phase contains uncertainties (15) that must be carefully considered to avoid errors in interpreting the results of the test. Figure X-2.7-1 depicts the drawdown configuration for two different hydrologic boundary conditions— discharge boundary and recharge boundary—and compares the rates of drawdown during pumping.

The drawdown rate for the impermeable-boundary condition, figure X-2.7-la, increases with time. This response could also reflect aquifer pinchout, fault zones filled with clay gouge, or decrease in hydraulic conductivity.

The drawdown rate for the recharge-boundary condition, figure X-2.7-lb, decreases with time. This response could also be caused by increased aquifer thickness, intersection with a highly permeable water-bearing fault zone or fracture trace, increases in hydraulic conductivity, or leakage through confining layers.

The response represented by the infinite aquifer is the unchanging rate of drawdown with time. This hypothetical infinite aquifer is a water-bearing geologic unit whose hydraulic properties are constant over a long distance in all directions, which is not a naturally occurring situation. Thus, the boundary effects at each test site should be verified by further field investigations through test drilling and surface geophysical investigations. Aquifer coefficients must be determined from the test data collected before the time the boundary effects become observable.

The drawdown distribution through time during an aquifer test affected by an impermeable boundary (fig. X-2.7-2) shows the data of the first 40 minutes to match both the Theis curve and the Jacob straight line. These data are not affected by the boundary and are used to calculate the transmissivity of the valley-fill deposits aquifer.: After 40 minutes, when the drawdown effects reach the impermeable boundary, the drawdown rate increases, as illustrated by the departure of the data from the Theis curve and the straight line.

The drawdown distribution in an aquifer test affected by a recharge boundary (fig. X-2.7-3) shows the data match the Theis curve and the Jacob straight line for only the first 10 minutes. These data are not affected by the boundary and are used to calculate the transmissivity of the aquifer. After 10 minutes, however, when the discharge rate is approaches the recharge rate, the drawdown rate decreases to zero, as illustrated by the departure of the data from the Theis curve and the straight line.

2.72 Well-bore storage

In many coal fields, bedrock aquifers are tight, that is the hydraulic conductivity is low. In such aquifers, the drawdown and recovery response of a pumping well is seriously affected by well-bore-storage effects; that is, discharge from the well is derived from a depletion of storage in both the aquifer and in the well bore. For pumping times greater than $25r_c^2/T$, the drawdown response in the pumped well would be within 5-percent error of the Theis solution (12). This relationship is presented graphically in figure X-2.7-4. For example, a 4-inch diameter well that fully penetrates a confined aquifer having a transmissivity of 10 ft^2/d would have to be pumped 100 minutes before the drawdown response would be closely approximated by the Theis solution. In tight aquifers, well-bore storage is likely to be a significant source of error in the analysis of pumping well responses by the methods described previously. The slug-test methods presented, however, are not affected by well-bore storage.

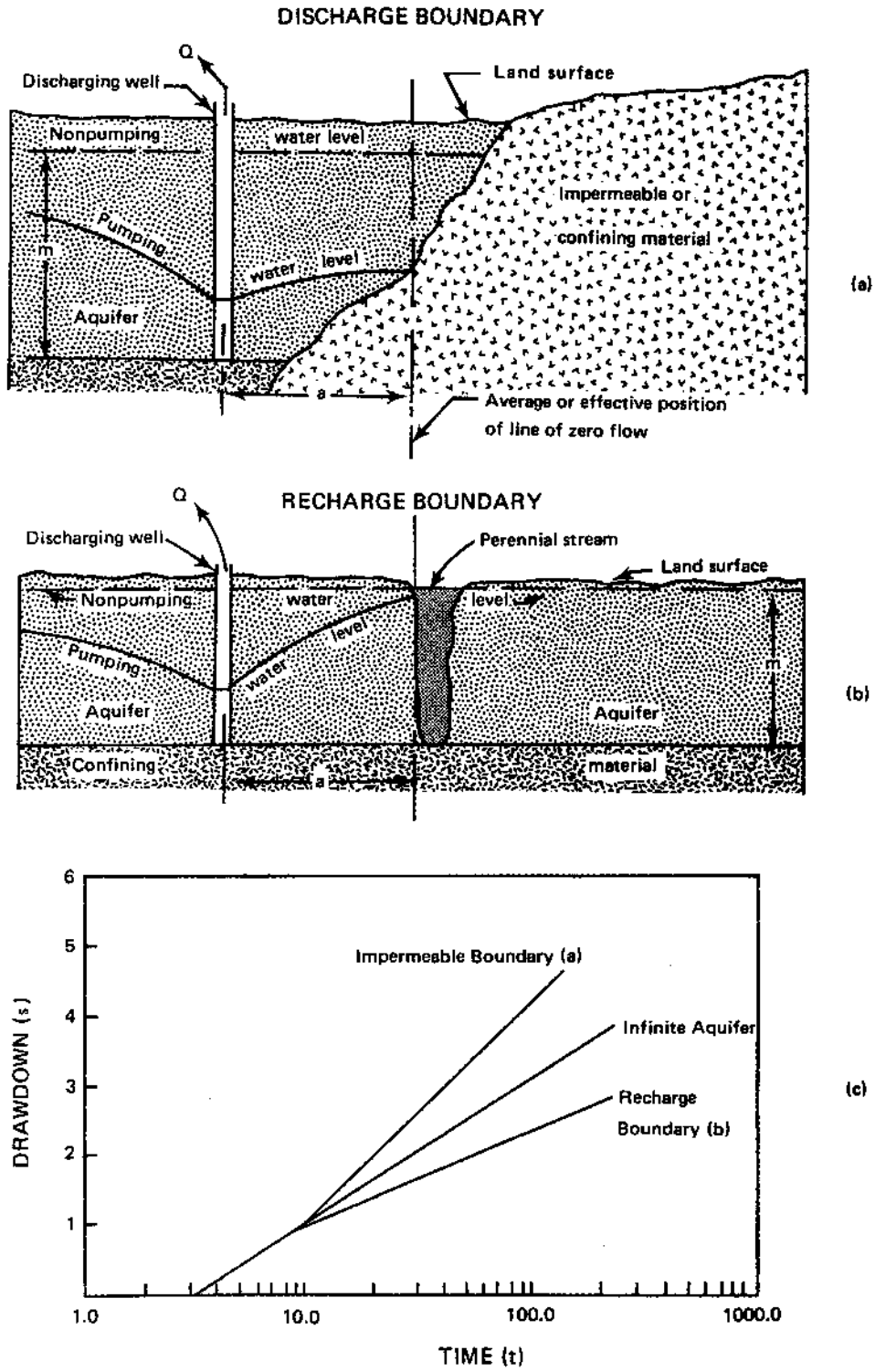


Figure X-2.7-1— Effects of recharge and discharge boundary conditions on drawdown rate.
(Parts A and B from Perris and others, 1962, figs. 35 and 37; Part C from Barrett and others, 1980, fig. 25)

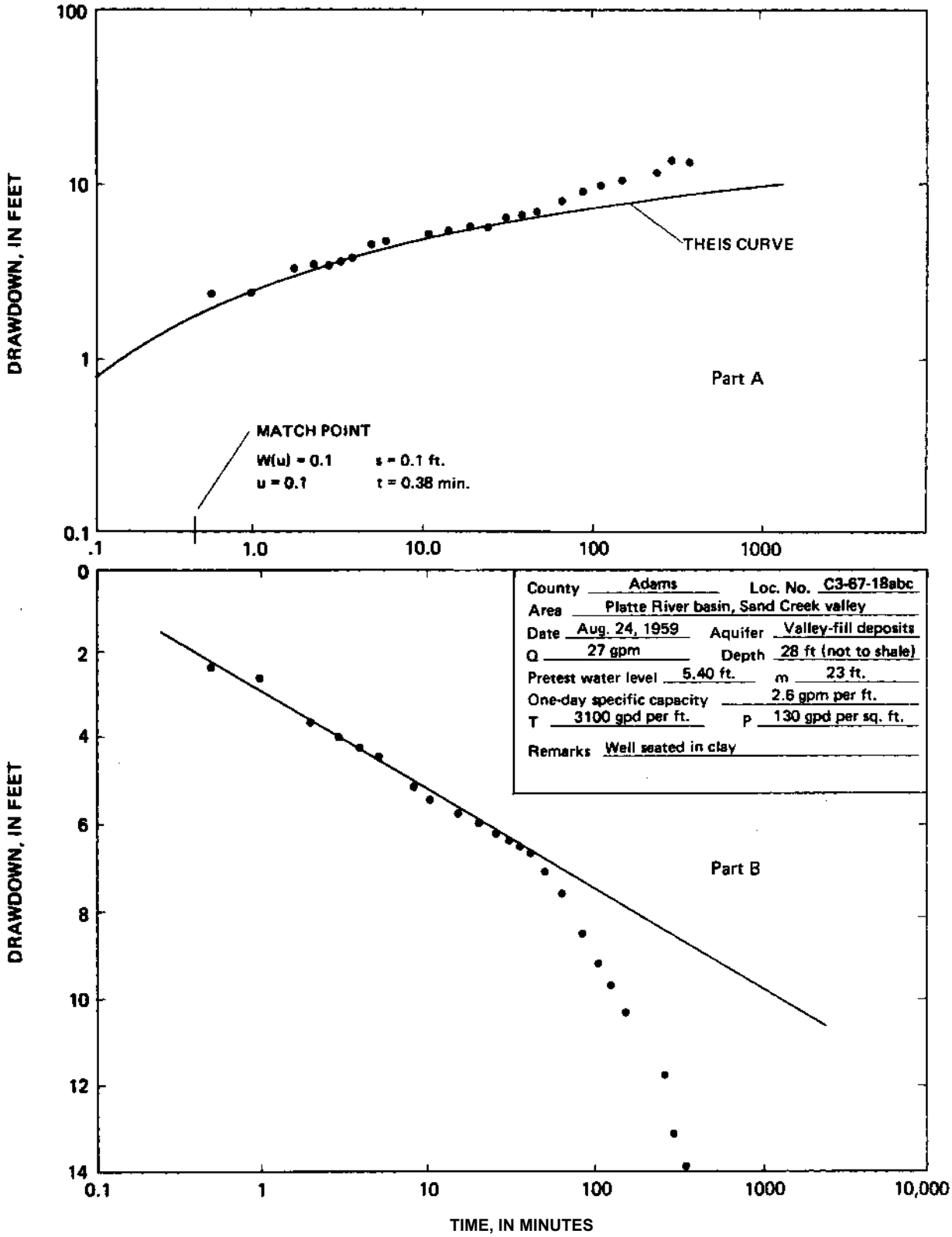


Figure X-2.7-2.— Aquifer-test results as affected by an impermeable boundary.
(Part A - drawdown increasing with increasing time in deviating from Theis curve (log s vs. log t plot)).
(Part B - drawdown increasing with increasing time in deviating from Cooper -Jacob straight-line plot (s vs. log t)).
(Data from Wilson, 1965, p. 216)

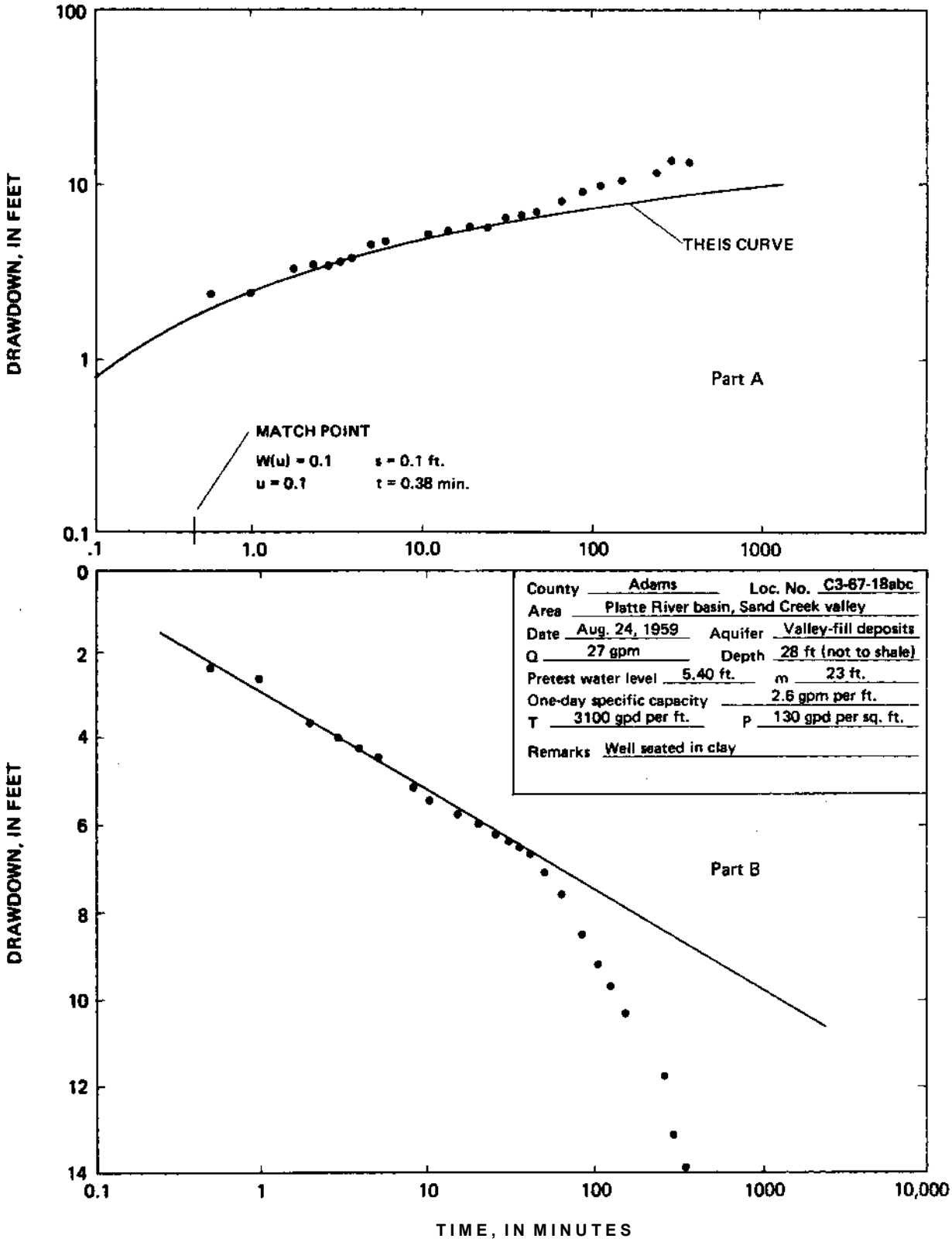


Figure X-2.7-3.— Aquifer-test results as affected by a recharge boundary.
(Part A - drawdown decreasing with increasing time in deviating from Theis curve (log s vs. lot t plot).
(Part B - drawdown decreasing with increasing time in deviating from Cooper-Jacob straight-line plot (s vs. log t).
(Data from Lang, 1960, table 1)

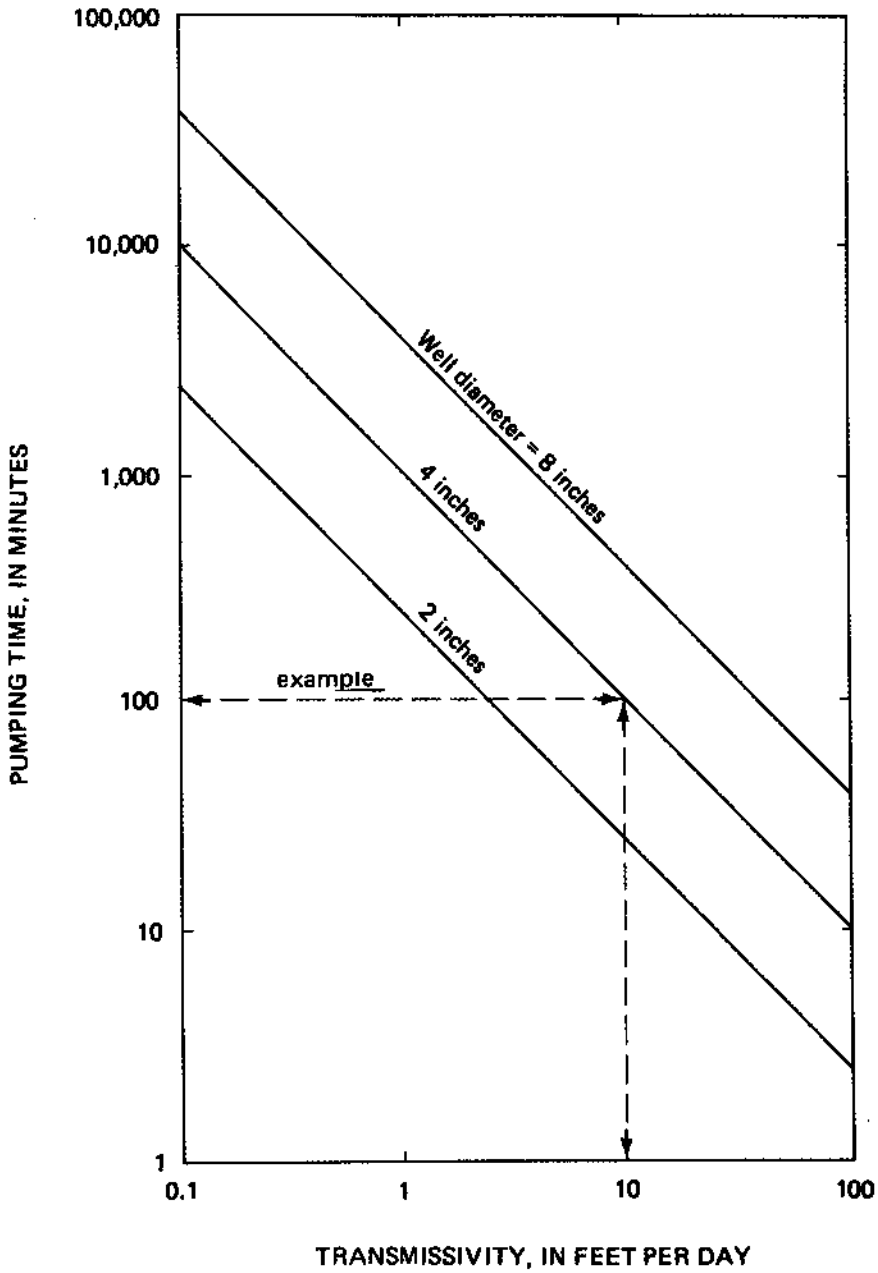


Figure X-2.7-4.— Pumping time for which the Theis solution is within 5 percent error of the theoretical drawdown response in pumping wells of indicated finite diameter.
(From Stoner, U.S. Geological Survey/ 1981, written communication)

2.8 References Cited for Aquifer Testing

(1) Barrett, James, Deutsch, P. C., Ethridge. F. G., Franklin, W. T., Heil, R. D., McWhorter, D. B., and Youngberg, A. D., 1980, Procedures recommended for overburden and hydrologic studies of surface mines: Ogden, Utah/ U.S. Department of Agriculture Forest Service/ General Technical Report IOT-71; 106 p.

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3.0 Qualitative Fractured Rock Hydrology

Most ground water in sedimentary terrain associated with coal deposits is related to fractures and secondary permeability. Fractures are the result of folding and faulting associated with earthquakes and mountain building processes. Fracturing commonly decreases with depth, except in the vicinity of fault structures. The greater the density of fractures, the greater the hydraulic conductivity of the bedrock unit. The hydraulic conductivity of fractured rock varies from 10 to 1000 times that of the adjacent unfractured or slightly fractured rock. The general pattern of fracture density with depth is shown in figure X-3.0-1.

Fault structures are planes of fractured rock material, and these planes vary in thickness from less than an inch to several feet. A geologic section with faults is shown in figure X-3.0-2. These planes can be identified from an interpretation of driller's logs, from geophysical investigations, and from fracture-trace interpretations (aerial photographs with a scale of 1:20,000). Fracture traces can be up to a mile long and from 5 to 65 feet wide (7). Photolinear features that are longer and wider are called lineaments. Fracture traces are commonly vertical, or near vertical, as shown in the block diagram in figure X-3.0-3. An example of photointerpreted fracture traces for a proposed permit area and adjacent area is shown in figure X-3.0-4. The high-permeability zones in the general area can discharge ground water through the adjacent area into the proposed permit area along these fracture planes. The orientation rosette in figure X-3.0-4 indicates that the two major directions of the fracture traces are north 13˚ west and east-west. Major mine adits should be oriented in directions other than these directions for maximum roof support and minimum mine inflow.

The determination of hydraulic properties of fractured rock aquifers is complex, and presentation of the analytical techniques is beyond the scope of this manual. Also, the drawdown patterns resulting from dewatering zones of fracturing are irregular because of the large variations in hydraulic conductivity (table X-l.4-1).

An aquifer test within fractured rock will initially exhibit linear flow along the high-permeability zones. With increased pumping time, however, the pumped water will be a combination of water from fractured rock, less fractured rock, and the nearby unfractured host rock. The effects of fracture-related permeability depend on the density of fractures in the aquifer volume to be tested.

Fractured-rock aquifers can be expected to follow the Theis solution more closely as fracture density increases. Data analysis by conventional methods is often possible in coal aquifers because of the closely spaced fractures in coal beds; commonly less than a few inches. However, only rough estimates of hydraulic properties of an aquifer unit can be expected from tests at wells that intersect only a few water-bearing fractures because testing in sparsely fractured aquifers commonly results in a complex drawdown response that reflects the hydraulic properties of both the fractures and the unfractured rock. For each of these components, the effective contribution to the drawdown response depends on fracture density and testing time. Other nonideal conditions commonly associated with fractured rocks are aquifer anisotropy and heterogeneity. In general, fracture density arid permeability of a particular rock type tends to decrease with depth (fig. X-3.0-1). Therefore, analyses of aquifer tests from shallow wells may indicate higher hydraulic-conductivity values than the average values for the entire thicknesses of overburden-coal aquifer systems.

Additional information on analytical aquifer testing techniques for fractured rock can be obtained from references (l), (2), (3), and (6).

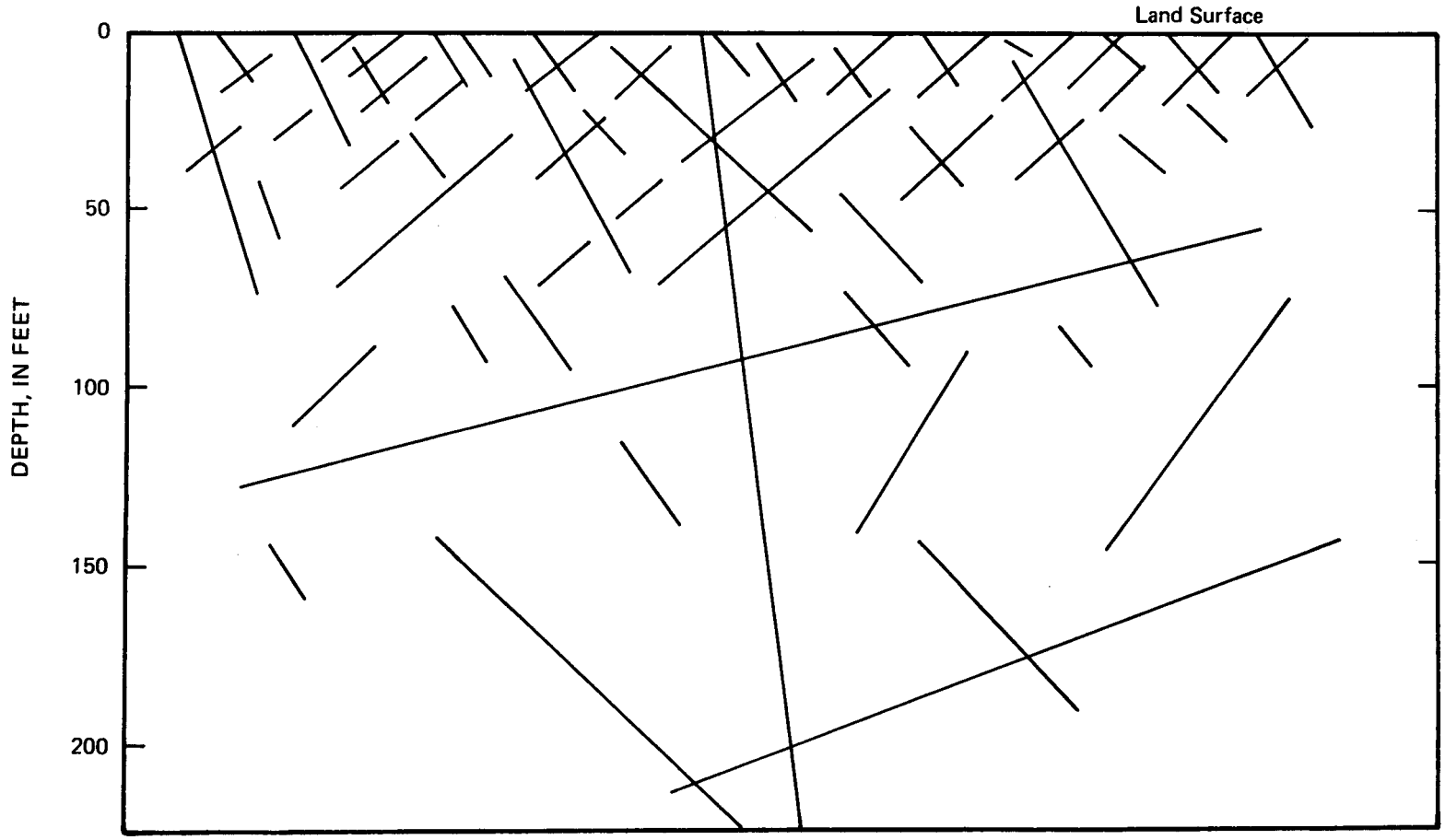

Figure X-3.0-1.— Idealized distribution of rock fractures with depth.

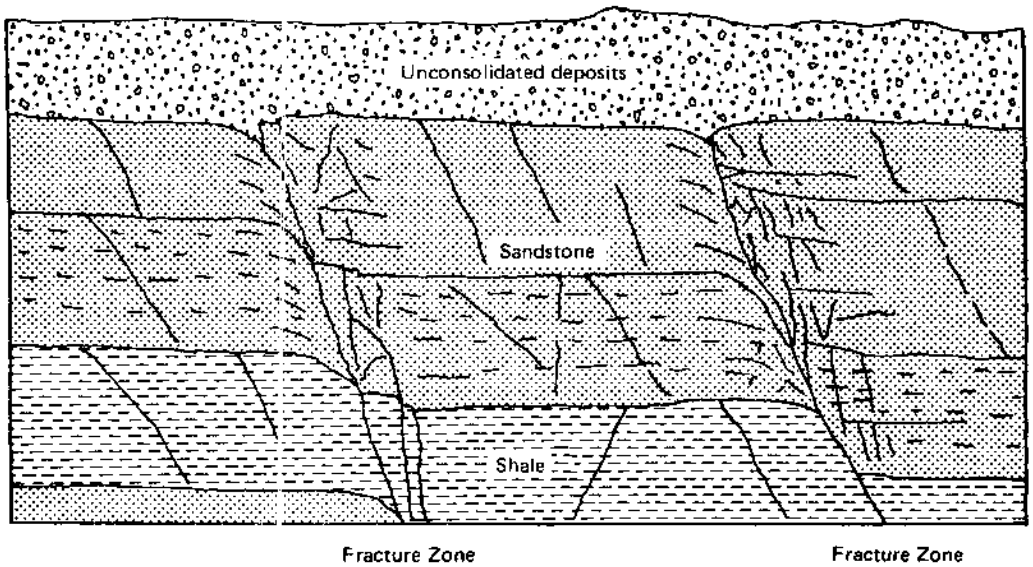

Figure X-3.0-2. — Vertical section showing buried fracture zones and joints in sedimentary bedrock,
(Modified from Meinzer, 1923a, fig. 68)

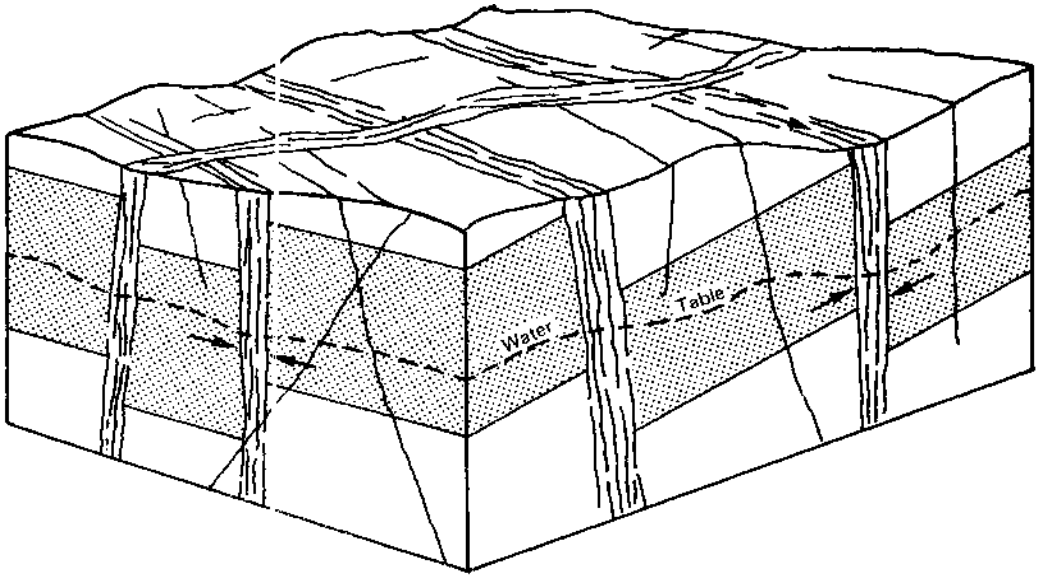

Figure X-3.0-3.— Idealized diagram of fracture traces and faults cross cutting sedimentary terrain.
(From Parizek and others, 1971)

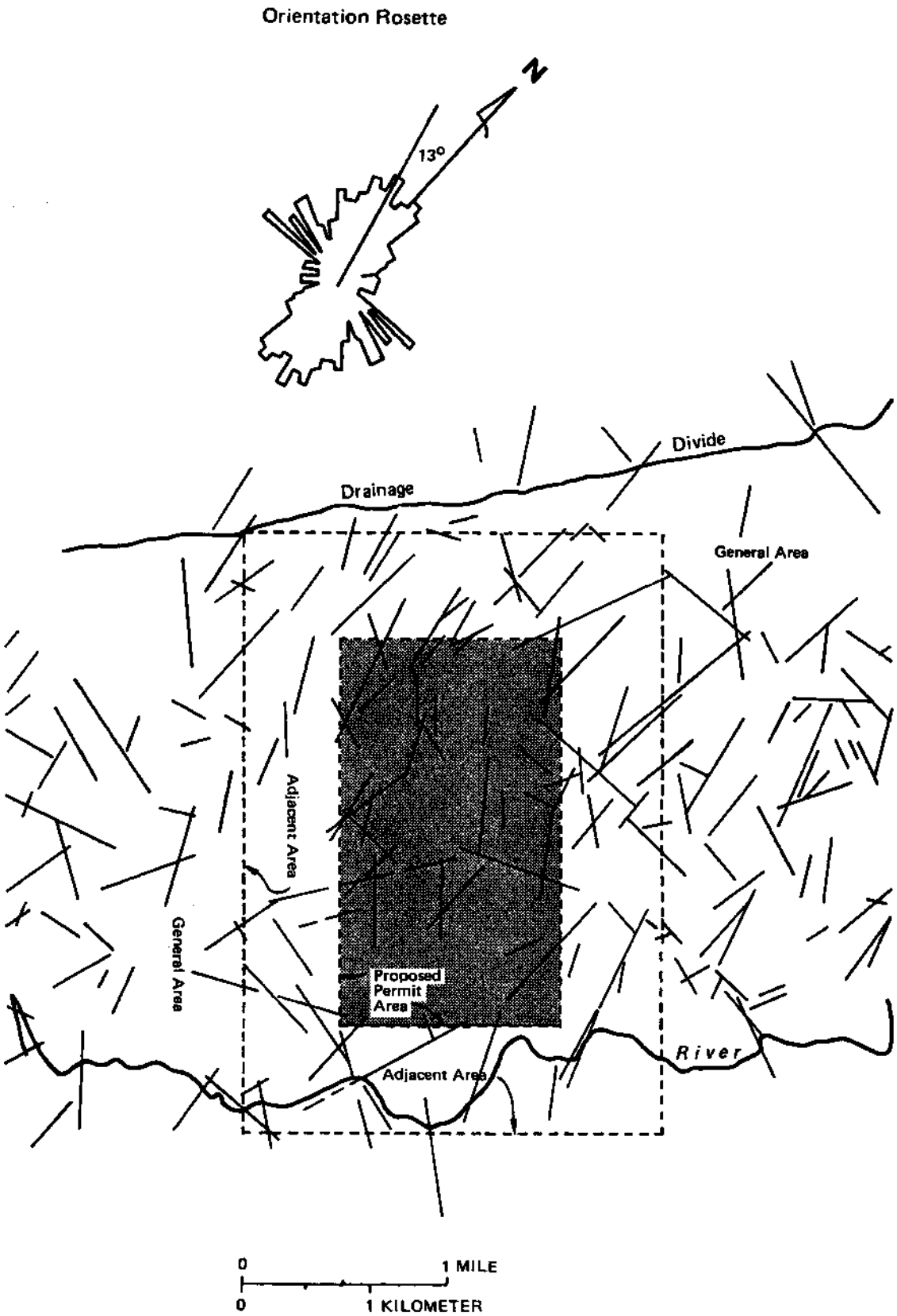

Figure X-3.0-4.— Linear fracture traces in a proposed permit area and vicinity. (Modified from Duigon, 1985, fig. 10)

3.1 References Cited for Qualitative Fractured Rock. Hydrology

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XI. RELATIONSHIP BETWEEN GROUND WATER AND SURFACE WATER

Pertinent 30-CFR[1] Sections:

- Description of hydrology and geology.
- Surface-water information.
- Ground-water information.
- Protection of hydrologic balance.
- Alternative water-supply information.

Streamflow at any site fluctuates seasonally and with variations in precipitation and water use and also reflects the geohydrologic properties of the streambed and adjoining aquifers. Streams are locations of ground-water discharge as well as channels for runoff from precipitation. Stream reaches that receive ground-water discharge are called gaining reaches; the ground-water conditions adjacent to such reaches are illustrated in plan view and cross section in figure XI-1A. Reaches that lose water by infiltration through the streambed are called losing reaches. During periods of little or no precipitation, flow decreases or goes dry wherever the water table declines, below the streambed. The ground-water conditions near losing reaches are illustrated in figure XI-1B.

Man's activities can alter the water-table altitude and thereby affect streamflow. The allegation that surface or underground coal-mining operations cause a significant long-term decrease or increase in stream low flow can be substantiated only through analysis of long-term hydrologic records and site-specific data collection. Such data would include: (1) periodic streamflow measurements of stream reaches within the general area; (2) continuous measurements at stream gaging stations near the upstream and downstream boundaries of the proposed mine area; (3) periodic water-level measurements in wells near the stream; (4) continuous measurements in selected wells between the mining operations and the stream; and (5) local precipitation measurements. Interpretation of streamflow data together with mine-pumpage information will aid in evaluating the validity of such allegations.

Information supplied by the mine-permit applicant to the regulatory authority includes low-flow data, which is a measure of the discharge characteristics of the adjoining aquifer (s). Streamflow records from many localities are analyzed and published by State and Federal agencies.

An essential component of a low-flow analysis is flow-duration curves. These curves are drawn from long-term mean daily discharge data from stream-gaging stations and show the percentage of time that a specific discharge was equaled or exceeded. Flow duration curves are a graphical presentation of the variation of stream flow discharge versus percent of time. Curves that are steep and intersect the percent line at values less than 90 are ephemeral and are not satisfactory for water supply purposes. Curves that are flat and do not intersect the percent line are perennial and have the potential to satisfy the water supply demands depending upon discharge available. Inclusion of flow-duration curves with the other hydrologic data help define the relationship between ground water and surface water at the site in question.

[1]CFR = Code of Federal Regulations

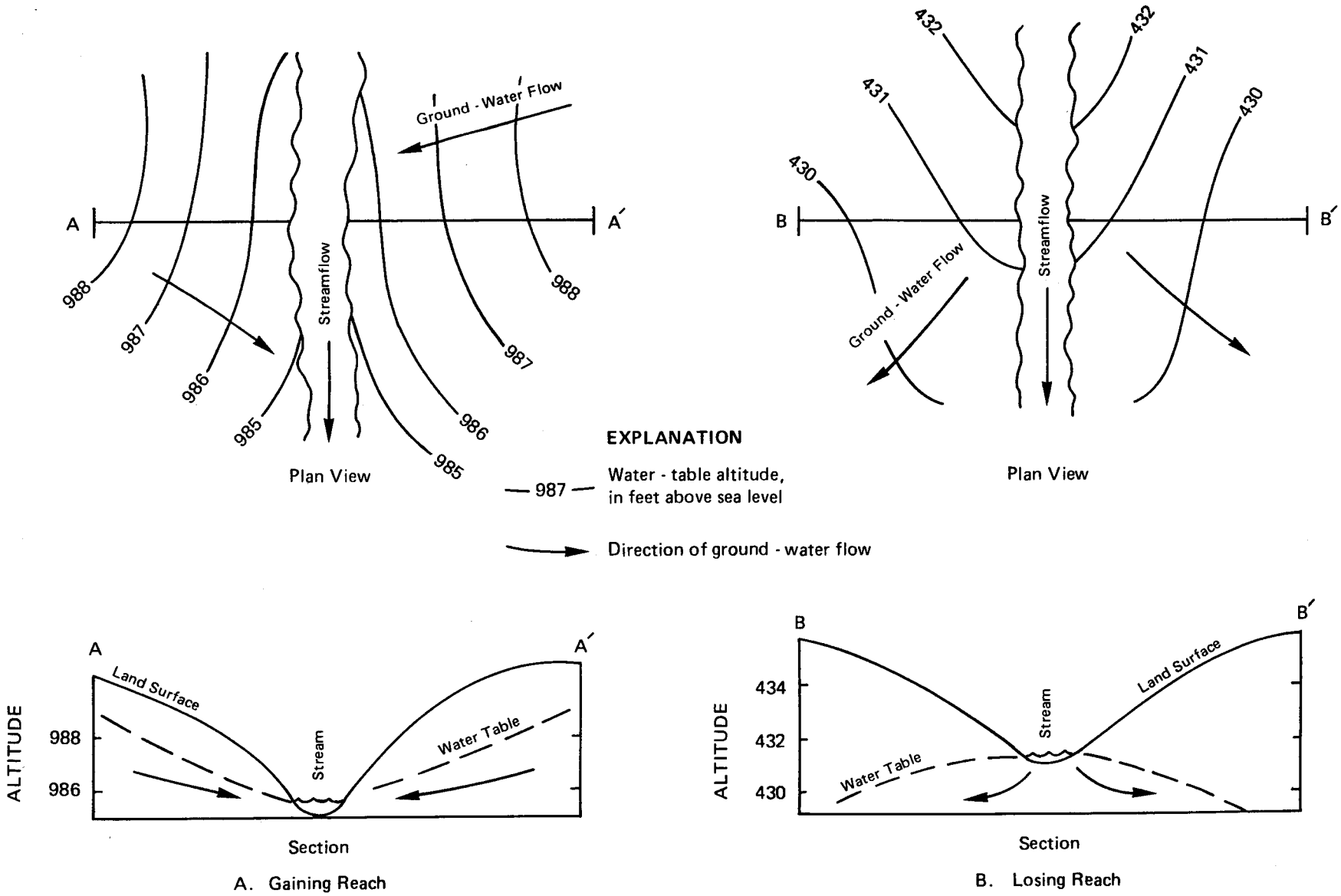

Figure XI-1.— Water-table altitude in relation to streambed altitude along a gaining stream reach (A) and a losing stream reach (B). (Modified from Meinser, 1923b, fig.26)

Flow-duration curves apply only to the period of record on which they are based; therefore changing land-use practices or streamflow use are reflected in the slope and shape of the curve. Surface-mine reclamation could affect streamflow significantly, and reservoirs may also modify streamflow. The percentage of drainage area affected by the activity influences the degree of change in the flow-duration curves.

Streamflow data from new gaging stations will not have sufficient record to construct flow-duration curves. The reader is referred to Searcy (1959) for more information on the construction and analysis of flow-duration curves.

Many reports on coal-area hydrology (chapter XV-1) include representative flow-duration curves. The example given in figure XI-2 is a composite flow-duration curve with ordinate values in discharge per mi^2 (square mile); flow-duration curves for individual gaging stations give ordinate values of discharge only. The shape and slope of the curve is a measure of streamflow variability and is controlled by the hydrologic and geologic characteristics of the drainage basin. Examples of flow-duration curves from two different basins with differing ground-water flow conditions are presented in figure XI-3. The steep curve (Brush Run) indicates negligible base flow and highly variable streamflow derived largely from precipitation runoff. This stream is underlain mostly by sandstone and shale that are low in ground-water storage. The flatter curve (Short Creek) reflects buried valley systems partly filled with saturated sand and gravel, which serve as a ground-water source to streams in that area. A curve with flat slope also indicates relatively uniform discharge from surface storage, such as discharge controlled by lakes or reservoirs.

Low-flow information is particularly useful in determining the probably adequacy of a stream for water supply or for receiving waste discharges. In the Ohio River region (Bloyd, 1974, p. A7), the stream discharge that is equaled or exceeded 90 percent of the time, called 90 percent flow, generally is assumed to consist entirely of ground water. In other regions of the country, however, percentages between 55 and 90 have been reported as base flow. The mean unit discharge at 90 percent duration in figure XI-2 is 0.12 $(ft^3/s)/mi^2$ (cubic feet per second per square mile) and ranges from 0.09 to 0.16 $(ft^3/s)/mi^2$. If a proposed mine-permit application was being made in the area represented by figure XI-2, and the drainage area at the permit site were 100 mi^2, the base-flow discharge would be about 12 ft^3/s but could vary between 9 and 16 ft^3/s. This would be the magnitude of stream flow discharge that the applicant would monitor and sample for ground-water quality monitoring.

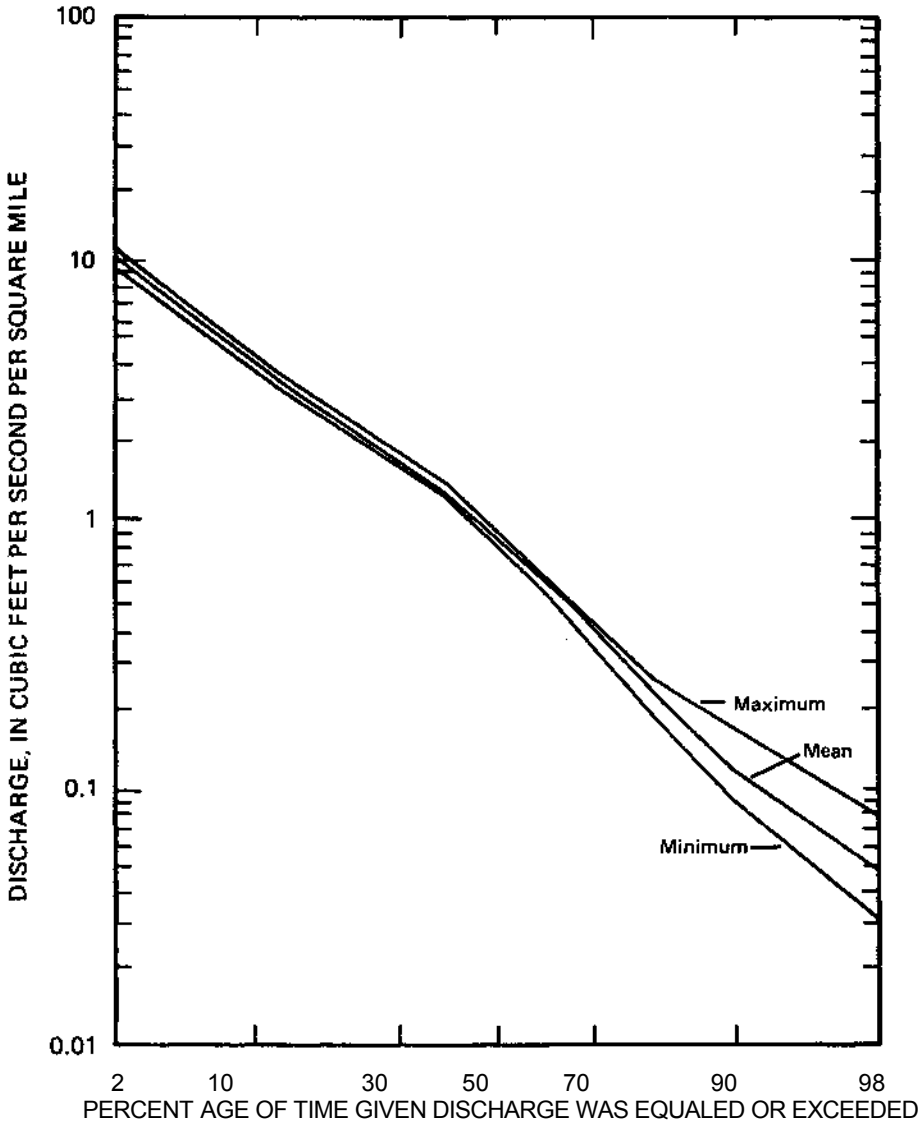

Figure XI-2.— Composite flow-duration curves, for Area 3 in western Pennsylvania. (From Herb and others, 1981, fig. 9.5.2-1)

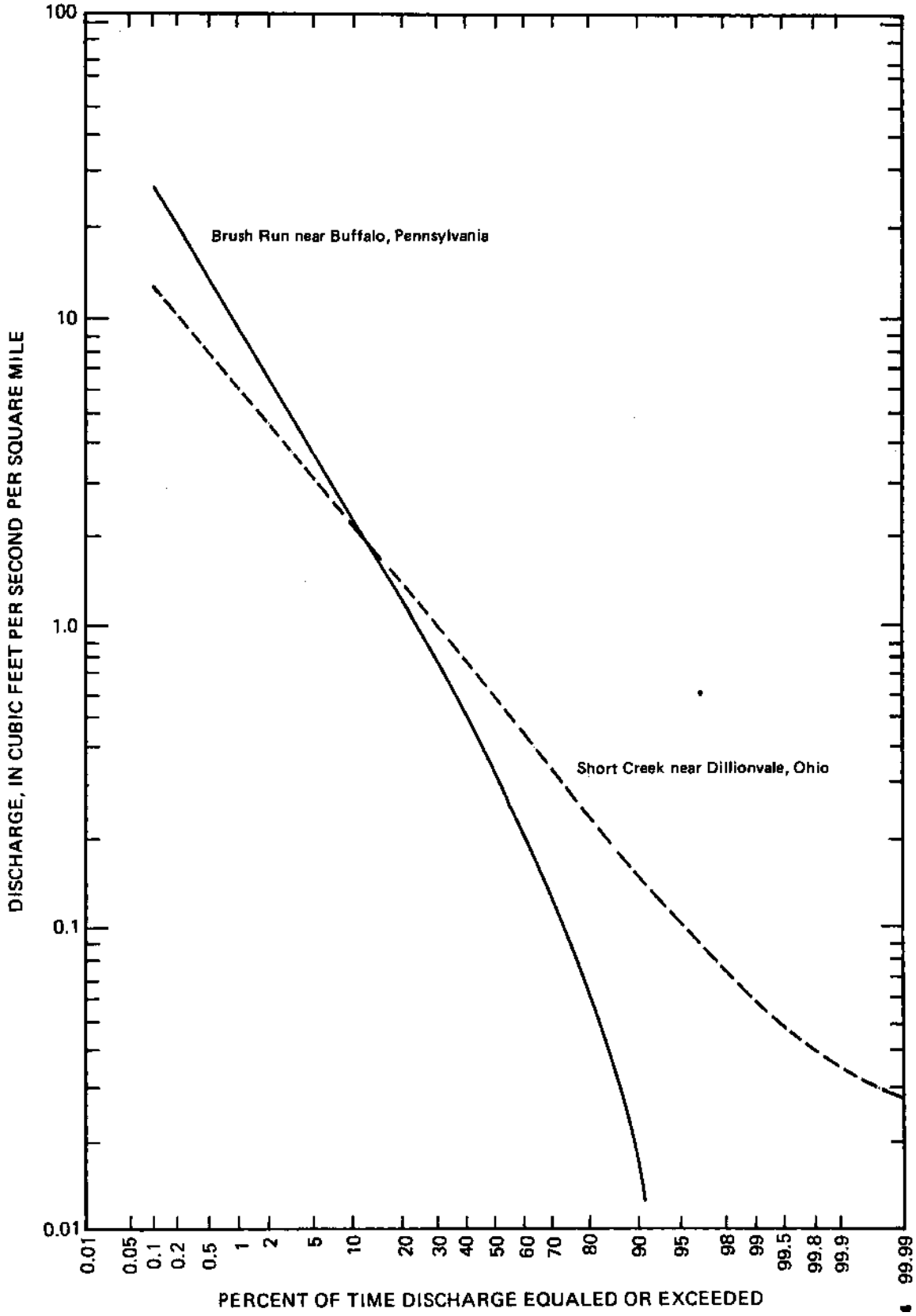

Figure XI-3.— Flow-duration curves for Brush Run near Buffalo, Pa., and Short Creek near Dillonvale, Ohio.
(From Roth and others, 1981, fig. 4.4-1)

XII. GROUND-WATER QUALITY

Pertinent 30CFR[1] Sections:

- Description of hydrology and geology
- Ground-water information
- Surface-water information
- Alternative water-supply information
- Protection of hydrologic balance
- Operation plan

The objective of this chapter is to aid the applicant in understanding the chemistry of the ground water within aquifers that may potentially be affected by mining within the permit area and adjacent area.

Federal regulations 30CFR, parts 780.21(b)(l) and 784.14(b)(l) as applied to ground water state:

> "Water quality descriptions shall include, at a minimum, total dissolved solids or specific conductance corrected to 25°C, pH, total iron, and total manganese."

Ground-water-sampling sites such as springs and base-flow sites can be sampled with little or no alteration of the natural chemical conditions of the water. Wells and test holes are not natural sites; thus, chemical analyses of water from these sources can reflect unnatural ground-water conditions, depending upon the drilling history, the type of well construction, well completion, and well-development, the well-pumping history, and the water-production system. Table XII-1 presents a checklist of factors that influence the quality of ground water from walls and test holes. These factors must be considered in the investigation of ground-water quality.

Water-quality data for both surface and ground water are available from the files of State and Federal agencies. (Sources of additional hydrologic information are given in chapter XV). A review of published reports on ground water quality may (1) provide information on the chemical types of ground water, (2) aid in determining the availability of potable water for water supply and water for mine spraying and washing operations, and (3) delineate the area acid mine drainage, if any.

Difference in the water quality within the ground-water flow system, from recharge points to discharge points is shown in figure XII-1. Solution chemistry and the mineral composition of soils and bedrock units largely control the concentrations of dissolved constituents. However, as the water moves from areas of recharge to areas of discharge, the dissolved-solids concentration increases. Ground-water in the local, shallow flow system and at the recharge area contains low dissolved solids and may be a calcium-magnesium-bicarbonate type water. Travel time through a shallow system may be months or years. In contrast, ground water in the regional, deep flow system and at the discharge area contains high dissolved solids and may be a sodium chloride type water. The travel time for these conditions may be hundreds or thousands of years. Ground water from coal-mine operations may be high in dissolved solids and may be a calcium sulfate-type water.

CFR[1] Code of Federal Regulations

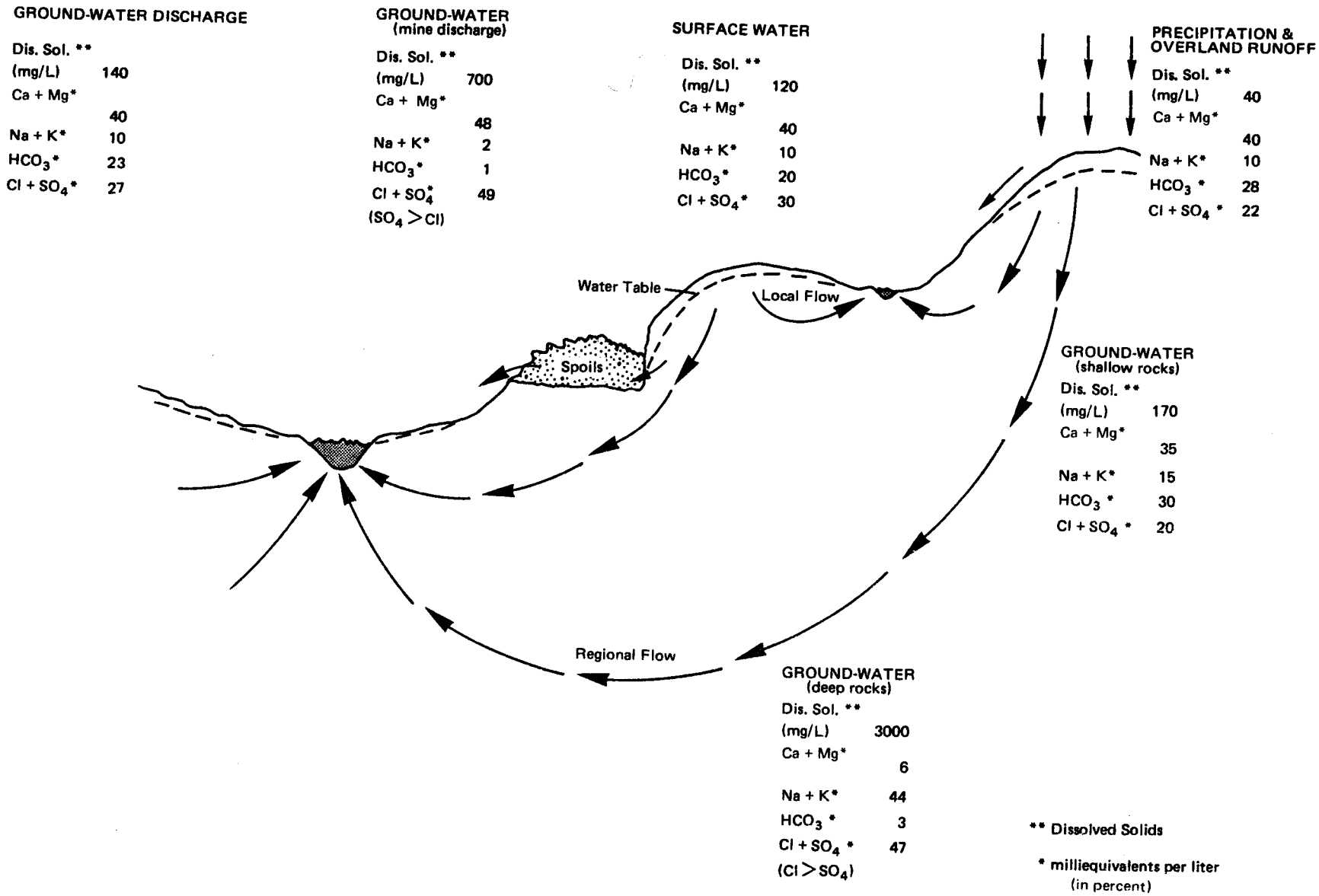

Figure XII-1.— Differences in chemical composition of water within surface-water and ground-water flow systems. (Modified from Hollowell and Koester, 1975, fig. 17)

After the available historical water-quality information has been reviewed, the first ground-water-quality inventory is made from ground-water samples collected from:

- wells and springs (chapter VII)
- base-flow stream sites (chapter XI)
- ground-water monitoring network (chapter XIV)
- test holes and core holes of the exploratory program (chapter XVI).

The sampling of ground water for chemical analysis requires experience, patience, care and appropriate equipment. During sampling, the water will change as it moves from the aquifer to the wellhead and to the analytical equipment. The major changes are in temperature and pressure. As stated in (10): "Some properties or constituents in ground water may change dramatically within a few minutes or hours after sample collection. Immediate analysis in the field is required if dependable results for these parameters - temperature, dissolved oxygen, pH, specific conductance, acidity, and alkalinity - are to be obtained." Therefore, onsite analysis is best for the most representative results.

Additional information on the determination of ground-water quality may be found in the references cited in chapter XVIII; these include Brown and others, 1970; Claassen, 1982; Fetter, 1980; Freeze and Cherry, 1979; Hem, 1970; Johnson Division, 1975; Rainwater and Thatcher, 1970; Todd, 1980; Wood, 1976; and U.S. Department of Interior, 1968; 1977a and 1981a.

As mentioned in chapter X-2.2, specific conductance can be measured during the aquifer test by a water-conductivity meter. Specific conductance is an indicator of the dissolved-ion concentration of a water sample. The major dissolved constituents in the water vary in proportion to specific conductance (9). The curve in Figure XII-2 depicts the decrease in specific conductance during an aquifer test as representative aquifer water replaces the altered water near the well. The water sample at t=200 minutes is considered to be the "true aquifer value" for specific conductance of the aquifer tested. Thus, the criteria used to determine the acceptability of a ground-water sample as being representative of the aquifer water include: (1) a visibly clear water, and (2) identical specific conductance, pH, and temperature readings on at least three successive samples (9).

A record of the hydrologist's field visit to water-quality sites is necessary for the compilation of ground-water quality data and to prove the measured chemical constituent concentrations in the ground water at the permit site to management and to the regulatory authority. An example of a comprehensive water-sample schedule is shown in figure XII-3. This multi-purpose form is completed at the time of sampling and can be used for a flowing or nonflowing well, a spring, a base-flow site, a lake or reservoir, or could be used during an aquifer test. The chemical factors to be measured and recorded in the field are temperature, pH, and specific conductance. One form should be used per sampling site per visit.

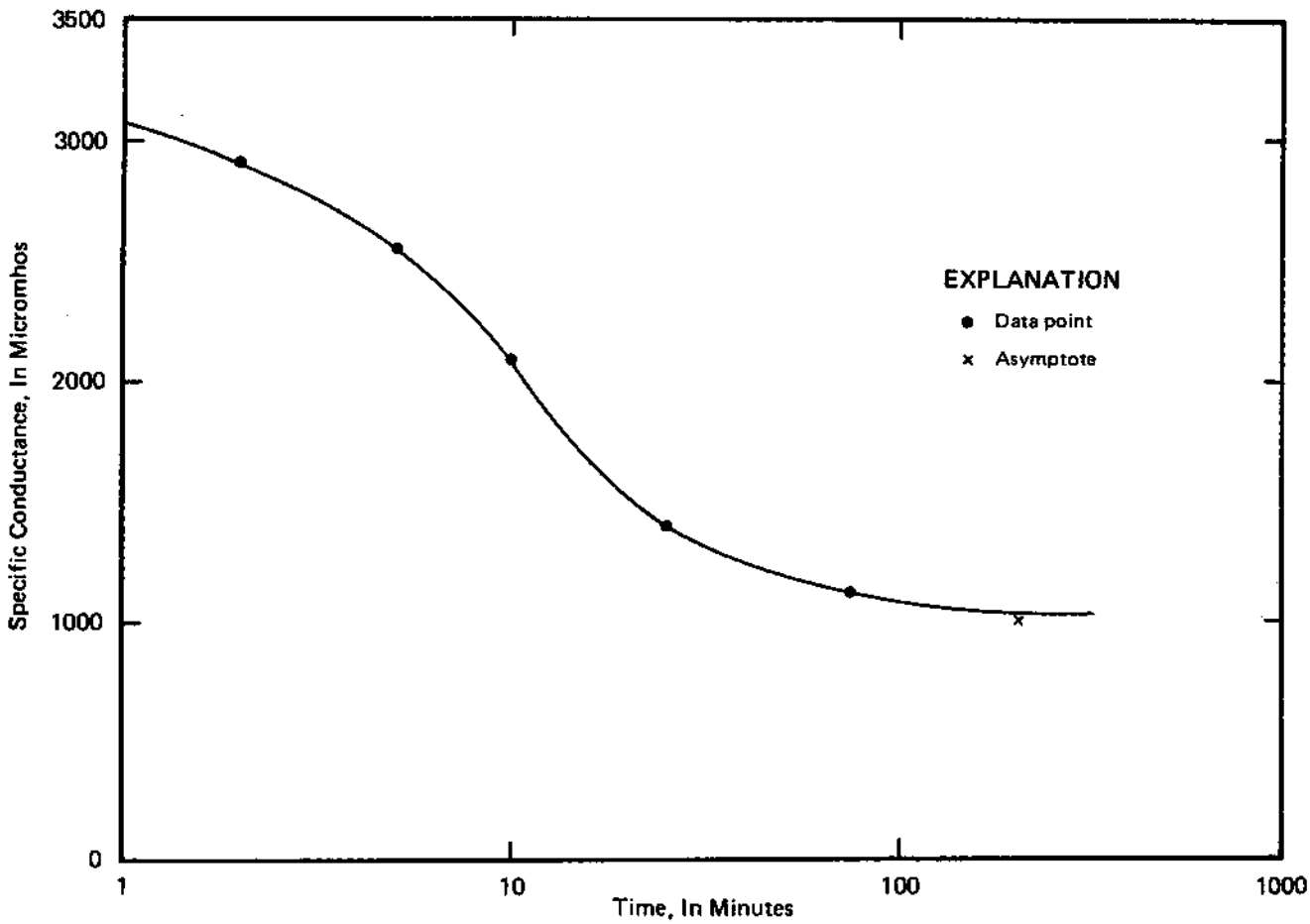

Figure XII-2.— Change in specific conductance with time during aquifer test. (From Claassen, 1982, p. 14)

PERMIT SITE _____

Source (cirle one) - flowing well, non-flowing well, spring, stream site, lake, pond, reservoir

Location description: Township_____ County_____ State_____

Owner's name_____ Address_____

_____ 1/4 _____ 1/4 _____ 1/4 Section _____ T ____ E/W R ____ N/S Field/Office No._____

Latitude_____ Longitude_____ 7½' Topo. Quad. Map Name _____

Date sample collected _____ Year_____ Time_____ Collected by_____

Water temperature (°C)_____ (°F)_____ pH_____ Specific Conductance(umho/cm)_____

Purpose of collecting sample_____

Appearance of sample(circle one) clear, rust colored, cloudy, clear with particles, muddy ODOR yes no

Sample number sent to lab. _____ Laboratory name _____ Address_____

SAMPLES COLLECTED(circle) General chemical Minor elements Radiochemical Other

Date submitted to lab. _____ _____ _____ _____

Date results received back_____ _____ _____

WELL - Type (circle one) - used, unused, flowing, test hole. Date _____ Time _____

Use(circle one) - commercial, domestic, irrigation, industrial, stock, public supply, abandoned

Driller's log yes no Water-bearing formation(s) _____

Depth of well _____ft(measured/reported) Cased to _____ft(meas./rept.) Casing diameter_____in.

Date drilled _____ Driller's name_____ Address_____

Well finish(circle one) open hole, screen, cemented, gravel pack CASING MATERIAL steel 'fiberglass'

Static water level_____ft Date measured_____ Depth sampled_____ft

Description of measuring point_____

Aquifer test - Static water level_____ft Date _____ Time_____

Date_____ Time test started_____ Volume bore-hole storage_____ft^3 _____gal

Yield_____gal/min Time_____ Pumping level_____ft Drawdown_____ft

Discharge sampled Date_____ Time_____ Quantity pumped before sampling_____ft^3_____gal

SPRING - Type (circle one) - perched, contact, fracture Use (circle one) unused, stock, domestic

Discharge_____gal/min(measured/reported/estimated)

Water-bearing formation _____

STREAM Gaging station name _____ Number_____

Gage height_____ft Discharge_____cubic feet per second (measured/estimated)

Sampling location(looking downstream) left bank center stream (depth of sample ___ft) right bank

LAKE OR RESERVOIR Name_____ Location_____ 7½' Topo. Quad. map name_____

Shore sample location _____ Off-shore sample location_____ Depth_____ft

ADDITIONAL NOTES

Figure XII-3.— Example of field water-sample schedule for chemical analysis to be completed at the time of sampling.
(Modified from Claassen, 1982, fig. 6)

Ground-water samples can be withdrawn from wells by the pump installed in the well, but the steel of the casing and pump column may cause the dissolved-iron values to be higher than those in the formation water (9). Discharge of more than two borehole volumes before sampling, will reduce this discrepancy. For example, a well with a static water level at 20 ft below land surface, with a well depth of 100 ft and a casing diameter of 4 inches has an approximate borehole volume of 7 ft^3. With a well discharge of 2 gal/min, three borehole volumes pumped to waste would take 78 minutes. Measurement of three identical specific conductance values in succession, as mentioned previously, would indicate "true-aquifer" quality. At wells without pumps, water samples can be withdrawn by (1) placing a submersible pump in the well, (2) using "thief samplers"[1], or (3) bailing and swabbing the well, which require a workover drilling rig.

The ground-water sampling can be done concurrently with the exploratory program (chapter XVI). As one or more of the test holes or core borings are drilled and logged (chapter VIII), each aquifer unit should be defined, selectively pumped, and sampled. The sampling of individual aquifers during test drilling would provide background information on the variation of ground-water quality both laterally (between test holes, wells, springs, and streams) and vertically (between aquifers above and below the coal beds to be mined).

Analysis of water samples from the first well and spring inventory from base-flow stream sites, and from the test-drilling program should be tabulated by (1) aquifer or surface-water site, (2) well opening, (3) depth of well or stream discharge, (4) location in relation to the proposed permit area, and (5) water type (major chemical constituents). An example of a tabulation of chemical constituents is shown in table XII-2. These samples are from wells and base-flow sites in the vicinity of the permit area, as shown in figure XII-4.

If anomalous results are obtained, the hydrologist should first check the analysis and calculations, and second, consider resampling. An example of an anomalous result would be a sodium chloride type water in an area of calcium-magnesium-bicarbonate-type water. Upon confirmation of the anomalous results, the investigator must consider the possibility of ground-water contamination, perhaps caused by waste disposal or petroleum-exploration activities. Documentation of anomalous results is important for the protection of all parties, as is notification to the regulatory authority. Contamination may also be derived from agriculture runoff, mining, nuclear power development, or disposal of refuse, sewage, and industrial wastes. Pollution is defined as a level at which contaminant concentrations are considered to be objectionable (2), (7).

The potability of the ground water is determined by comparing the physical, chemical, and microbiological analyses of the water with the U.S. Environmental Protection Agency's 1983 Drinking Water Standards, which are presented in table XII-3.

[1]Well Reconnaisance Corporation, Houston, Texas

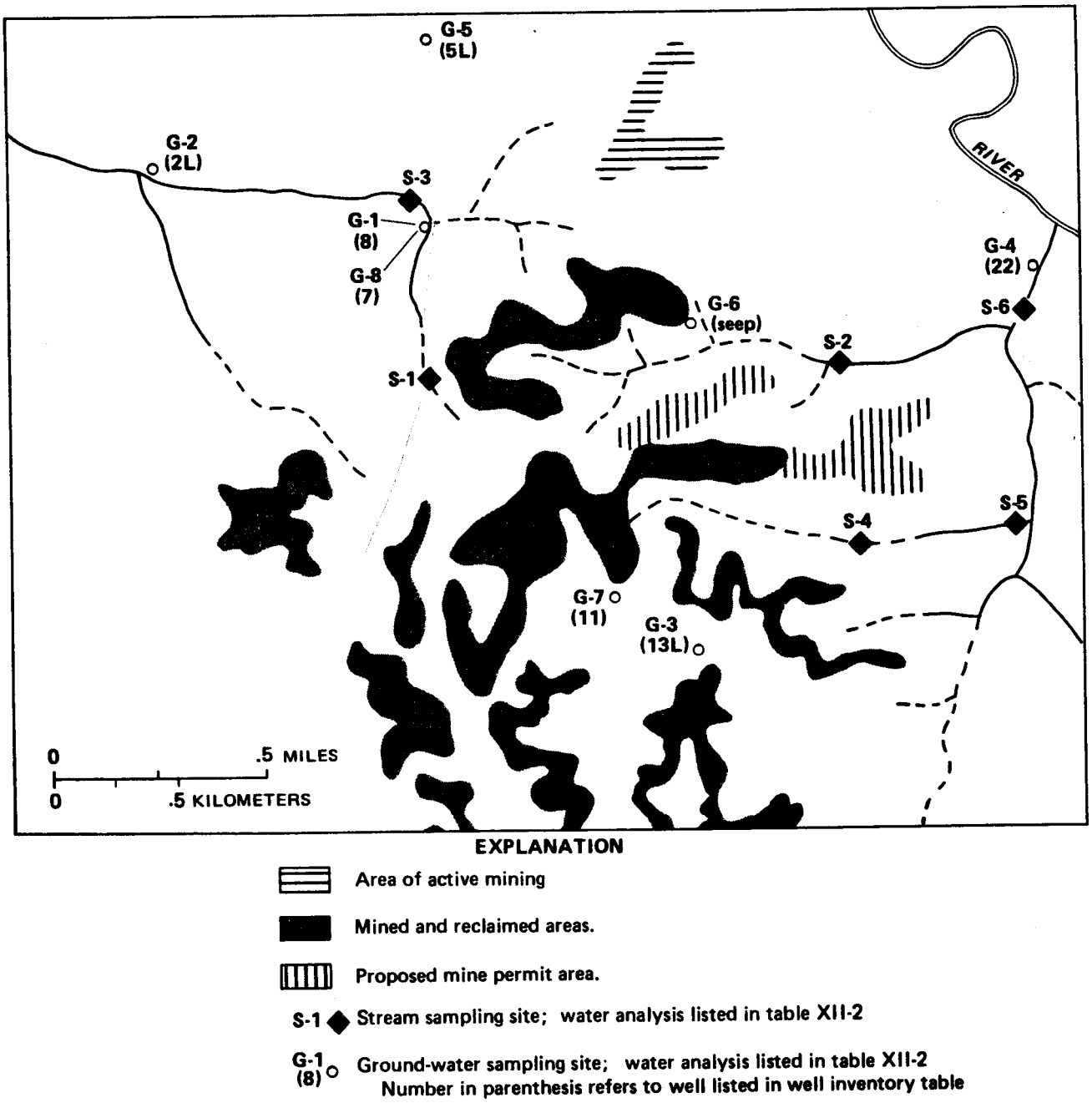

Figure XII-4.— Example of location map of mining activities, proposed permit area, and water-quality sampling sites.
(From Norris, 1991, fig. 2)

One method of comparing the results of chemical analyses of ground water is with a trilinear diagram (figure XII-5). This diagram consists of two lower triangles that show the percentage distribution, on the milliequivalent basis, of the major cations (Mg^{++}, Ca^{++}, and Na^{+} plus K^{+}) and the major anions (Cl^{-}, SO_4^{-}, and ($CO_3^{-\,++}$ plus HCO_3^{-}), and a diamond-shaped part above that summarizes the dominant cations and anions to indicate the final water type. This classification system shows the anion and cation facies in terms of major-ion percentages. The water types are designated according to the area in which they occur on the diagram segments. Many coal-hydrology reports (chapter XV-1) describe the ground-water types with trilinear diagrams such as this.

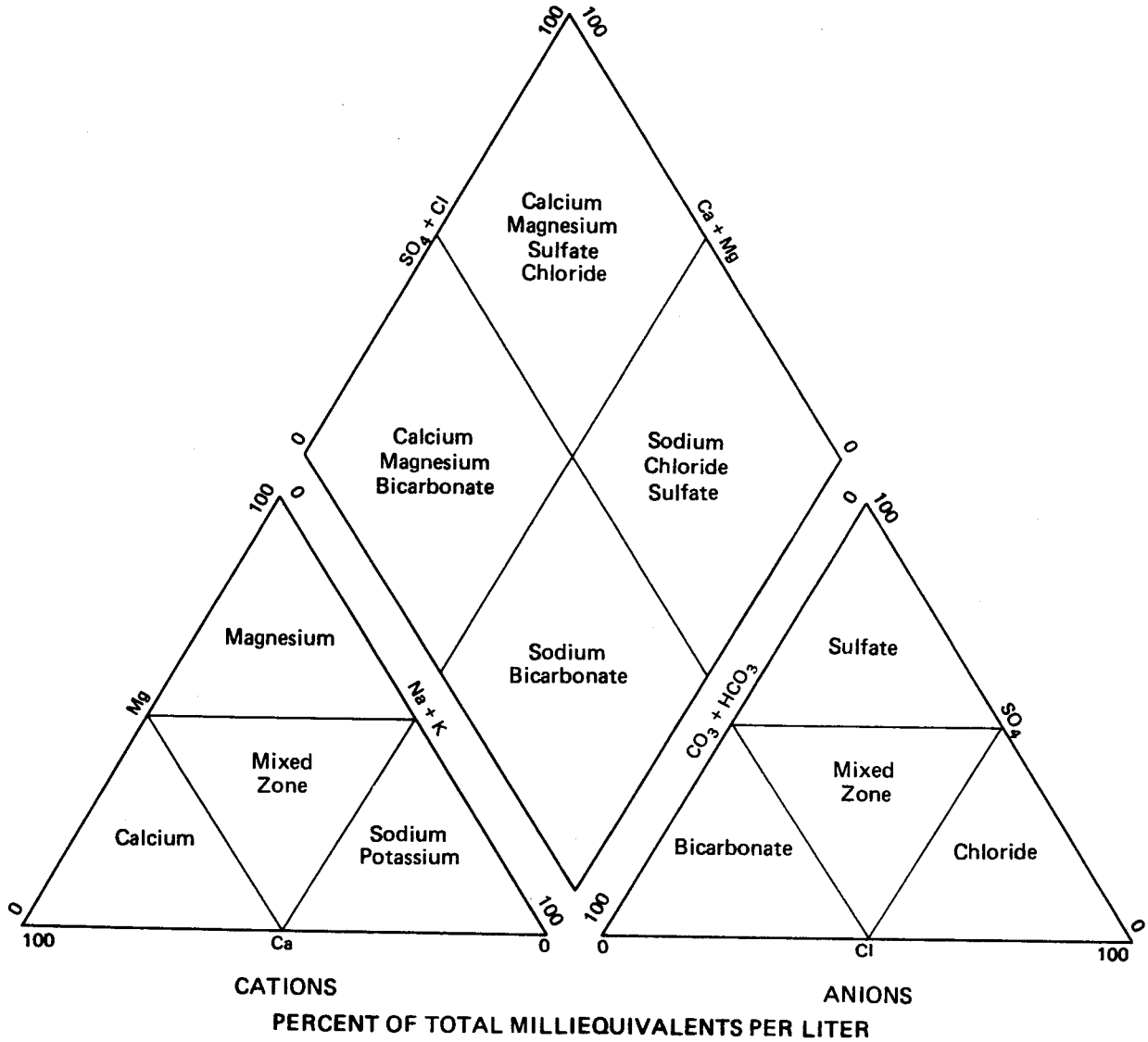

Figure XII-5.— Trilinear diagram showing water-type categories.
(From Piper, 1944, fig. 1, and Roybal and others, 1983, fig. 4.7-1)

An example of a ground-water chemical analysis is shown in table XII-4; a plot of the values on a trilinear diagram are shown in figure XII-6. The high chloride content of the water sample from well 2085 (and point no. 2) suggests that the water is contaminated (6). The conversion factors from milligrams per liter to milliequivalents is given in references (3) and (7).

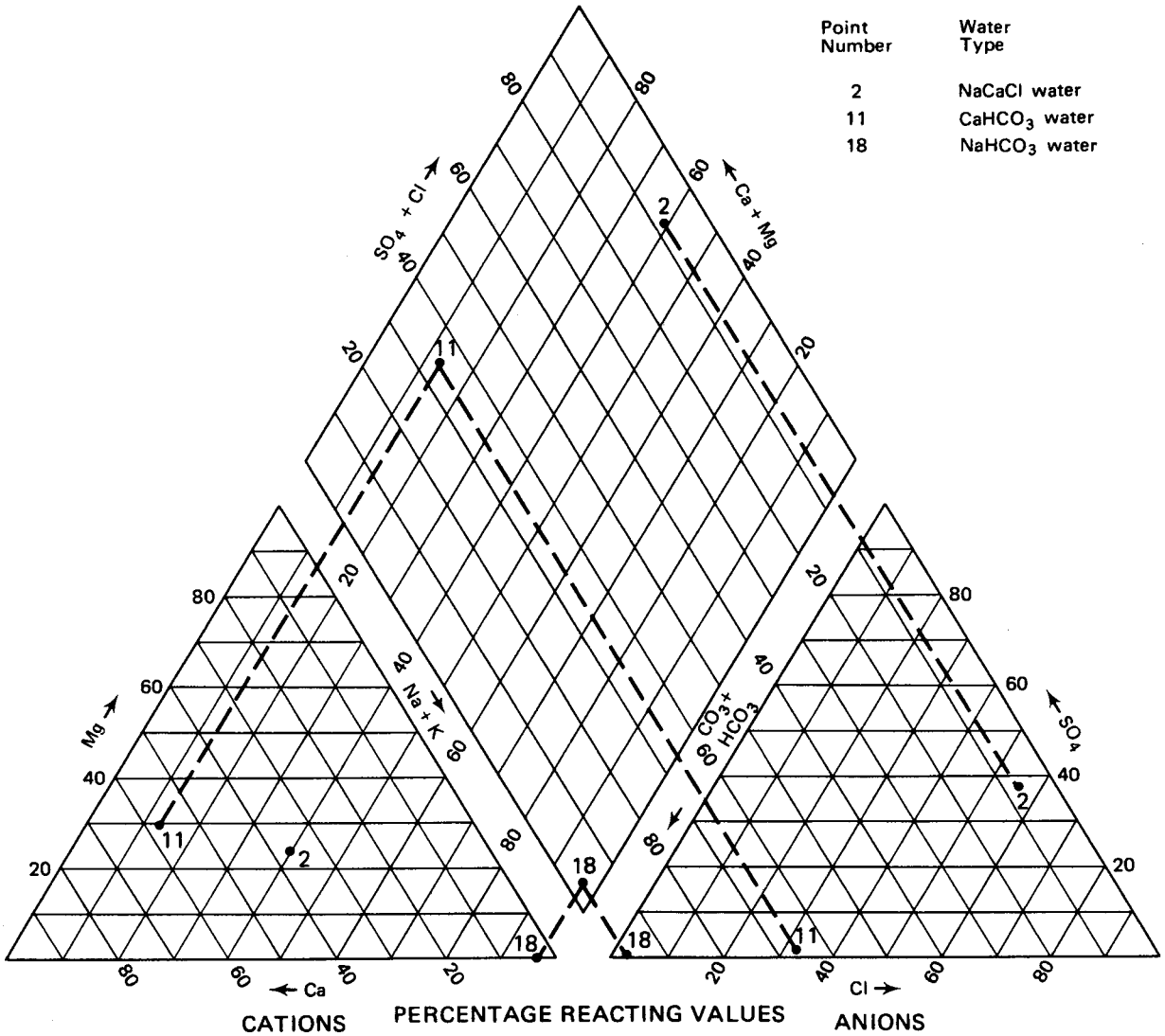

Figure XII-6.— Water-quality data from table XII-4 as plotted on trilinear diagram. (In part from Schiner and Runnel, 1976, fig. 12)

Table XII-1. – Checklist of data requirements for water-source definition and aquifer representation of ground-water samples.
(Modified from Claassen, 1982, table 1.)

A. Drilling history
   1. Well depth and diameter
   2. Drilling method and drilling-mud composition
   3. Lithologic data from cores or cuttings
   4. Well development before casing installation
   5. Geophysical logs obtained

B. Well-completion data
   1. Casing sizes and depths
   2. Casing material(s)
   3. Cemented intervals
   4. Plugs and stabilizers left in the hole
   5. Gravel packing: volume, sizes, and type of "gravel" material
   6. Screened, perforated, or milled casing intervals that allow water to enter the borehole
   7. Pump type, setting, intake location, construction materials, and pump-column type and diameter

C. Well pumping history
   1. Rate
   2. Frequency

D. Estimation of effect of contaminants introduced into aquifer during well drilling and completion on native water quality

E. Effect of inplace water-production system on the composition of ground-water sample.
   1. Addition of contaminants
   2. Removal of constituents
      a. Sorption
      b. Precipitation
      c. Degassing

Table XII-2. – Chemical constituents in surface water and ground water, (from Harris, 1981, table 2.)

[ft^3/s, cubic feet per second; ft, feet; mg/L, milligrams per liter; H, hydrogen; HCO_3, bicarbonate; CO_2 carbon dioxide; Fe, iron; Mn, manganese; 0, oxygen; SO_4 , sulfate; °C, degrees Celsius; Qal, Quaternary alluvium.]

SURFACE WATER

Stream Site*	Date	Instantaneous Discharge (ft^3/s)	Total Sediment (mg/L)	Acidity as H+ (mg/L)	Air temp. (° C)	Bicarbonate HCO_3 (mg/L)	Carbon dioxide CO_2 (mg/L)	Carbonated CO_3 (mg/L)	Dissolved iron Fe (mg/L)	Suspended iron Fe (mg/L)	Dissolved manganese Mn (mg/L)	Suspended manganese Mn (mg/L)	Dissolved oxygen 0 (percent)	Dissolved oxyen 0 (mg/L)	pH Field (units)	Specific Conductance field (micromhos)	Dissolved sulfate SO_4 (mg/L)	Water Temp (°C)
S-1	4-11-79	0.10 (est)	5	—	16.5	59	376	0	0.01	0.12	0.02	0.	78	9.6	5.4	350	120	6.5
	7-11-79	0.02	—	0.0	—	77	39	0	.02	.29	.40	.01	—	—	6.5	440	140	18.0
S-2	4-11-79	0.21	5	2.0	—	1	32	0	.23	.11	3.30	0	85	10.2	4.7	650	290	7.5
	7-12-79	0.03	—	1.3	—	0	0	0	.12	1.50	5.00	0	—	—	4.3	830	370	17.5
S-3	4-17-79	0.15	13	0.0	19.0	36	289.	0	.05	.50	.47	.03	100	11.6	5.3	380	150	10.5
	7-11-79	0.03	—	—	—	112	1.4	0	.03	.39	.08	.02	—	—	8.1	480	130	22.0
S-4	4-17-79	0.29	3	0.0	18.5	0	0	0	.84	.06	10.00	1.00	96	10.0	3.6	1,400	910	14.0
	7-12-79	0.05	—	4.1	—	0	0	0	.51	.07	15.00	0	—	—	3.8	1,500	990	18.5
S-5	4-17-79	0.29	5	0.0	18.5	0	0	0	.45	.08	8.60	0	110	11.2	4.0	1,200	740	13.5
	7-11-79	0.03	—	3.3	—	0	0	0	.31	.05	14.00	0	—	—	3.2	1,250	970	20.0
S-6	4-17-79	1.66	10	—	—	0	0	0	.19	.15	3.60	0	91	9.4	4.1	675	340	14.5
	7-12-79	0.31	—	0.5	—	4	51	0	.08	.09	4.40	0	—	—	5.1	860	400	19.0

GROUND WATER

Well*	Date	Aquifer Group	Well Depth (ft)	Acidity as H+ (mg/L)	Air temp. (Deg C)	Bicarbonate HCO_3 (mg/L)	Carbon dioxide CO_2 (mg/L)	Carbonated CO_3 (mg/L)	Dissolved iron Fe (mg/L)	Suspended iron Fe (mg/L)	Dissolved managanese Mn (mg/L)	Suspended manganese Mn (mg/L	pH Field (units)	Specific Conductance field (micromhos)	Dissolved sulfate SO_4 (mg/L)	Water Temp (°C)
G-1 (8)	4-10-79	2	205	—	15.0	459	463	0	0.22	0.18	0.03	0	6.2	770	33	11.5
G-2 (2L)	4-18-79	3	253	0.0	—	515	21	0	.05	.11	.02	0	7.6	1,000	4.7	11.5
G-3 (13L)	4-18-79	3	535	0.0	22.5	906	15	0	.04	.07	.02	0	8.0	1,650	3.8	12.5
G-4 (22L)	4-24-79	Qal	34	0.0	—	430	17	0	6.20	3.80	.03	.17	7.6	605	2.6	14.0
G-5 (5L)	4-18-79	2	68	0.0	18.5	580	369	0	.37	-	.02	—	6.4	2,000	1100	13.0
G-6 (seep)	4-18-79	Spoil	—	7.0	21.5	0	0	0	1.20	0	37.00	0	3.2	2,100	1300	13.0
G-7 (11)	4-30-79	1	36	—	—	146	12	0	.09	.12	.01	0	7.3	951	230	11.5
G-8 (7)	7-11-79	2	200	—	—	530	27	0	.12	.08	.01	0	7.5	680	15	14.0

*locations shown on figure XII-4.

Table XII-3.– Environmental Protection Agency, 1983, Drinking Water Standards (information from Code of Federal Regulation 340, 1983, parts 141.11, 141.12, 141.13, 141.14, and 143.3)

National Interim Primary Drinking-Water Regulations (Data in milligrams per liter unless otherwise specified, tu = turbidity; pCi/L = picocurie per liter; mrem = millirem (one thousands of a rem).	
Contaminant	Maximum contaminant levels
Inorganic Chemicals (part 141.11)	
Arsenic	0.05
Barium	1.
Cadmium	0.010
Chromium	0.05
Lead 0.05	
Mercury	0.002
Nitrate(as N)	10.
Selenium	0.01
Silver	0.05
Fluoride	1.4-2.4
Organic chemicals (part 141.12)	
Chlorinated hydrocarbons	
Endrin	0.0002
Lindane	0.004
Methoxychlor	0.1
Toxaphene	0.005
Chlorophenoxys:	
2,4-D	0.1
2,4,5-TP Silvex	0.01
Total trihalomethanes (the sum of the concentrations of bromodichloramethane, dibromochloramethane, tribronomethane (bronoform) and trichloromethane (chloroform))	0.10
Turbidity (part 141.13)	1-5 tu
Microbiological (part 141.14)	
Coliform bacteria	1 per 100 mL(mean)
National Secondary Drinking-Water Regulations (part 143.3)	
Chloride	250
Color	15 color units
Copper	1
Corrosivity	noncorrosive
Foaming agents	0.5
Iron	0.3
Manganese	0.05
Odor	3 threshold odor number
pH	6.5-8.5 units
Sulfate	250
Total dissolved solids (TDS)	500
Zinc	5

Table XII-4.– Determination of ground-water type from selected chemical analyses of northern Mercer county, Pennsylvania.
(Modified from Schiner and Runnel, 1976, tables 1A and 3)

[mg/L, milligrams per liter; meq/L, milliequivalents per liter; LSE, land surface elevation.
Aquifers – Qd, Pleistocene drift; Pco, Connoquenessing Formation (sandstone);
Msl, Shenango Formation (sandstone)
Cations – Na^+, sodium; K^+, potassium; Ca^{++}, calcium; Mg^{++}, magnesium;
Anions – CO_3^{--}, carbonate; HCO_3^-, bicarbonate; SO_4^{--}, sulfate; Cl^-, chloride.]

A. Well and chemical data

Well number	Point number	Aquifer	Well depth (feet)	Water level below LSE (feet)	Dissolved solids (mg/L)	Specific conductance (laboratory) (micronhos)	PH (laboratory)
1056	18	Msl	212	153	324	530	8.3
2074	11	Pco	115	55	72	179	6.2
2085	2	Qd	17.0	12.24	130	500	5.9

B. Concentrations of selected constituents from selected ground-water samples.

Well number	Cations (mg/L)				Anions (mg/L)			
	Na^+	K^+	Ca^{++}	Mg^{++}	CO_3^{--}	HCO_3^-	SO_4^{--}	Cl^-
1056	124	2.0	1.6	0.5	4	331	6.5	1.6
2074	4.1	.5	19	5.8	0	49	22	14
2085	31	14	30	13	0	18	79	83

C. Conversion of above concentrations to equivalent-weight units.

Well number	Cations (mg/L)					Anions (mg/L)				
	Na^+	K^+	Ca^{++}	Mg^{++}	total*	CO_3^{--}	HCO_3^-	SO_4^{--}	Cl^-	total*
1056	5.39	0.051	0.08	0.04	5.56	0.133	5.42	.135	0.045	5.74
2074	.18	.013	.95	.48	1.62	0	.80	.042	.40	1.24
2085	1.35	.358	1.50	1.07	4.28	0	.30	.64	2.34	4.28

D. Conversion of the equivalent-weight units to percentages

Well number	Cations (percent of total)			Anions (percent of total)			Water type
	$Na^+ + K^+$	Ca^{++}	Mg^{++}	$CO_3^{--} + HCO_3^-$	SO_4^{--}	Cl^-	
1056	97 .8	1.4	0.7	96.8	2.4	0.8	$NaHC0_3$
2074	11 .8	58.5	29.6	64.8	3.4	31.9	$CaHC0_3$
2085	39.9	35.0	25.0	6.9	38.4	54.7	NaCaCl

* Total equivalents of anions and cations do not match exactly because of analytical errors and unreported minor constituents.

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(5) Piper, A. M., 1944, A graphic procedure in the geochemical interpretation of water analyses: American Geophysical Union Transactions, v. 25, p. 914-923.

(6) Schiner, G. R., and Kimmel, G. E., 1976, Geology and ground-water resources of northern Mercer County, Pennsylvania: Pennsylvania Department of Environmental Resources, Bureau of Topographic and Geologic Survey, Water Resources Report no. 33, 136 p.

(7) Todd, D. K., 1980, Groundwater hydrology (2d ed.): New York, N. Y., John Wiley and Sons, 535 p.

(8) Norris, S. E., 1981, Hydrology of a coal mining area in southeastern Ohio: U.S. Geological Survey Open File Report, 80 p.

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(10) Wood, W. W., 1976, Guidelines for collection and field analysis of ground-water samples for selected unstable constituents: U.S. Geological Survey Techniques of Water Resources Investigations Book 1, chap. D2, 24 p.

(11) Roybal, F. E., and others, 1983, Hydrology of Area 60, Northern Great Plains, and Rocky Mountain Coal Provinces, Nav Mexico, Colorado, Utah, and Arizona: U.S. Geological Survey Water Resources Investigations, Open File Report 83-203, 80 p.

XIII. POTENTIAL GEOHYDROLOGIC IMPACTS OF COAL MINING

Pertinent 30CFR[1] Sections:

- Description of hydrology and geology
- Ground-water information
- Surface-water information
- Cross sections, maps, and plans
- Protection of hydrologic balance
- Operation plan

1. Introduction

Both surface and underground mining have the potential to disrupt and permanently alter the physical and chemical characteristics of aquifer system(s). The changes may include:

1. Reduction of ground-water quantity through the removal of aquifers in the overburden, or of the coal itself;
2. Changes in ground-water storage as measured by significant water-level declines;
3. Changes in ground-water flow directions, (such as through aquifer dewatering related to "dry" mining operations, and through increased interaction between water-bearing rock units);
4. Alteration of stream base flow by creating losing reaches in areas of ground-water level declines, and creating gaining reaches in areas of mine refuse, abandoned mines, and, mine subsidence; and,
5. Alteration of chemical characteristics of ground water and as base flow of streams; also the degradation of ground-water quality through acid-mine drainage.

The impacts of these changes on the aquifer system(s) outside the permit area and adjacent area depend upon:

1. Value and use of the ground-water resources in the general area: (Are water supplies for municipalities and industries solely dependent upon potable ground water? Or is surface water the major water resource?)
2. Availability of alternative water supplies: (Are deeper aquifers available for water supply? Or could surface water be developed for water supply?)
3. Magnitude of the proposed mining operation relative to the ground-water availability: (Is the affected area inconsequential compared to the size of the aquifer system and the availability of ground water?)
4. Volume of coal-spoil piles and isolation of water draining from spoils from the general area.

[1] CFR = Code of Federal Regulations

2. Changes in Ground-Water Flow

Surface and underground coal mining can cause aquifer destruction, significant water-level declines in the vicinity of the excavation, and local changes in directions of ground-water flow.

Where the minable coal beds are below aquifers in the overburden and(or) below the base level of streams, the mine-excavation pit serves as a sump for ground-water discharge. The pumping necessary to dewater the working pit causes a decrease in saturated thickness of the overlying aquifer, which may cause wells and springs in the immediate area to go dry. (Partially penetrating water-supply wells could also "go dry" for other reasons, such as increased nearby pumpage, or prolonged drought. Careful hydrologic monitoring and investigation within the general area, will determine whether the wells and springs went "dry" as a result of mining.)

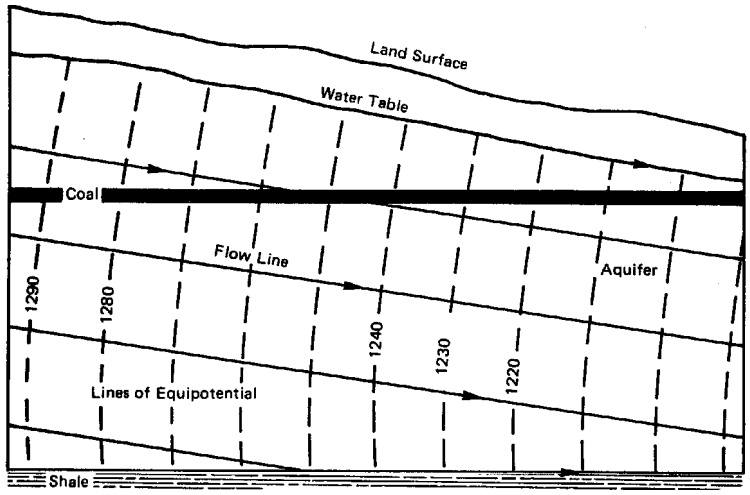
In surface mining, blasting can also cause changes in ground-water flow. A secondary effect of the use of explosives is the increased fracturing which increases the hydraulic connection between previously confined water-bearing rock units. In underground mining, underclays or shale beds, which can act as impermeable hydraulic boundaries, limit the infiltration into the excavation site. However, high hydrostatic heads and rock pressure on the pillars have caused mine floors to buckle and have allowed ground water to discharge into the underground mines.

An idealized ground-water flow system, within a flat-lying sedimentary bedrock (aquifer containing a commercial coal bed is illustrated before and during surface mining in fig. XIII-2-1. The coal excavation forms a hydraulic sink, which causes changes in ground-water directions. A similar setting before and during underground mining is illustrated in fig. XIII-2-2. The potentiometric maps in fig. XIII-2-3 illustrate the changes in ground-water flow before and during surface mining of the D-l coal aquifer in the Decker, Mont., area. The premining natural sink, or ground-water discharge area, was the Tongue River Reservoir, which has a spillway elevation of 3424 ft. After 3 years of mining, and with the mine floor at an elevation below 3380 ft. the ground water was locally diverted toward the mined area.

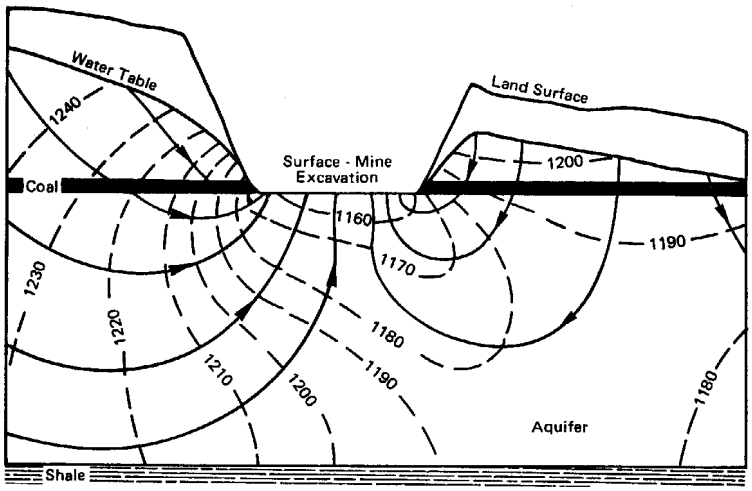
The change in ground-water flow is defined by the change in discharges from spring and in ground water levels (chapter XIV) within the adjacent area. Four-year well hydrographs from aquifers in an area affected by mining are shown in fig. XIII-2-4. (This effect is also evident in fig. IX-5). Details on the placement of observation wells are presented in the next chapter, table XIV-2.

The maximum drawdown within the mine-permit area in fig. XIII-2-3 during the 3-year period was 38 ft. The water-level-change map, fig. XIII-2-5, illustrates the estimated water-level declines, over a 20-year period of mining along the edge of the permit area at the time of cessation of mining. The maximum drawdown during this period is about 90 ft.

The areal extent and long-term effect of mining on ground-water flow depend on the geologic, hydrologic, and climatologic conditions at the mine site and the management of the spoils and "last cut" lakes. Generally water levels will begin to rise to premining equilibrium conditions upon completion of mining and reclamation.



A. PREMINING GROUND - WATER FLOW



B. DURING MINING GROUND - WATER FLOW

Figure XIII-2-1.— Directions of ground-water flow in sedimentary sequence at a surface-mine area, before and during excavation. Modified from Wilson and Hamilton, 1978 fig. 4

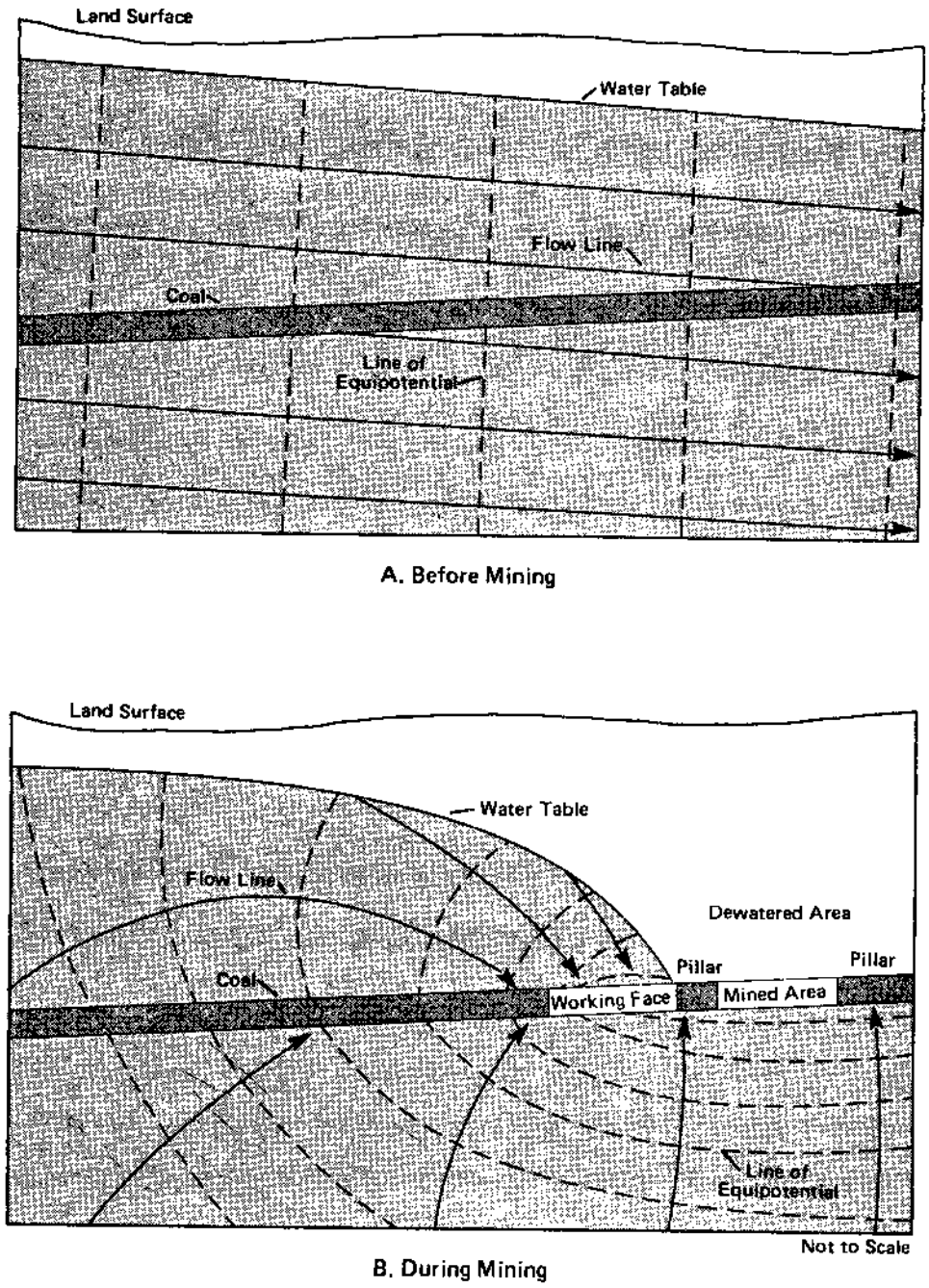


Figure XIII-2-2.— Directions of ground-water flow in a sedimentary sequence near an underground mine before and during excavation.
(From Lines and others, 1984, fig. 3.2-2)

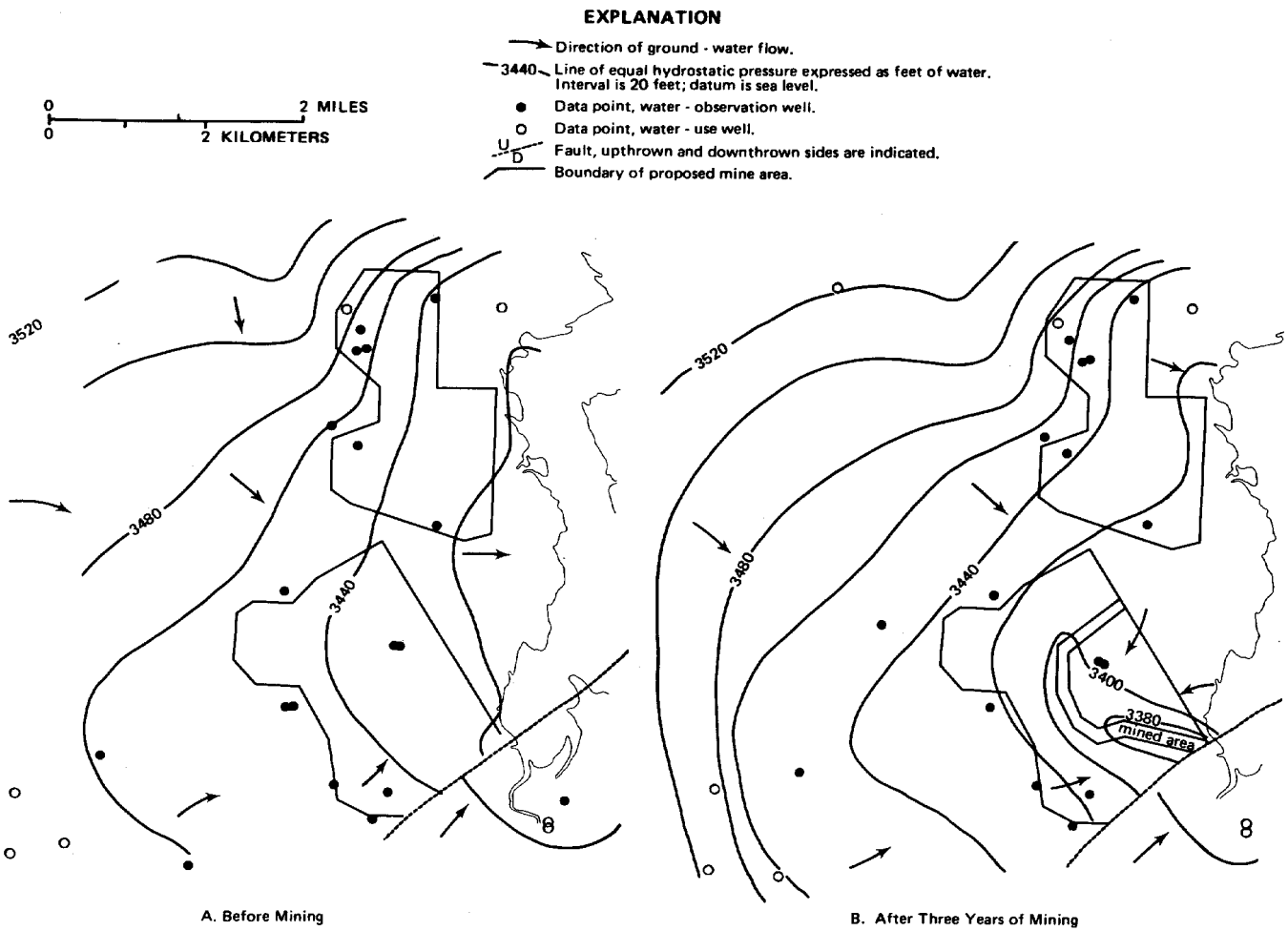


Figure XIII-2-3— Potentiometric surface maps of coal aquifer (D-1) before and after 3 years of mining in Decker, Montana area.
(From VanVoast and Hedges, 1975, pls. 4 and 7)

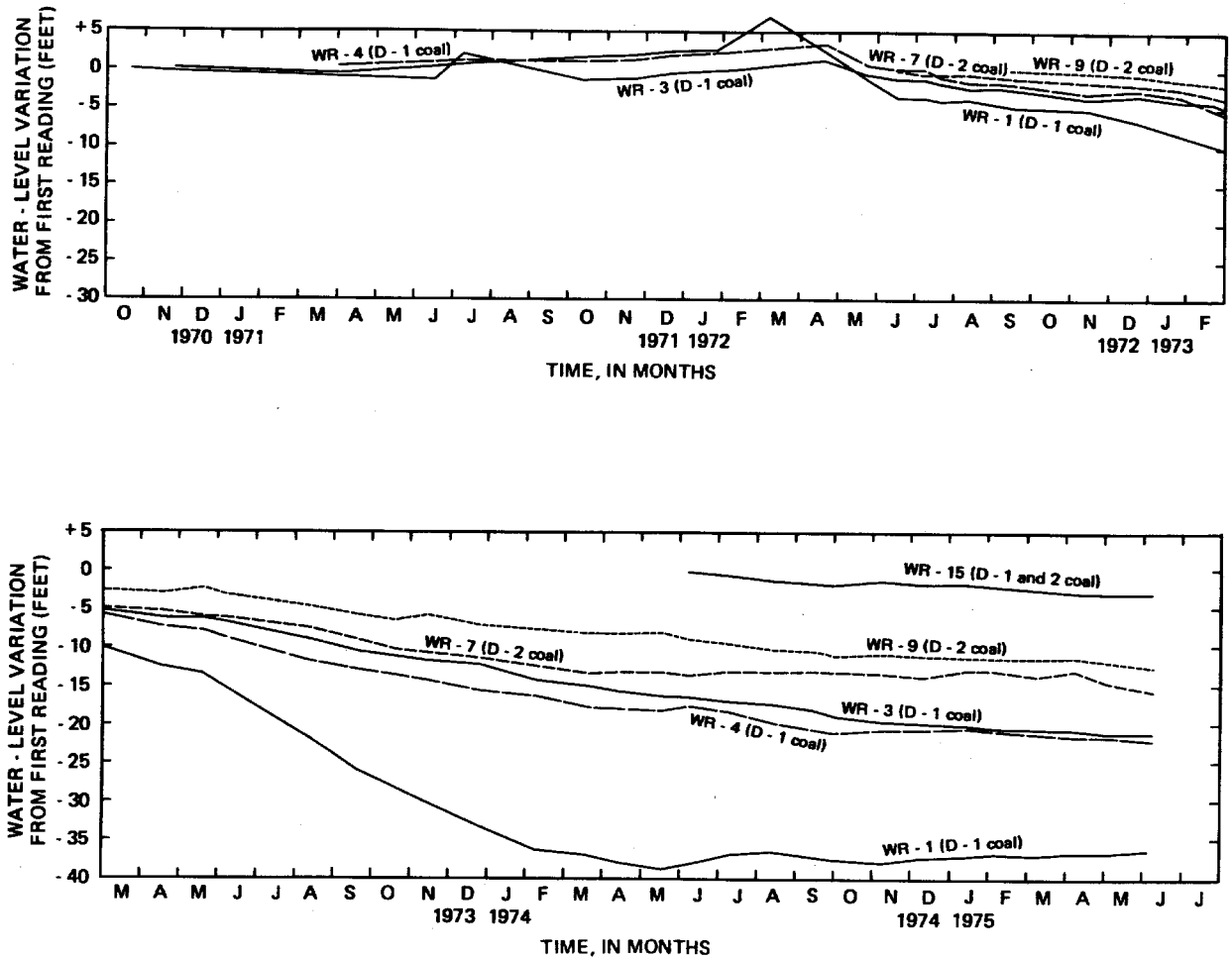


Figure XIII-2-4.— Water-level changes in selected observation wells before and during mining in the Decker, Montana area. (Modified from VanVoast and Hedges, 1975, pl. 10)

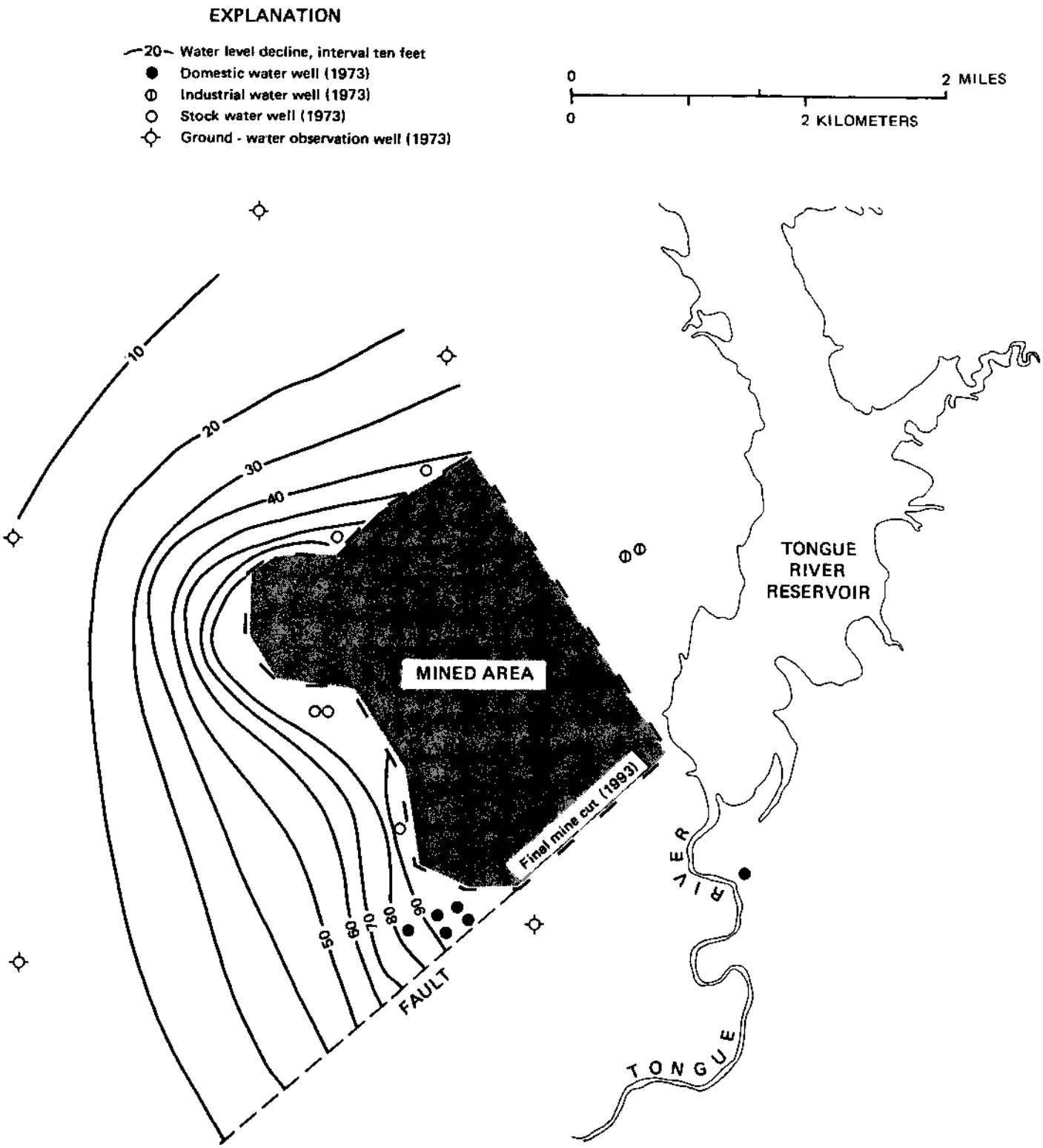


Figure XIII-2-5.— Predicted water-level declines at time of cessation of mining in D-l aquifer near Decker, Montana after 20 years of mining. (From VanVoast, 1974, fig. 11)

3. Changes in Ground-Water Storage and Modification of the Relationship between Ground Water and Surface Water

Surface and underground coal mining operations have the potential to create and increase the storage capacity of ground-water reservoirs through the formation of mine-spoil piles and the use of explosives. This alteration can modify storm runoff and baseflow characteristics. Streamflow can also be modified by the direct discharge of mine water.

In surface-mine operations, the excavation of coal and the associated backfilling with disturbed overburden creates an unconsolidated deposit with increased effective porosity and hydraulic conductivity. The increase in ground-water storage (porosity) can range from 1 percent to 30 percent.

In underground mining, the excavation of coal can cause subsidence cracks in the overburden, even where the mine depth is as much as 600 ft. This subsidence creates a fractured rock mass with an increased effective porosity and hydraulic conductivity. The percent of increase is highly variable. The effect of subsidence on shallow aquifers generally diminishes with increasing depth of underground mining. However, the extent of bedrock fracturing and subsidence depends upon mining methods, such as the "room and pillar" method and the "long-wall" method. In some reported cases, the effect of underground mining on overlying shallow aquifers was of short duration because the fractured overburden bedrock adjusted back to its original position with the cessation of mining.

The increase in effective porosity and hydraulic conductivity causes a comparable increase in aquifer storativity. This increase has several possible effects on the aquifer system(s), depending on whether the mining is at land surface or underground:

1. Surface operations and associated backfilling of overburden:
    a. creation of an unconsolidated (water-table) aquifer.
    b. increased discharge from the mine spoils, which increases stream base flow.
    c. degradation of base-flow quality through the hydration and oxidation of pyritic minerals within the spoils.
    d. degradation of shallow ground-water quality by the infiltration of water through mine spoil into the shallow aquifer.
2. Underground operations and associated subsidence:
    a. lowering of water table through the increased interconnection of confined aquifers and through dewatering.
    b. reduction in evapotranspiration by the removal of vegetation and the lowering of shallow water table.
    c. reduction in base flow where mining operations are beneath streams, which creates losing reaches (chapter XI) and as dewatering is continued,
    d. large fluctuations in ground-water levels, as much as several hundred feet, while pumping to maintain "dry" mine conditions.
    e. diversion of ground water out of the drainage basin.

Some of these effects are long lasting; others diminish and may recover to pre-mining conditions.

The effect of changes in ground-water storage on the ground-water flow system in the general area may be defined by:

1. measurements of water levels in observation wells (chapter XIV), tapping:
   a. mine spoils
   b. aquifers downgradient of the spoils (for surface-mine operations), and
   c. overburden aquifers potentially affected by underground mining.
2. measurement of spring discharges.
3. measurement of discharge at streamflow sites upgradient and downgradient from both surface- and underground-mining operations.
4. aquifer testing of the created spoil piles and of the aquifers within the subsidence area.
5. analysis of observation-well hydrographs.

A planimetric map and cross section of an area in West Virginia in which surface- and underground-mining of the Lower Kittanning coal continued from 1895 until 1971 are shown in figure XIII-3-1. The ground-water-storage modification is reflected in the change in stream base flows; the geologic setting is flat-lying coal, GS-1 (see chapter IV), the hydrologic setting is a coal bed in contact with an unconfined bedrock aquifer, HS-E (see chapter VI), and the coal bed is an unconfined aquifer, HS-F(2). The area of greatest increase in base flow is near Norton, where the maximum unit discharge increased from 0.27 $(ft^3/s)/mi^2$ in October 1965 to 4.25 $(ft^3/s)/mi^2$ in April 1979. The base-flow yield for unmined basins in this general area ranges between 1 and 2 $(ft^3/s)/mi^2$.

Flow-duration curves for three sites in West Virginia — Grassy Run, with a drainage area (DA) of 2.86 mi^2, Roaring Creek (DA 29.2 mi^2) and Sand Run (DA 14.5 mi^2) are given in figure XIII 3-2. The Grassy Run and Roaring Creek stations are near Norton (fig. XIII 3-1); the Sand Run station is a few miles to the west. Nearly all of the small basin has been mined out, whereas less than half of the large basin and none of the intermediate basin, has been mined. All three basins are similar in geology, topography, climate, and vegetation. Comparison of the unit base-flow discharges demonstrates the effect of mining on the ground-water discharge: Grassy Run (mined out) is 0.42 $(ft^3/s)/mi^2$, Roaring Creek (half mined) is 0.065 $(ft^3/s)/mi^2$, and Sand Run (unmined) is 0.03 $(ft^3/s)/mi^2$. Greater infiltration in the mined area, and the conversion of ephemeral streams to perennial streams are related to the increased ground-water storage due to mining. In this example, mining caused ground-water discharge to the stream to increase an order of magnitude.

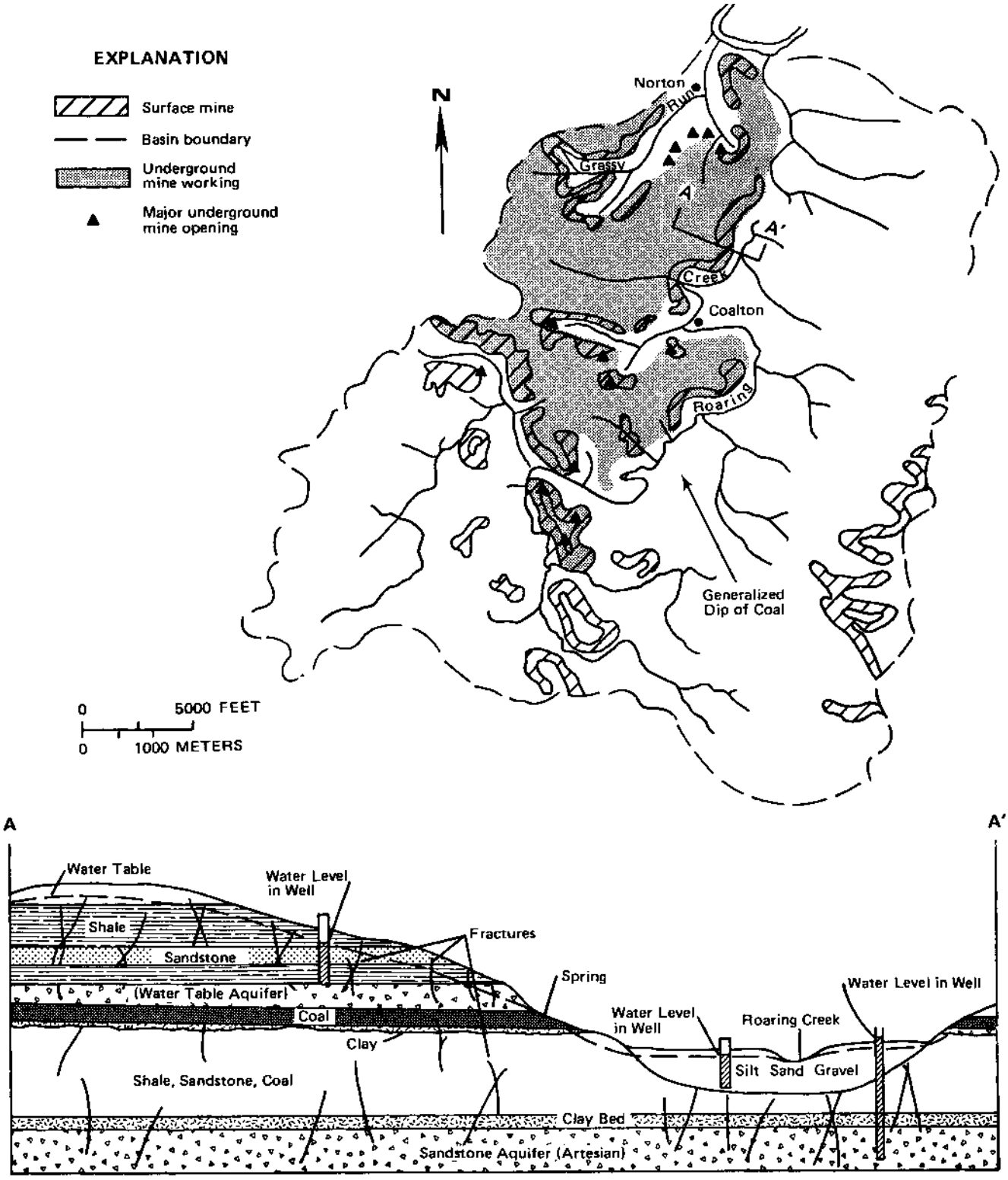


Figure XIII-3-1.— Area where mining caused increases in base flow of streams. (Effects on base flow are plotted on fig. XIII-3-2.) (Section A-A1 illustrates the geologic and hydrologic settings.) (Modified from Hobba, 1981, figs. 1.3-8 and 2.1.1-A)

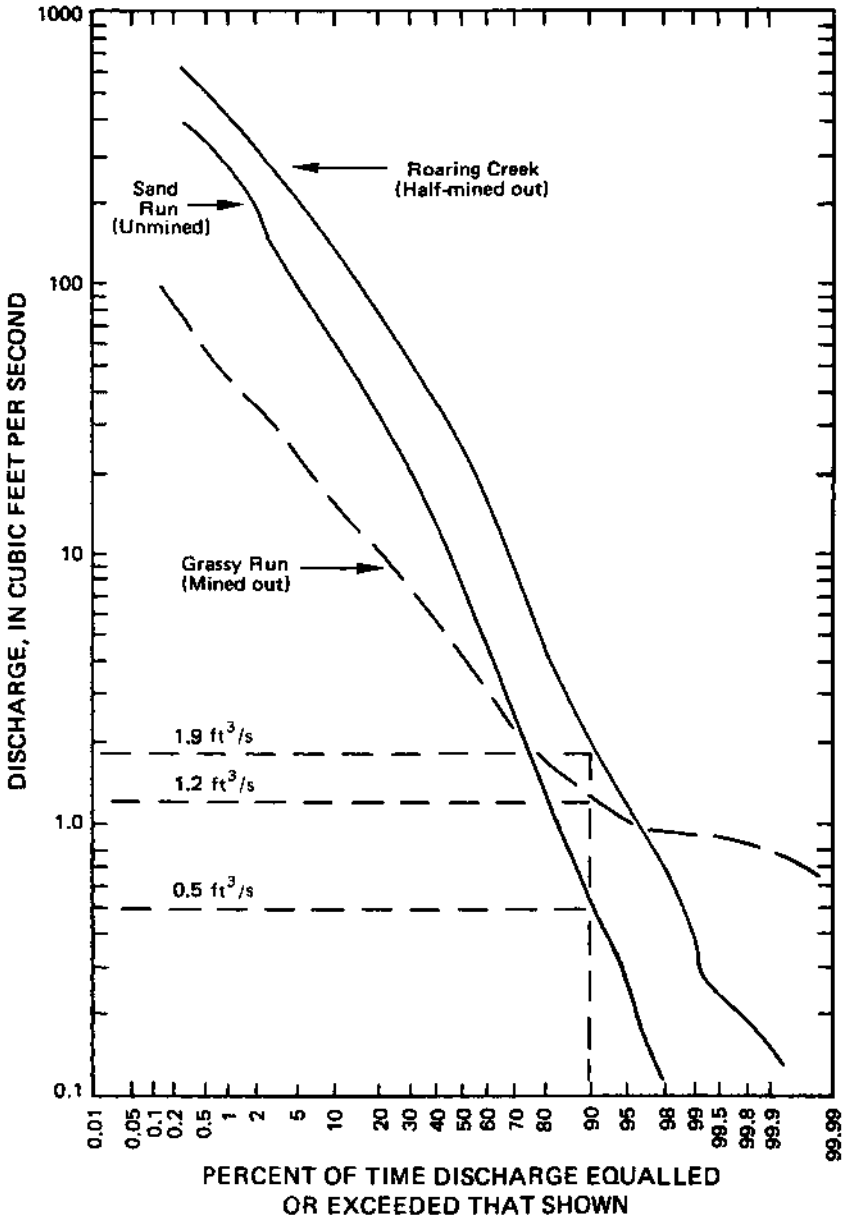


Figure XIII-3-2.— Flow-duration curves of three streams in the some terrain but mined to differing degrees.
(Modified from Hobba, 1981, fig. 2.2.2-B)

4. Modification of Ground-Water Quality

The chemical quality of ground water is locally variable (chapter XII), as a result of chemical reactions with the minerals in the soil-, and the unsaturated and saturated zones. Ground water within local shallow flow systems (chapter IV) is generally of good quality. In the coal areas, ground water within the regional flow system, commonly extends deeper than 300 ft, is highly mineralized, and generally does not meet the drinking-water standards (See table XII-4.). The changes in ground-water chemistry as the water moves from the local flow system to the regional flow system are plotted in figure XII-1. These changes included increased dissolved solids and a change in chemical composition.

A generalized vertical section showing ground-water flow in layered sedimentary strata containing coal seams was given in figure V-2; a detailed version, shown in figure XIII-4-1, indicates (1) the variation of hydraulic head with topographic and hydrologic position, (2) the movanent of ground water from the uplands down to the alluvium and the river, (3) the tendency of the water table to parallel land surface, and (4) the transition zone between the connate brine of the deep flow system and the freshwater of the local system.

The ground-water quality in an unmined area of a local flow system can be a calcium-magnesium bicarbonate type with pH of 6.5 to 7.0 and low iron and sulfate concentrations. As shown in figure XIII-4-2, the ground-water flow system changes during surface- and underground-mining. In surface mining, spoils are created, and the pyrite minerals in the disturbed shale bedrock are oxidized to form sulfuric acid and "yellow boy". The simplified formula is

$$FeS_2 + H_2O + O_2 \longrightarrow Fe(OH)_3 + H_2 SO_4 .$$

In underground mining, not only is the local water table lowered, the ground-water flow direction changes from dominantly horizontal to dominantly vertical and, with the fractured overburden, the oxygenated water yields acidic water, as with surface mining, which is called acid mine drainage (MD).

The common characteristics of AMD are (1) pH less than 4.0, (2) iron concentrations of about 10 mg/L; and (3) sulfate concentrations greater than a 1,000 mg/L.

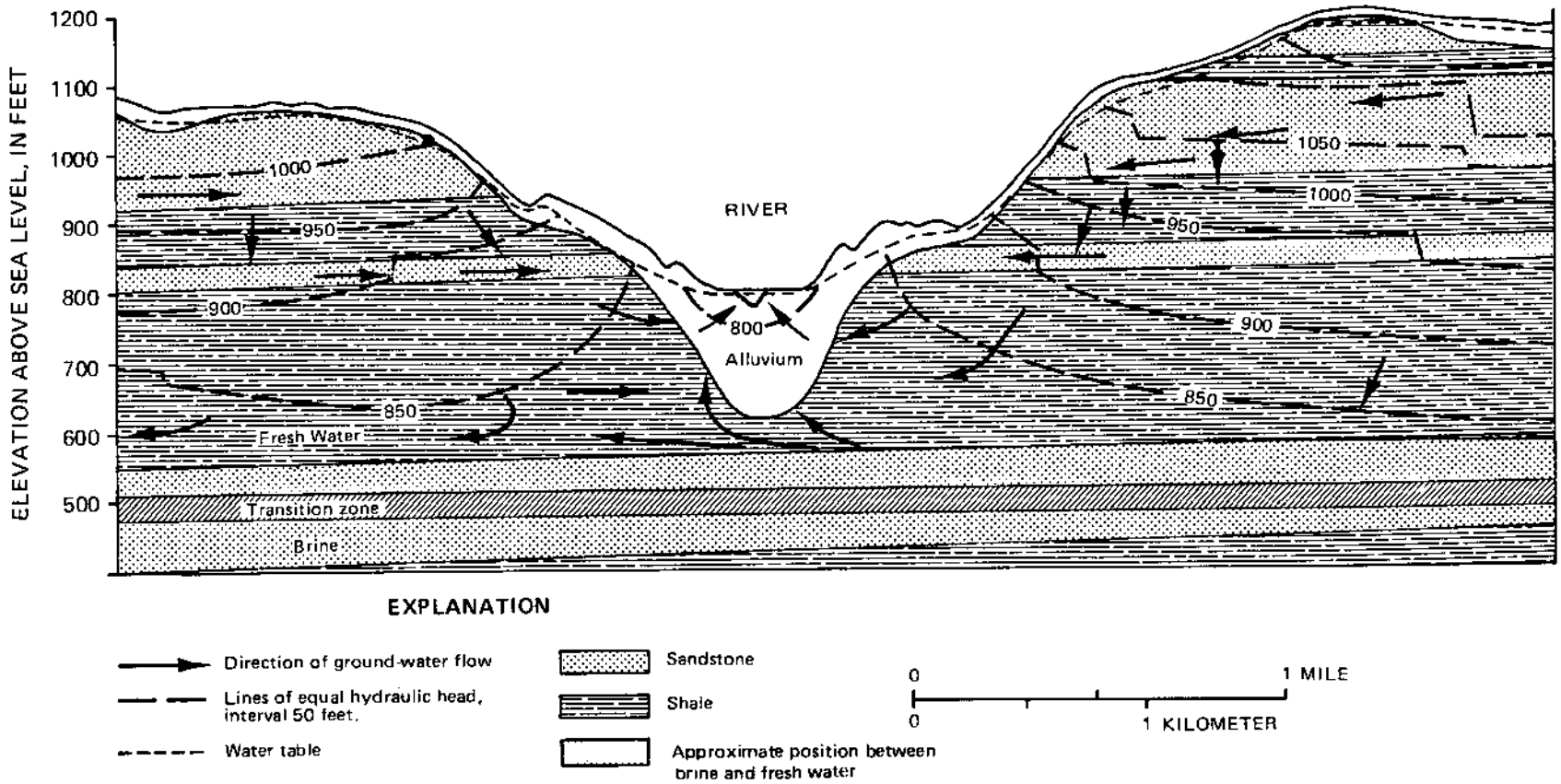


Figure XIII-4-1.— Example of a idealized geologic and hydrologic section in a sedimentary sequence showing directions of ground-water flow.
(Modified for Carswell and Bennett, 1963, pl. 3)

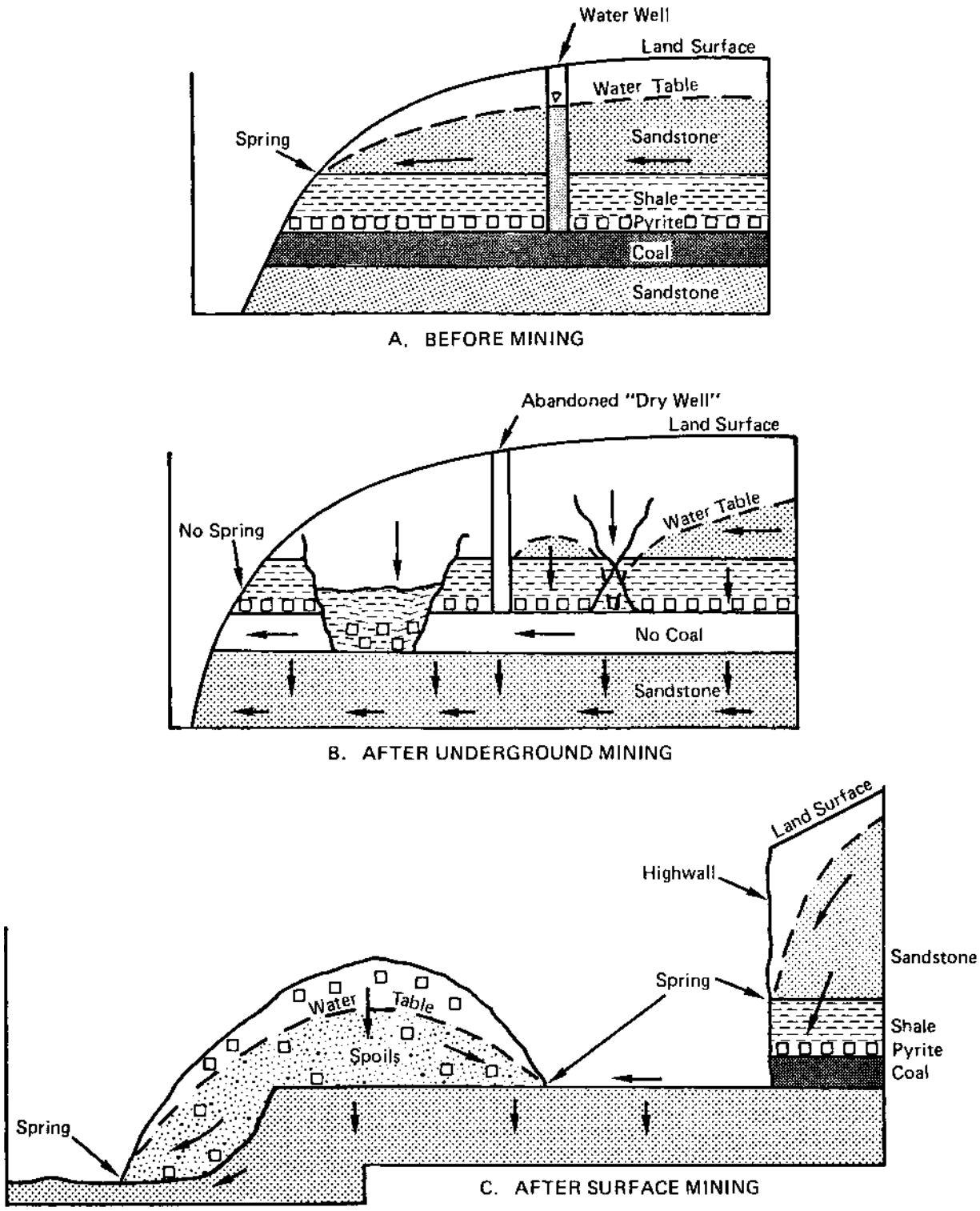


Figure XIII-4-2.— Effects of surface- and underground-coal mining on ground-water flow. (Modified from A.I.P.G., 1983, and Enrich and Merritt, 1969)

At surface- and underground-mining sites as well as abandoned mines, AMD discharges to streams, where it degrades surface-water quality, and into shallow aquifers, where it affects ground-water quality. A summary of these characteristics in ground water from a mined area in southwestern Pennsylvania is given in Table XIII-4-1. Other effects can include increased concentrations of total dissolved solids, including aluminum and manganese. Water of acid-mine drainage is typically hard, has objectionable amounts of iron that causes the staining of clothes and porcelain, has a laxative effect and a bad taste, and requires extensive filtration, softening, and settling before domestic use. Water with low pH may be corrosive and adversely affect commercial treatment processes including coagulation and chlorination. Water for cooling purposes outside the pH range of 5.0 to 8.9 are considered unusable for industrial purposes. The trilinear diagrams in figure XIII-4-3 summarize (1) ground-water quality in selected noncoal-bearing areas in western Virginia where the water type is calcium-magnesium bicarbonate, and (2) ground-water quality in adjacent mined and coal bearing areas, where water type is calcium-magnesium sulfate.

Ground-water quality can also be modified by other mineral-resource production activities such as intensive pumping of ground water, active petroleum production, abandoned oil and gas wells, and waste disposal. Intensive pumping of the ground water within the local flow system, for water supply can cause a significant reduction in hydrostatic head at the wells and cause an upward migration of salty ground water. Figure XIII-4-4 illustrates the upcoming of deep saltwater. Such well discharges commonly have concentrations of chloride in excess of 250 mg/L, which gives the water a salty taste.

A summary of the range and mean concentration of chemical constituents of ground water affected and unaffected by coal mining and saltwater intrusion in southern West Virginia is given in table XIII-4-2. Streamflow in this area is generally the calcium bicarbonate type, but ground water is variable. It may be contaminated by calcium sulfate water from mines or by brine disposal in the oil-and gas-producing areas. Ground-water discharge from abandoned mines in the headwaters results in an increase of the dissolved-solids concentration of the receiving stream (Ehlke and others, 1982).

Ground water from bedrock wells tapping the Lower Pennsylvanian Series (Pottsville age), that are affected, by saltwater typically has high specific conductance, dissolved solids, and chloride, whereas ground water from wells tapping the same system that is affected by coal has high specific conductance and dissolved solids, but also has high hardness, dissolved iron, and sulfate. This water is also typically low in alkalinity and pH. Characteristic ground water from the Lower Pennsylvanian Series that is unaffected by mining or saltwater intrusion has neutral pH (about 7), low specific conductance, dissolved solids, hardness, chloride, and sulfate, but high concentrations of dissolved iron. The ground water of best quality is in the alluvium, which is low in specific conductance, alkalinity, chloride, hardness, iron, and manganese.

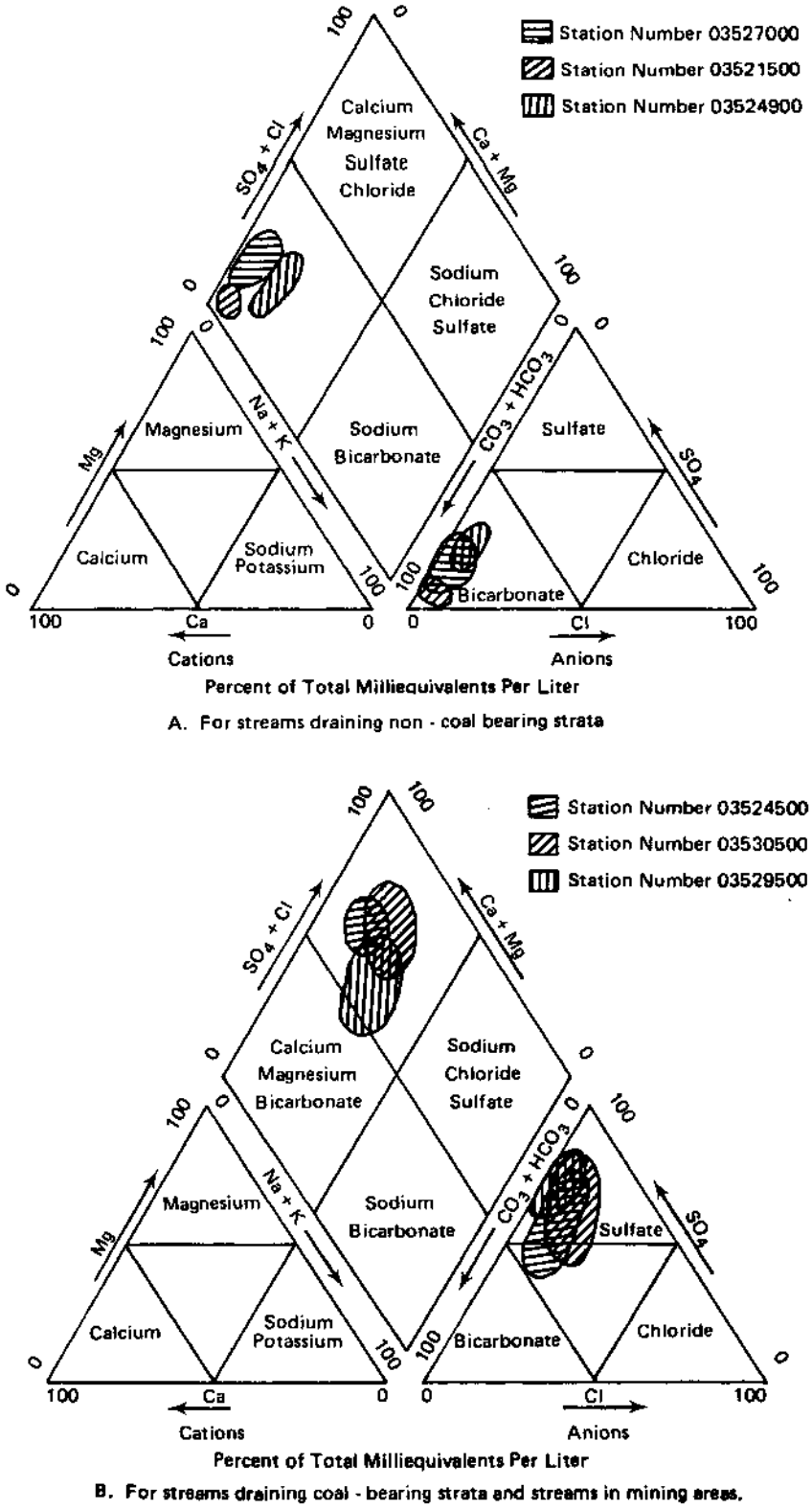


Figure XIII-4-3.— Trilinear diagrams showing quality of water in six streams draining sedimentary strata in western Virginia.
(From Hufshmidt and others,1981, fig. 5.1)

Active petroleum exploration and development commonly results in the production of brine (salty water) from deep formations. The improper disposal of brine can affect the quality of the ground water within the shallow flow system. Disposal methods include temporary storage in holding ponds and reinjection into the petroleum-production zones by pressure flooding.

Active and abandoned oil and gas wells that are improperly cased or are uncased allow brines and other fluids to discharge at the land surface or into aquifers of the local flow system. Fracture traces (chapter X-3.0) also allow the movement of brines and other fluids into the shallow flow system (Harrison, 1983).

Waste disposal operations may develop an effluent, or leachate, that has the chemical make-up of the waste material. Waste disposal could be of industrial, municipal, or agricultural origin: A hypothetical hydrogeologic cross section in figure XIII-4-5 shows common practices of land use, water use, and waste disposal in relation to the ground-water system. All of the practices shown affect the quality of ground water and, to some extent, the quality of stream-flow. Table XIII 4-3 lists some chemical constituents commonly found in ground water that originate from the wastes of the respective industries.

The effect of mining on water quality in the general area may be defined by sampling the following within the permit area and upgradient and downgradient from it before, during, and after mining:

1. water from observation wells (See chapter XIV) that tap the overburden, the aquifers, and the spoils?
2. spring discharges;
3. base flow of streams.

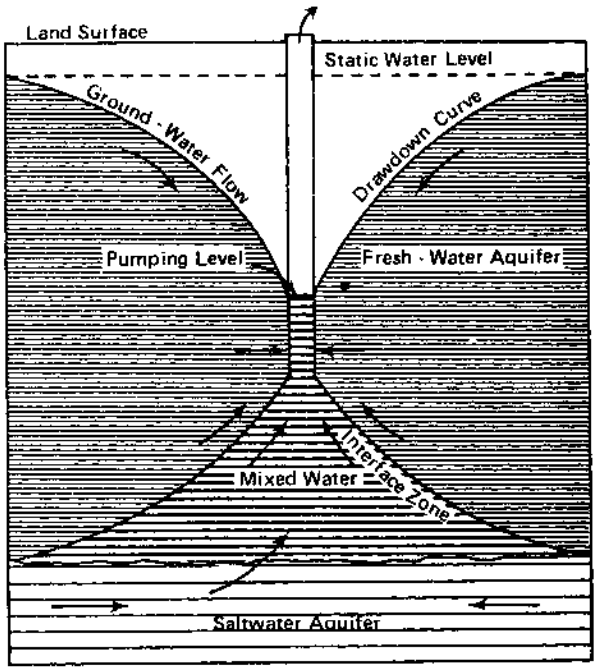


Figure XIII-4-4.— Upcoming of saline ground water into well discharge as a result of heavy pumping.
(Modified from U.S. Geological Survey, 1984, fig. 23)

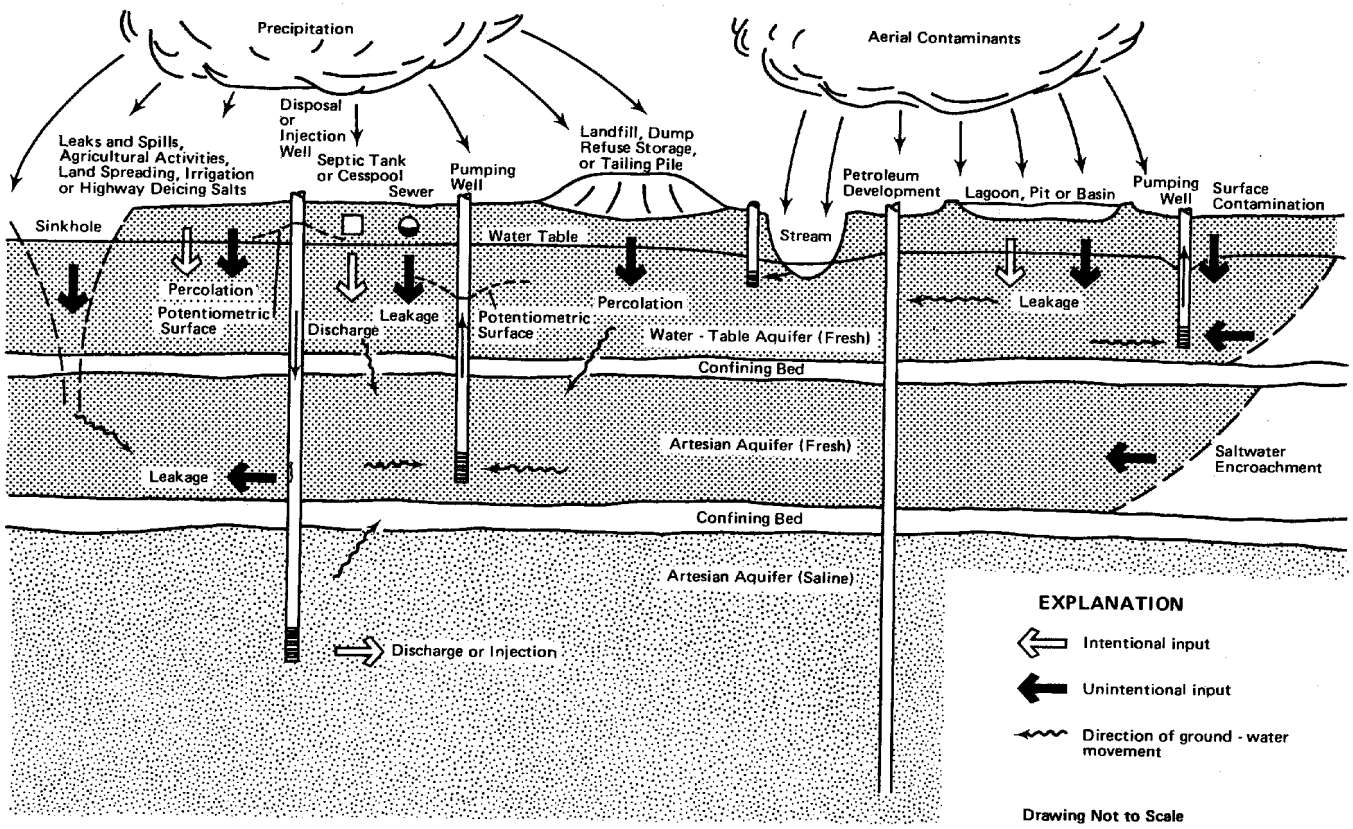


Figure XIII-4-5.— Typical sources and routes of ground-water contamination. (From U.S. Environmental Protection Agency, 1977a)

Table XIII 4-1.– Areas of suspected ground-water degradation due to coal mining in southwestern Pennsylvania.
(From Sgambat and others, 1980, table 8; and Green International, Inc., 1976.)
[Fe, iron; 804, sulfate; mg/L, milligrams per liter.]

County and township	Watershed	Average concentrations Fe mg/L	SO_4 mg/L	pH units
ALLEGHENY COUNTY				
West Deer Township	West Branch Deer Creek	6	922	3.83
Fawn Township	Bull Creek	50	–	–
Frazer, Harmar, & Springdale Townships	Little Deer Creek	22	1,307	6.71
Findley Township	Potatoe Garden Run	69	793	–
Penn, Patton, North Versailles , Mifflin & Pittsburgh Townships	Turtle Creek	21	433	–
ARMSTRONG COUNTY				
Madison & Washington Townships	Mahoning Creek & Allegheny River	34	665	3.05
Rayburn & East Franklin Townships	Cowanshannock Creek & Allegheny River	21	2,380	2.98
North & South Buffalo Townships	Allegheny River	82	2 ,631	3.45
BUTLER COUNTY				
Allegheny Township	Bear Creek	20	560	2.40
Connoquenessing Township	Little Connoquenessing Creek	14	475	3.60
Jackson Township	Connoquenessing Creek	7	560	–
FAYETTE COUNTY				
Springfield & Stewart Townships	Trib. Youghiogheny River	25	3,312	4.07
INDIANA COUNTY				
Banks Township	South Brady Run	37	829	4.48
Cherryhill Township	Two Lick Creek Little	34	955	4.26
Brush Valley & Center Townships	Yellow Creek Brush Creek Black Lick Creek Two Lick Creek	64	1,714	3.86
WESTMORELAND COUNTY				
Setfickley, Rostraver, South Huntingdon Townships	Sewickley Creek	23	1,076	5.05
South Huntingdon Township	Sewickley Creek	–	3,075	4.02

Table XIII 4-2. – Ground-water quality affected and unaffected by mining and/or salt-water intrusion.
(From Ehlke, and others, 1982, p. 31.)
[mg/L, milligrams per liter; $CaCO_3$, calcium carbonate.]

		Specific Conductivity (micromhos per centimeter)	pH(units)	Alkalinity (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Hardness as $CaCO_3$ (mg/L)	Hardness non -carbonate (mg/L)	Dissolved solids (sum) (mg/L)	Dissolved iron (mg/L)	Dissolved manganese (mg/L)	No. of wells
A. Comparison of water analyses from wells unaffected by mining or salt water												
Geologic material												
Quaternary alluvium	Max.	710	7.3	246	29	110	200	110	443	0.17	0.06	14
	Min.	100	5.51*	12	0	11	26	0	55	0	0	
	Mean	224	6.6	57	8.7	38	77	23	136	.10	.019	
Upper Pennsylvanian formations	Max.	1,000	8.9	435	120	100	300	53	646	32.0	3.9	94
	Min.	100	6.21*	0	1.0	0.1	3	0	119	0	0	
	Mean	499	7.2	229	19	21	109	3. 7	318	1.686	.274	
Lower Pennsylvanian formations	Max.	930	8.3	435	180	88	230	75	588	16.0	9.9	191
	Min.	45	4.51*	9	0.8	0	3	0	21	.01	0	
	Mean	269	7.0	94	14	34	68	6.5	152	3.266	.232	

* median value

B. Comparison of water analyses from wells tapping the lower Pennsylvanian Series (Pottsville age) that are unaffected, affected by mining, and affected by salt water

Water type											
				Maximum values							
Unaffected	930	8.3	435	180	88	230	75	588	16.0	9.9	191
Affected by mining	2,000	8.0	130	250	1,200	1,300	1,300	1,790	180.	9.9	38
Affected by salt water	3,500	7.6	254	1,000	3	210	38	1,930	9.8	.65	10
				Minimum values							
Unaffected	45	4.5	9	0.8	0	3	0	21	0.01	0	191
Unaffected by mining	70	4.1	0	1.0	0.4	24	13	42	0	0	38
Affected by salt water	650	6.7	123	140	0	32	0	385	.06	0.01	10
				Mean values							
Unaffected	269	7.0*	94	14	34	68	6.5	152	3.27	0.232	191
Affected by mining	482	6.6*	32	19	172	183	150	324	16.5	4.23	38
Affected by salt water	1,250	.2*	174	304	1.2	100	3.8	696	2.587	.196	10

* median value

Table XIII 4-3.– Industrial wastewater constituents having or indicating significant ground-water contamination or potential. (From Hammer & MacKichan, 1981, table 5-2; and U.S. Environmental Protection Agency, 1977b.)

[COD - chemical oxygen demand; TOC - total organic carbon; Heavy metals include: aluminum, calcium, chromium, cobalt, copper, gold, iron, lead, manganese, mercury, nickel, platinum, Rare Earths, silver, tin, vanadium, zinc, and others.]

PULP AND PAPER INDUSTRY			
Ammonia	Heavy metals	Phenols	TOC
COD	Nutrients (nitrogen & phosphorous)		Total dissolved solids
Color	pH	Sulfite	
PETROLEUM REFINING INDUSTRY			
Ammonia	Cyanide	pH	Total phosphorous
Chloride	Iron	Phenols	Turbidity
Chromium	Lead	Sulfate	Zinc
COD	Mercaptans	Sulfide	
Color	Nitrogen	TOC	
Copper	Odor	Total dissolved solids	
STEEL INDUSTRIES			
Ammonia	Cyanide	Phenols	Zinc
Chloride	Iron	Sulfate	
Chromium	pH	Tin	
ORGANIC CHEMICALS INDUSTRY			
COD	pH	Total dissolved solids	
Cyanide	Phenols	Total nitrogen	
Heavy metals	TOC	Total phosphorous	
INORGANIC CHEMICALS, ALKALIES, AND CHLORINE INDUSTRY			
Acidity/alkalinity	Chromium	Phenols	
Aluminum	COD	Sulfate	
Arsenic	Cyanide	Titaniun	
Boron	Fluoride	TOC	
Chloride	Iron	Total dissolved solids	
Chlorinated benzenoids & polynuclear aromatics	Lead	Total phosphorous	
	Mercury		
PLASTIC MATERIALS AND SYNTHETICS INDUSTRY			
Ammonia	Mercaptans	Phosphorous	
Chlorinated benzenoids & polynuclear aromatics	Nitrate	Sulfate	
	Organic nitrogen	Total dissolved solids	
COD	Zinc	pH	
Cyanide	Phenols		
NITROGEN FERTILIZER INDUSTRY			
Ammonia	COD	Phosphate	
Calcium	Iron	Sodium	
Chloride	Nitrate	Sulfate	
Chromium	Organic nitrogen compounds	Total dissolved solids	
	PH	Zinc	
PHOSPHATE FERTILIZER INDUSTRY			
Acidity	Dissolved solids	Nitrogen	Uranium
Aluminum	Fluoride	pH	
Arsenic	Iron	Phosphorous	
Calcium	Mercury	Sulfate	

XIV. GROUND-WATER MONITORING PLAN

Pertinent 30CFR[1] Sections:

Ground-water information
Cross sections, maps, and plans
Hydrologic balance
Operation plan

The objectives of a ground-water monitoring plan for a mining area are to:

1. define the premining ground-water conditions in terms of quantity and quality;
2. monitor water-level changes in potentially impacted aquifers during and after mining operations and to provide documentation;
3. monitor water-quality changes in surface water (base flow) and ground water during and after mining operations and to provide documentation;
4. monitor directions of ground-water flow in the vicinity of mining operations;
5. monitor potentially dangerous ground-water conditions such as hydraulic-head differences across fault zones, or across confining beds separating aquifers from coal seam excavations, or within fault zones that might connect surface-water features, such as rivers, with mining excavations; and,
6. satisfy regulatory authority requirements for ground-water monitoring.

The considerations and procedures for developing a ground-water monitoring plan to satisfy these objectives includes the following:

1. Time and frequency of measurement of:
   a. ground-water levels
   b. surface-water discharge
   c. chemical quality of ground water and surface water
2. Hydrologic data collection sites:
   a. precipitation station
   b. ground-water sites—springs and wells
   c. surface-water sites—low-flow sites, swamps, ponds, lakes, reservoirs, and mine discharge sites,
   d. mine spoils
3. Activities causing variations in ground-water quantity and quality:
   a. natural—precipitation, evaporation, and transpiration,
   b. man-related stresses—ground-water use (pumping, See chapter VII), and mine discharge.
4. Aquifers that could be potentially impacted by proposed mining operations (See chapter XIII):
   a. bedrock aquifers in the overburden,
   b. bedrock aquifer in the underburden,
   c. coal as an aquifer.
   d. unconsolidated deposits aquifer in the overburden or within the adjacent area,
   e. mine spoils.

[1] CFR = Code of Federal Regulations

5. Hydrologic measurements:
   a. ground-water levels (See chapter IX)
   b. streamflow discharge(s) (See chapter XI)
   c. pumpage - recharge and discharge (See items 3a and 3b above and chapter VII).
   d. determination of aquifer characteristics (hydraulic properties) (See chapter X, section 2).
   e. ground-water quality sampling routine, including wells, springs, and low-flow stream sites (See chapter XIII, section 4).
6. Hydrologic boundaries (See chapter X, section 2.71).
7. Ground-water modeling (See chapter XV, section 7).

Features 1 and 2 are discussed below; features 3 through 7 are discussed elsewhere in the manual, as noted.

Time and Frequency of Measurement

The monitoring period starts prior to permitting to obtain base-line information and extends throughout the mining and reclamation operations. The schedule and frequency of measurements is subject to the approval of the regulatory authority. The frequency of measurements is flexible, depending upon:

1. Regulations – 'Permanent Regulatory Program (30CFR parts 780.21 and 784.14' – states "…water levels shall be monitored and data submitted to the regulatory authority at least once every three months for each monitoring location."
2. The amount of geohydrologic information available for the permit area (chapter XV)
   – When little information is available, measuring and sampling are frequent, such as biweekly, to develop a data base for the permit area and adjacent area and to define the hydrologic setting?
   – As hydrologic data are compiled, tabulated, and interpreted, and if changes in hydrologic conditions are considered natural, measuring and sampling may became less frequent, such as monthly or bimonthly;
3. Season
   – Water levels (chapter IX) and ground-water quality (chapter XII) change in response to precipitation. For example, the premining water-level October 1970 to March 1972 in the Decker, Mont, area shows a natural variation in recharge to the aquifers (fig. XIII 2-4). Annual precipitation in the area during 1970 - 1975, was above the mean annual for the area.
4. The impact(s) of the mining operation upon the aquifer system(s) (chapter XIII)
   – If water levels drop significantly (2 ft/month) and water-quality characteristics indicate signs of acid mine drainage, measurements and sampling frequency are increased to weekly bi-weekly. In figure XIII 2-4, the negative water-level variations from March 1972 to June 1975 illustrate the impact of excavation dewatering on the aquifers. locations of the observation wells in relation to the permit areas are shown in figure XIV-1. The resulting increase in depth to water is shown in figure 3X-5.
   – As the impacts of the mining operation become more pronounced, water-level recorders are installed, additional water-quality samples are analyzed, and, new monitoring sites, such as wells, springs, and stream sites, are added to the monitoring plan.

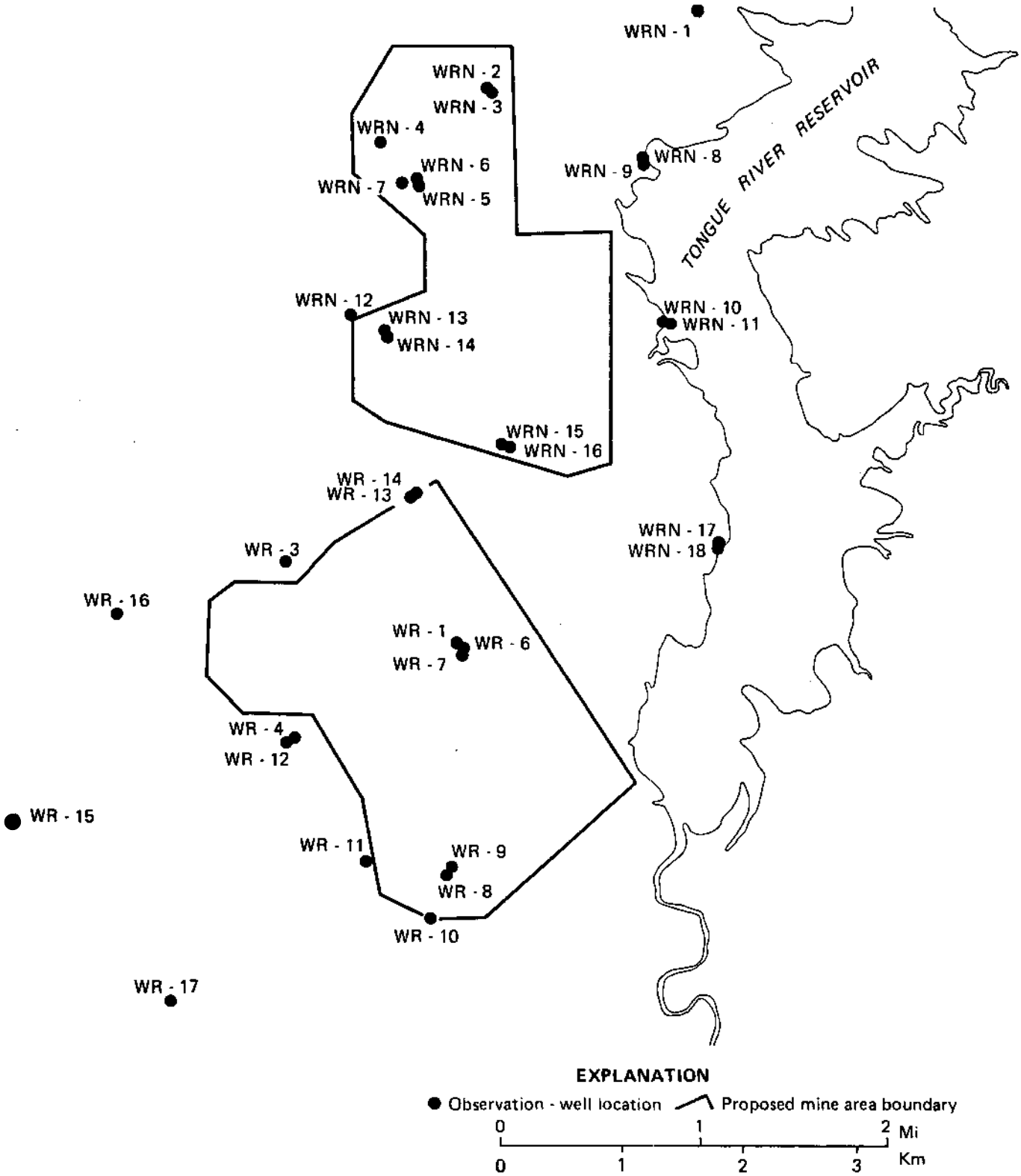


Figure XIV-1.— Observation-well system for proposed mine areas near Decker, Montana. (From VanVoast and Hedges, 1975, pl. 3)

Hydroloqic Sites

The hydrologic sites to be monitored before and during mining include a precipitation station, springs, wells, low-flow stream sites, swamps, ponds, lakes, reservoirs, mine-discharge sites, and mine spoils. The selection of monitoring sites after mining depends upon the effect of mining upon the hydrologic system but should include mine spoils within the permit and adjacent areas.

Precipitation station

Precipitation station records the snowfall and rainfall. A weighing-bucket recording rain gage would document the rainfall on the general area. This information is important when correlated with changes of base flow and changes of water levels in observation wells. For example, an extensive period of prolonged rainfall, in which water levels in wells fall and perennial streams go dry could indicate a potential aquifer-dewatering problem.

Ground water

Monitoring sites for ground water include observation wells, selected springs, and low-flow sites. Observation wells are located within the permit area and adjacent area and, to a lesser extent, within the general area. These wells are completed in aquifers that could be potentially impacted by mining operations; these aquifers can be both in bedrock overburden and underburden relative to the coal deposit. Overlying or nearby alluvial deposits may also be affected. The locations at which monitoring is advisable are listed in table XIV-1.

The purposes of the monitoring network are (1) measurement of water levels, (2) measurement of water quality, and (3) determination of aquifer properties, namely, transmissivity and storativity (storage coefficient). Changes in water levels in observation wells, completed in the aquifers, may reflect the effect of mining on the aquifer systems. The components of a monitoring network include the time period of monitoring—before, during, and after mining; the aquifer being monitored; and the position of measurement within the aquifer system—upgradient and downgradient from the proposed mine site. A suggested criteria for identifying observation wells within a monitoring network is given in table XIV-1. The alphabetic symbols, shown in this table, are introduced to demonstrate the applicability of this criteria to an example permit area, such as shown in figures XIV-2 and 3. Most of the wells installed before mining can be used during and after mining. Special attention should be given to the installation of special wells in the mine spoils to monitor the potential acid mine drainage.

An example premining ground-water monitoring plan for a combined surface-and underground-mining permit application involving several aquifers is given in figure XIV-2. A summary of measurements locations, for the example permit area, within the three areas—permit, adjacent and general—and the aquifers to be monitored is given in table XIV-2. The 16 wells are capable of monitoring water levels, and, water quality conditions in the overburden, underburden, and to a limited extent, the alluvium. In addition, a streamgaging station is established at the upstream and downstream ends of the affected watershed.

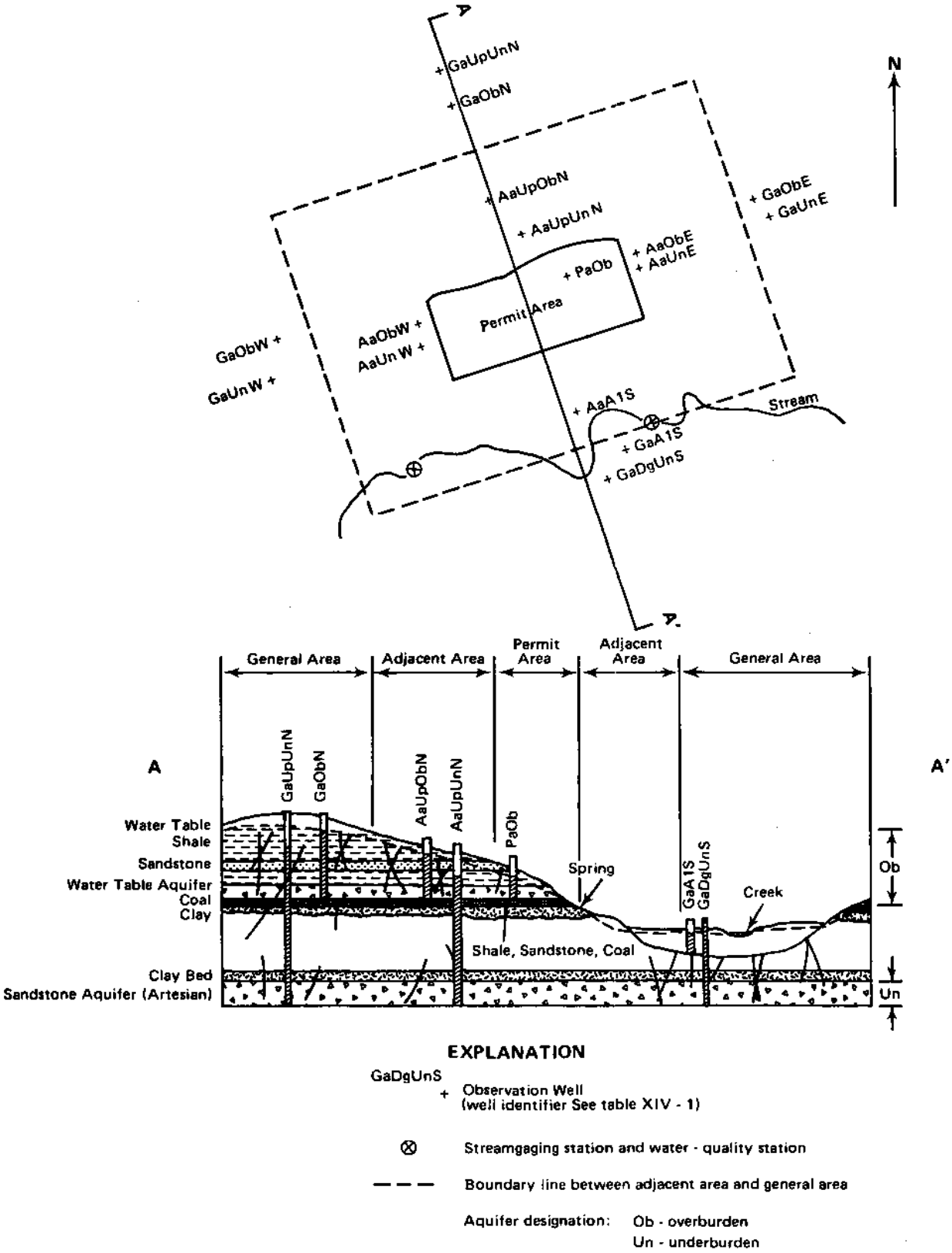


Figure XIV-2.— Planimetric map and vertical cross section of permit area showing ground-water monitoring plan before mining.

An example postmining ground-water monitoring plan for the same permit application is given in figure XIV-3; well locations and aquifers to be monitored are summarized in table XIV-3. Of the 19 wells listed 16 are from the premining program. If the bedrock aquifers within the general area were not impacted during mining, they need not be monitored after mining. Additional wells are drilled in the mine spoils and in the near-surface underburden (Un2); during mining in the permit area and in the adjacent area as applicable. Monitoring continues into the reclamation period as required by the regulatory authority.

The positioning of the observation wells depends on several factors including the nature of the aquifer—confined or water-table, hydrologic boundaries— streams or change in bedrock, and aquifer properties. Observation wells are also positioned between the permit area and surface water features to determine the direction of ground-water flow to or from the stream. Wells with four-inch diameter casings can be used for aquifer testing and for obtaining ground-water quality samples. After the aquifer properties are determined, the response time of the aquifer can be more accurately estimated. Knowledge of the confined nature of the aquifer(s) also aids in the selection of distance for the observation wells. As indicated in figure X-1,4-1, the drawdown in a confined systems (S = 0.0001) affects a greater area than the drawdown in a water-table system (S = 0.001). With the common low transmissivity of bedrock containing the coal seams, drawdown affects generally do not extend into the general area.

As an example, observation wells in the Decker mine area (fig. XIV-1) are within the permit area, on the perimeter of the permit area, and ½ mi, 1 mi, and 1½-mi from the permit area. The observation well most distant from permit area (WR-15) is completed in both the D-l and D-2 coal aquifers. After 3 years of mining, the water-level decline in this well was 3 feet. The storage coefficient for the confined aquifer (D-2 coal) is about 0.00003; and, for the water-table aquifer (D-l coal and Clinker), ranges from 0.1 and 0.3 (VanVoast and Hedges, 1975). The measured range in transmissivity of the D-l and D-2 coal beds combined was from 44 to 84 ft^2/d (Thompson and VanVoast, 1981).

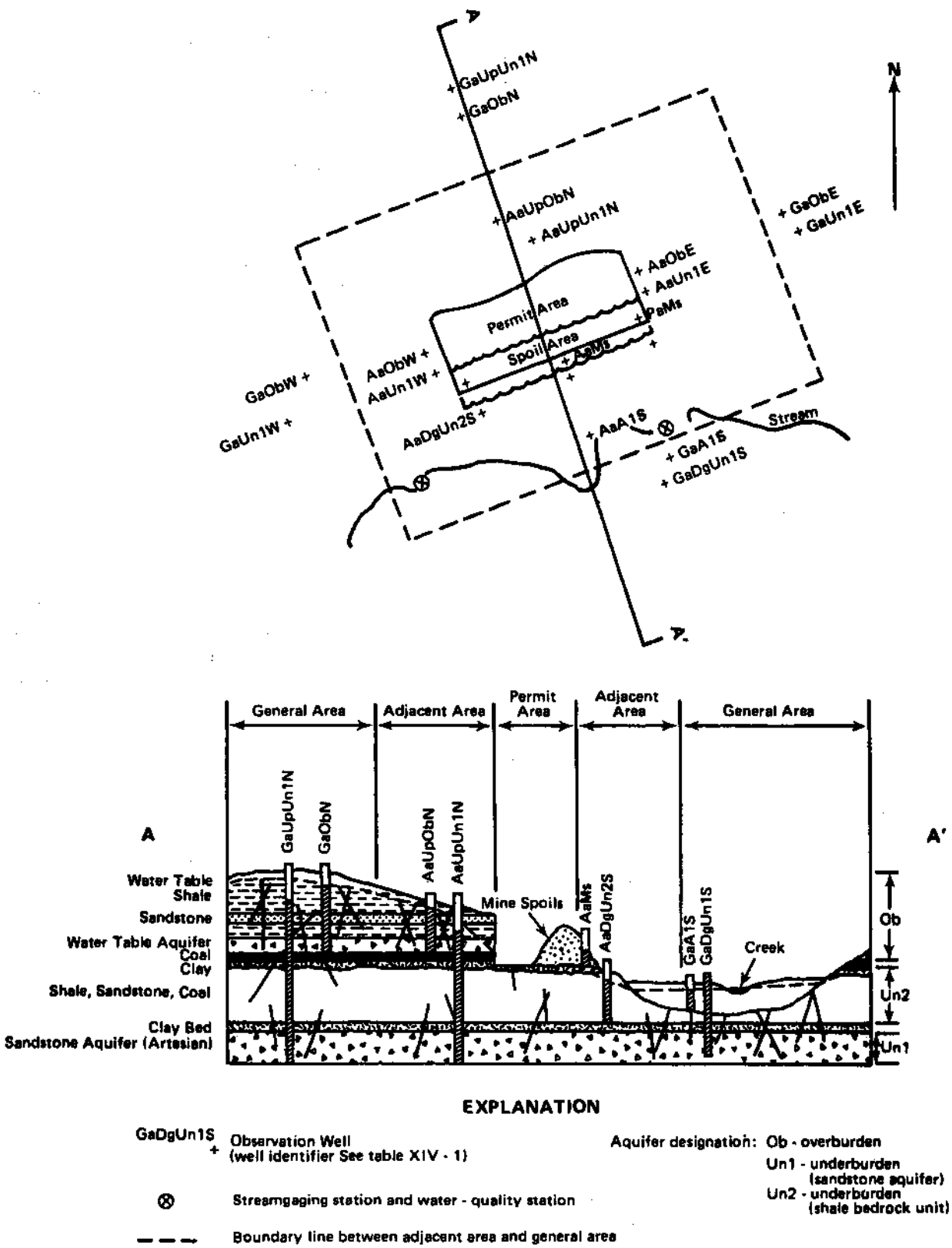


Figure XIV-3.— Planimetric map and vertical cross section of permit area showing ground-water monitoring plan after mining.

If significant water-level declines occur at the most distant observation wells, additional wells should be installed even farther from the permit area, as dictated by the regulatory authority. The distance of these additional wells can be determined from the aquifer transmissivity and storage coefficient. An approach is to:

(1) divide the discharge from the working pit, Q1, by the length of the pit to obtain Q,
(2) assume a drawdown, s, of 0.01 ft,
(3) use the T-value obtained in prior testing and the S-value from prior testing or from estimation (Lohman, 1972, p. 53).
(4) from a modification of equation X-2.3-1, calculate W(u) from the equation:

$$W(u) = \frac{4\pi T s}{Q} \qquad \text{XIV-1}$$

(5) determine u from table X-2.3-1, or any table of W(u) versus u (Lohman, 1972; Ferris and others, 1963; U.S. Department of Interior, 1981a; Johnson Division, 1975),
(6) from a modification of equation X-2.3-2, calculate r from the equation:

$$r^2 = \frac{4 T t u}{S} \qquad \text{XIV-2}$$

An example of an observation-well tabulation (table XIV-4) lists the well location, well numbers, well depths, land-surface altitude at the well head, the water-level altitude, and aquifers tapped. Hydrographs of water-level changes during mining are given in figure XIII-2-4. (The potentiometric map for the D-l coal aquifer after 3 years of mining, was given in figure XIII 2-3.) Chemical analyses of water samples from selected observation wells during the 3 year period of mining are presented in table XIV-5.

Surface water

Continuous-recording streamflow gages are installed upstream and downstream of the permit area as shown on figures XIV-2 and XIV-3. For ground-water purposes, only the low-flow stage-discharge relationship is significant (See chapter XI). Streamflow stations enable the determination of base flow and chemical quality of base flow. Water quality monitors that measure specific conductance, pH, dissolved oxygen, and temperature could also be installed at these sites.

The interaction between streamflow and ground water is determined from measurements of water levels in observation wells near the stream; but can also be determined from this well-and stream-stage-recording combination, and from other observation wells within the adjacent area and permit area.

Mine Spoils

Monitoring the quality of water within the spoil piles requires that observation wells, preferably 4-inch diameter, be installed in the waste-spoil piles. Observation wells should also be installed downgradient of the spoil material to determine what effect, if any, water from the mine-spoil pile has on water in the underlying bedrock unit. An example of well positions in mine spoils is shown in figure XIV-3.

Table XIV-1.– Criteria for locating observation wells.

[alphabetic symbols in parentheses represent components in the monitoring network; the components in the three columns are independent of each other, as demonstrated in tables XIV-2 and 3 and figures XIV-2 and 3.]

Time of Measurement	Potentially Impacted Aquifer Systems	Position of Measurement within the aquifer system(s)
		Compass Direction of the Observation Well Relative to the Permit Area North (N); South (S); East (E); West (W)
	Alluvium(Al)	
		General Area* (Ga) hydraulically upgradient (Up)
	Overburden (Ob)	
Before Mining		
		Adjacent Area (Aa) hydraulically upgradient (Up)
	Underburden (Ub)	
		Adjacent Area (Aa) lateral hydraulic measurement
During mining		
	Coal (CD	
		Permit Area (Pa)
	Mine spoils (Ms)	
		Adjacent Area (Aa) hydraulically downgradient (Dg)
After mining		
		General Area* (Ga) lateral hydraulic measurement
		General Area* (Ga) hydraulically downgradient (Dg)

* measurement position in General Area is necessary if mining impacts Adjacent Area significantly.

Table XIV-2.– Suggested observation-well network before mining.

[applicant refer to figure XIV-2 for map showing locations of observation wells and refer to table XIV-1 for explanation of alphabetic symbols.]
(Subject to approval by regulatory authority.)

Area	Position of measurement observation wells	Aquifer System	Geologic Material
General Area (Ga)	GaObN GaObW GaObE	Overburden (Ob) (water table aquifer)	Fractured sandstone and shale
	GaUpUnN* GaUnW GaUnE GaDgUnS	Underburden (Un) (confined aquifer)	Sandstone
	GaAlS	Alluvium(Al) (water-table aquifer)	Silt, sand, and gravel
Adjacent Area(Aa)	AaUpObN AaObW AaObE	Overburden (Ob) (water-table aquifer)	Fractured and sandstone shale
	AaUpUnN AaUnW AaUnE	Underburden (Un) (confined aquifer)	Sandstone
	AaAlS	Alluvium(AL) (water-table aquifer)	Silt, sand, and gravel
Permit Area (Pa)	PaOb	Overburden (Ob) (water-table aquifer)	Fractured and sandstone shale

* example - observation well located in the General Area hydraulically upgradient of the permit area monitoring the underburden aquifer north of the permit area.

Table XIV-3. – Suggested observation-well network after mining.

[applicant refer to figure XIV-3 for map showing locations of observation wells and refer to table XIV-1 for explanation of alphabetic symbols.]
(Subject to approval by regulatory authority.)

Area	Position of measurement observation wells	Aquifer System	Geologic Material
General Area (Ga)	GaObN * GaObW * GaObE *	Overburden (Ob) (water-table aquifer)	Fractured sandstone and shale
	GaUpUn1N * GaUn1W * GaUn1E * GaDgUnlS *	Underburden No.l (Uhl) (confined aquifer)	Sandstone
	GaAlS	Alluvium (Al) (not optional - necessary for water quality comparison with water from AaAl)	Silt, sand, and gravel
Adjacent Area (Aa)	AaUpObN AaObW AaObE	Overburden (Ob) (water-table aquifer)	Fractured sandstone and shale
	AaUpUn1N AaUn1W AaUn1E	Underburden No.1(Un1) (confined aquifer)	Sandstone
	AaDgUn2S **	Underburden No.2 (Un2) (confined aquifer)	Shale, sandstone, clay, and coal
	AaAlS **	Alluvium (Al) (water-table aquifer)	Silt, sand, and gravel.
	AaMs **	Mine Spoil (Ms) (water-table aquifer)	
Permit Area (Pa)	PaMs **	Mine Spoil (Ms)	

* perhaps optional depending upon the impacts during mining, if aquifers in the General Area were not impacted during mining, observation wells are not necessary after mining.
** primary objective is monitoring of ground-water quality.

Table XIV-4.– Example of data on wells in an observation-well network in Decker mine area, Montana.
(From VanVoast and Hedges, 1975, plate 3.)

Well location	Decker well number		Land-surface altitude (feet)	Well Depth (feet)	Water-level altitude, April, 1975 (feet)	Aquifer monitored
8S 40E 26 OCCB	WRN	1	3,463	40	3,434	D-2 Coal
8S 40E 33 $AACB_1$		2	3,492	90	3,439	D-2 Coal
8S 40E 33 $AACB_2$		3	3,491	59	3,438	D-l Clinker
8S 40E 33 CABB		4	3,493	39	3,479	D-l Coal
8S 40E 33 $CADA_1$		5	3,475	85	3,459	D-2 Coal
8S 40E 33 $CADA_2$		6	3,476	50	3,465	D-l Coal
8S 40E 33 CADC		7	3,482	49	3,472	D-l Coal
8S 40E 34 DEAD		8	3,424	50	3,417	D-2 Coal
8S 40E 34 DBDA		9	3,424	185	3,422	D-3 Coal
9S 40E 03 $DABA_1$		10	3,433	79	3,421	D-2 Coal
9S 40E 03 $DABA_2$		11	3,437	50	3,417	D-l Coal & Clinker
9S 40E 04 BCAA		12	3,525	77	3,456	D-l Coal & Clinker
9S 40E 04 $CABC_1$		13	3,515	124	3,452	D-2 Coal
9S 40E 04 $CABC_2$		14	3,514	78	3,448	D-l Coal
9S 40E 09 $AADD_1$		15	3,500	140	3,426	D-2 Coal
9S 40E 09 $AADD_2$		16	3,500	89	3,418	D-l Clinker
9S 40E 11 $CBCC_1$		17	3,424	104	3,418	D-2 Coal
9S 40E 11 $CBCC_2$		18	3,425	20	3,416	Alluvium
9S 40E 08 DCAA	WR	3	3,612	215	3,431	D-l Coal
9S 40E 09 $BDDA_1$		14	3,598	192	3,419	D-l Coal
9S 40E 09 $BDDA_2$		2	3,595	192	—	D-2 Coal
9S 40E 09 BDDB		13	3,592	247	3,436	D-2 Coal
9S 40E 16 ABCA		1	3,498	104	3,404	D-l Coal
9S 40E 16 $ABCD_1$		6	3,499	135	3,406	D-l Coal
9S 40E 16 $ABCD_2$		7	3,498	207	3,445	D-2 Coal
9S 40E 17 DACB		4	3,585	220	3,428	D-l Coal
9S 40E 17 DACC		12	3,486	230	3,427	D-l Coal
98 40E 18 ABAD		16	3,640	237	3,451	D-l & D-2 Coal Combined
9S 40E 19 BAC		15	3,685	390	3,445	D-l & D-2 Coal Combined
9S 40E 21 $ACCA_1$		8	3,537	165	3,426	D-l Coal
9S 40E 21 $ACCA_2$		9	3,537	255	3,458	D-2 Coal
9S 40E 21 BCAC		11	3,575	210	3,429	D-l Coal
9S 40E 21 BCAD		5	3,574	200	—	D-l Coal
9S 40E 21 CADA		10	3,537	169	3,426	D-l Coal
9S 40E 29 BBAC		17	3,570	300	3,455	D-l & D-2 Coal Combined

* refer to referenced report for detailed explanation of township-range-section and quarter-quarter-quarter-quarter subdivision of section; the subscripted number indicates the number of wells inventoried within the 2½ acre area.

Table 5.– Chemical analyses of waters from observation wells in the Decker area, southeastern Montana. (From VanVoast & Hedges, 197, table 4.)

[Analyses by Montana Bureau of Mines and Geology water laboratory, Butte. Concentrations in milligrams per liter.]

[Analyses by Montana Bureau of Mines and Geology water laboratory, Butte. Concentrations in milligrams per liter.]

Observation well location	Well number	Date of collection	Temperature (°C)	Calcium	Magnesium	Sodium	Potassium	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Silica (SiO_2)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Iron (Fe)	Manganese (Mn)	Dissolved solids (calculated)	Hardness as $CaCO_3$: Carbonate	Hardness as $CaCO_3$: Noncarbonate	Sodium adsorption ratio	Specific Conductance (micromhos at 25°C.)	pH
D-1 UPPER AND LOWER COALS COMBINED																						
9S. 40E. 16ABCD	WR- 6*	8/14/71	12	4.2	0.7	435	5.9	1,156	0	6.6	3.5	5.0	3.5	0.0	0.00	0.0	1,621	13	8	51.7	1,585	8.2
D-2 COAL																						
9S. 40E. 16ABCD$_2$	WR- 7	8/13/71	14	4.6	1.0	413	6.4	1,087	0	3.8	3.5	5.1	4.3	0.0	0.00	0.0	1,529	15	0	45.5	1,515	8.2
9S. 40E. 03DABA	WRN-10	4/02/75	12	74	57	448	13	698	0	787	15	13	2.0	.3	.00	.01	2,108	420	0	9.5	2,384	7.9
9S. 40E. 09AADD	WRN-15	4/30/75	11	5.2	2.3	415	4.2	1,132	0	2.8	20	7.1	2.2	.5	.59	.03	1,592	22	0	38.1	1,595	8.0
D-1 and D-2 COALS COMBINED																						
9S. 40E. 18ABAD	WR- 16	4/14/74	-	5.2	1.9	415	3.6	1,123	0	5.5	11	7.5	3.3	4.7	.10	.00	1,581	21	0	39.4	1,640	7.9
9S. 40E. 29BBAC	WR- 17	6/04/74	-	5.9	2.5	458	4.3	1,105	58	3.7	9.2	25	3.3	.0	.00	.00	1,675	25	0	39.9	1,816	8.9

* refer to figure XIV-1 for well location.

XV. SOURCES OF PUBLISHED (GEOLOGIC AND HYDROLOGIC INFORMATION

Pertinent 30CFR[1] Sections:
- Description of hydrology and geology.
- Ground-water information.
- Surface-water information.
- Cross sections, maps, and plans.

1. U.S. Geological Survey Coal Area Hydrology Reports

Coal-area hydrology reports, published by the U.S. Geological Survey, contain a text with maps, charts, graphs, and other illustrations and provide hydrologic information to describe the hydrology of areas within the coal provinces. The areas represented by each report is shown in figure XV-1-1. The information should be useful to mine owners and operators and to consulting engineers in the preparation of permits and also to regulatory authorities in appraising the adequacy of permit applications. These reports are available at no charge from the U.S. Geological Survey offices listed in table XV-1-1.

A need for hydrologic information and analysis on a scale never before required nationally was recognized when the "Surface Mining Control and Reclamation Act of 1977" was signed into law as Public Law 95-87, August 3, 1977. The hydrologic information presented in, or available through sources identified in, these reports may be used in describing the hydrology of the general area of any proposed mine. However, it is expected that this information will be supplemented by the applicant's site-specific information as well as data from other sources to provide a detailed coverage of the hydrology of the mine and vicinity and the anticipated hydrologic consequences of the proposed mining operation.

The coal area reports include discussions of bedrock geology, water use, hydrologic networks, surface-water information, chemical quality of surface water, ground-water information, chemical quality of ground water, and hydrologic-data-collection stations.

[1]CFR = Code of Federal Regulations

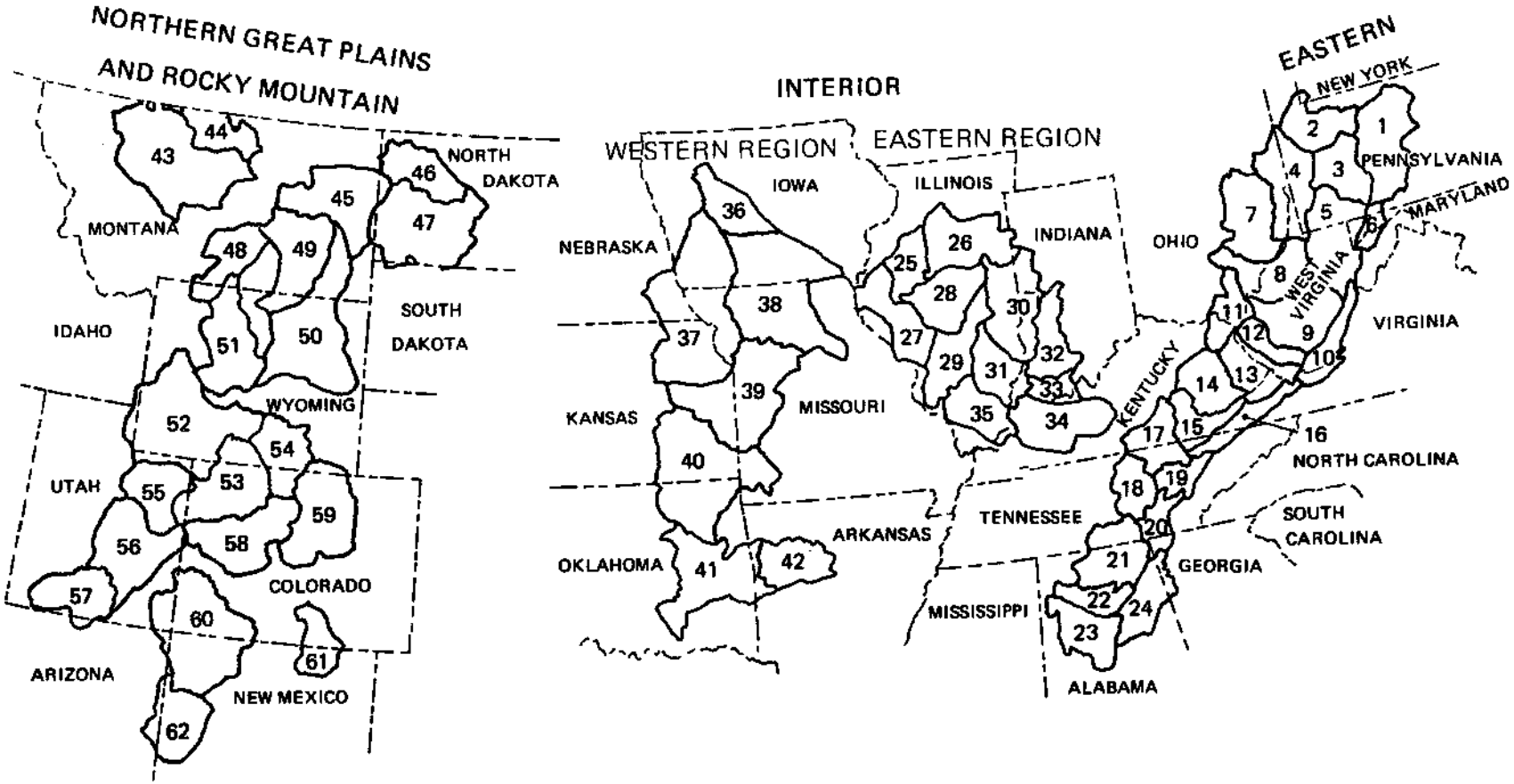


Figure XV-1-1.— Index maps of U.S. Geological Survey coal hydrology reports in Northern Great Plains, Rocky Mountains, Interior, and Eastern Coal Provinces .

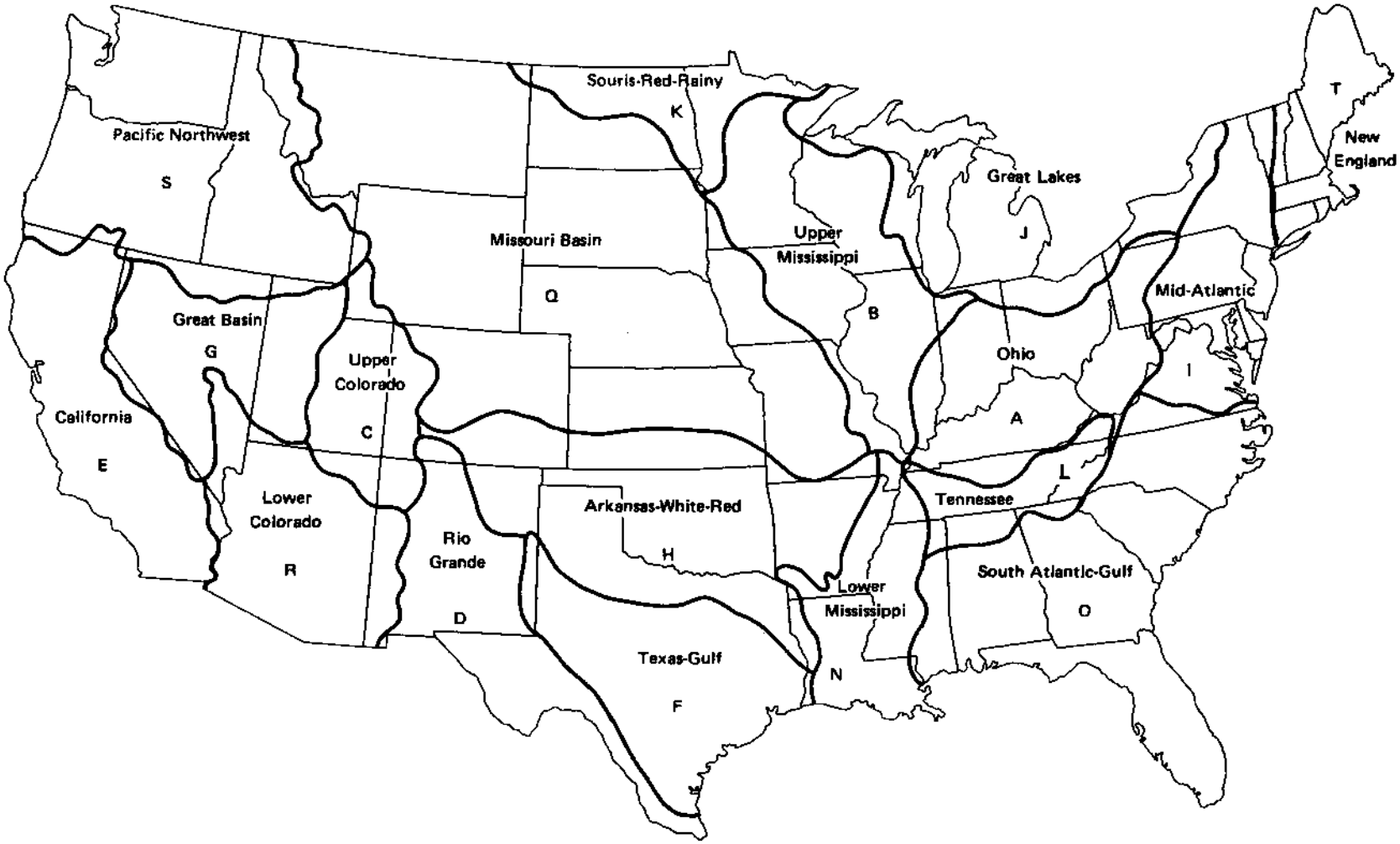


Figure XV-2-1.— Geographic index to the series, U.S. Geological Survey Professional Paper 813, "Summary Appraisals of the Nations Ground-Water Resources. Boundaries shown are those established by the U.S. Water-Resources Council for Water-Resources Regions in the United States.
(From Sinnott, 1982)

Table XV 1-1.– COAL AREA HYDROLOGY REPORTS

Can be obtained at no cost from the following U.S. Geological Survey (USGS)
Please write or call: District Chief, USGS, Water Resources Division
U.S. Geological Survey, Water Resources Division

State	Address and Telephone Number (s)	Area Report	Open-file Number
Alabama	5200 19th Avenue	22	81-135
	Tuscaloosa, Alabama 35401	23	80-693
	(Telephone: FTS-229-2957 or (205) 752-8104)	24	81-1113
Arkansas	Room 2301 Federal Office Building	42	82-636
	700 West Capitol Avenue		
	Little Rock, Arkansas 72201		
	(Telephone: FTS-740-6391 or (501) 378-6391)		
Colorado	Building 53, Denver Federal Center	53	
	Mail Stop 415, Box 25046	58	
	Denver, Colorado 80225	59	
	(Telephone: FTS-234-5092 or (303) 234-5092)	61	83-132
Illinois	Champaign County Bank Plaza	25	81-636
	4th Floor	26	
	102 East Main Street	27	
	Urbana, Illinois 61801	28	
		29	82-858
		30	82-1005
	(Telephone: FTS-958-5353 or (217)398-5353)	31	
		35	81-403
Indiana	6023 Guion Road, Suite 201	30	82-1005
	Indianapolis, Indiana 46254	32	81-498
	(Telephone: FTS-336-8640 or (317) 927-8640)	33	81-423
Iowa	P.O. Box 1230, Roan 269, Federal Building	38	82-1014
	400 South Clinton Street		
	Iowa City, Iowa 52244		
	(Telephone: FTS-863-6251 or (319) 337-4191)		
Kansas	1950 Avenue A, Campus West	40	
	University of Kansas		
	Lawrence, Kansas 66044		
	(Telephone: FTS-75 2-2300 or (913) 864-4321)		
Kentucky	Room 572, Federal Building	14	81-137
	600 Federal Place	15	81-809
	Louisville, Kentucky 40202	34	82-638
	(Telephone: FTS-352-5241 or (502) 582-5241)		
Maryland	208 Carroll Building	6	83-33
	8600 LeSalle Road		
	Towson, Maryland 21204		
	(Telephone: FTS-922-7872 or(301) 828-1535)		
Missouri	1400 Independence Road	39	
	Mail Stop 200		
	Rolla, Missouri 65401		
	(Telephone: FTS-277-0824 or (314) 341-0824)		

Table XV 1-1.– (continued)

State	Address and Telephone Number (s)	Area Report	Open-file Number
Montana	Federal Building, Drawer 10076	45	83-527
	Helena, Montana 59626	46	
		47	
	(Telephone: FTS-585-5263 or (406) 449-5263)	48	
		49	82-682
New Mexico	505 Marquette, NW, Room 720	60	83-203
	Western Bank Building	62	
	Albuquerque, New Mexico 87102		
	(Telephone: FTS-474-2246 or (505) 766-2246)		
North Dakota	821 E. Interstate Avenue	47	
	Bismarck, North Dakota 58501		
	(Telephone: FTS-783-4601 or (701) 255-4011)		
Ohio	975 West Third Avenue	4	81-343
	Columbus, Ohio 43212	7	81-815
	(Telephone: FTS-943-5553 or (614) 469-5553)	11	84-233
Oklahoma	Room 621, 215 Dean A. McGee Ave	41	
	Oklahoma City, Oklahoma 73102		
	(Telephone: FTS-736-4256 or (405) 231-4256)		
Pennsylvania	Federal Building, 4th Floor	1	82-223
	P.O. Box 1107, 228 Walnut Street	2	82-647
	Harrisburg, Pennsylvania 17108	3	81-537
	(Telephone: FTS-590-5414 or (717) 782-4514)	5	81-538
Tennessee	A-413 Federal Building	17	81-1118
	U.S Courthouse	18	81-492
	Nashville, Tennessee 37203	19	81-901
		20	82-440
	(Telephone: FTS-852-5424 or (615) 251-5424)	21	82-679
Utah	1016 Administration Building	55	
	1745 West 1700 South	56	83-38
	Salt Lake City, Utah 84104	57	
	(Telephone: FTS-588-5663 or (801) 524-5663)		
Virginia	200 W. Grace Street, Room 304	16	81-204
	Richmond, Virginia 23220		
	(Telephone: FTS-925-2427 or (804) 771-2427)		
West Virginia	Federal Building and Courthouse, Room 3416	8	
	500 Quarrier Street, East	9	81-803
	Charleston, West Virginia 25301	10	82-864
		12	81-902
	(Telephone: FTS-924-1300 or (304) 343-6181, ext. 310)	13	82-505
Wyoming	P.O. Box 1125	50	
	Cheyenne, Wyoming 82003	51	83-146
	(Telephone: FTS-328-2153 or (307) 778-2220)	52	
		54	

2. U.S. Geological Survey Professional Paper 813
"Summary Appraisals for Nation's Ground-Water Resources"

The U.S. Geological Survey Professional Paper 813 consists of 21 chapters, each of which summarizes the ground-water resources of part of the united States - a river basin, a part of a major river basin, or a State. A geographic index map for this publication series (chapters A through U) is shown in figure XV-2. The listing of the bibliographic references for each chapter for the coal-bearing states is presented in table XV 2-1.

The analyses of ground-water resources presented in these reports describes:

(1) the significance of the ground-water resources in relation to the regional water supply;
(2) identification of the regional aquifers, including their geologic framework and aquifer characteristics;
(3) estimated quantity of ground water available;
(4) chemical quality of ground water;
(5) existing and potential problems associated with ground-water use; and
(6) the relationship between streamflow and ground-water flow.

Mine-permit applicants can become informed of general geologic and ground-water conditions within a specific area by referring to the applicable report. Any publication within the Series can be purchased from

Superintendent of Documents
U.S. Government Printing Office
Washington, D.C. 20402

Copies are also available for inspection at designated Federal document repository libraries at the U.S. Geological Survey Public Inquiries Offices (PIO). Additional information on PIO's may be obtained from

U.S. Geological Survey
National Center Rm. 1C402, Mail Stop 302
Reston, VA. 22092
Phone: (703) 860-6167

There are 10 PIO's in the United States: Anchorage, AK; Dallas, TX; Denver, CO; Los Angeles, CA; Menlo Park, CA; Reston, VA; Salt Lake City, UT; San Francisco, CA; Spokane, WA; and Washington, DC.

Table XV 2-1.– Listing of bibliographic references for U.S. Geological Survey Professional Paper 813 Series for conterminous coal-bearing states.

CHAPTER DESIGNATION LETTER	AUTHOR (S)	YEAR OF PUBLICATION	WATER RESOURCES REGION	NUMBER OF PAGES
A	Bloyd, R. M., Jr.	1974	Ohio	41
B	Bloyd, R. M., Jr.	1975	Upper Mississippi	22
C	Price, Don and Arnow, Ted	1974	Upper Colorado	40
D	West, S. W. and Broadhurst, W. L.	1975	Rio Grande	39
E	Thomas, H. E. and Phoenix, D. A	1976	California	51
F	Baker, E. T., Jr. Wall, J. R	1976	Texas-Gulf	29
G	Eakin, T. E. , Price, Don and Harrill, S. R.	1976	Great Basin	37
H	Bedinger, M. S. and Sniegocki, R. T.	1976	Arkansas-White-Red	31
I	Sinnott, Allen and Gushing, E. M.	1978	Mid-Atlantic	32
J	Weist, W. G., Jr.	1978	Great Lakes	30
K	Reader, H. 0.	1978	Souris-Red-Rainy	25
L	Zurawski, Ann	1978	Tennessee	35
N	Terry, J. E., Bosnian, R. L., and Bryant, C. T.	1979	Lower Mississippi	41
O	Cederstrom, D. J., Boswell, E. H., and Tarver, G. R.	1979	South Atlantic-Gulf	35
Q	Taylor, O. J.	1978	Missouri Basin	41
R	Davidson, E. S.	1979	Lower Colorado	23
S	Foxworthy, B. L.	1979	Pacific Northwest	39
T	Sinnott, Allen	1982	New England	23

3. National Water Data Exchange (N7WDEX)

The following description of NAWDEX is from Roth and Cooper (1984) on coal area 11.

NAWDEX is an national confederation of water-oriented organizations working together to make their data more readily accessible and to facilitate a more efficient exchange of water data.

Services are available through a Program Office located at the U.S. Geological Survey's National Center in Reston, Virginia, and through a nationwide network of Assistance Centers located in 45 States and Puerto Rico, which provide local and convenient access to NAWDEX facilities. (See figure XV3-1). A directory is available on request that provides names of organizations and persons to contact, addresses, telephone numbers, and office hours for each of these locations titled - Directory of Assistance Centers of the National Water Data Exchange (NAWDEX), U.S. Geological Survey Open-File Report 83-262.

NAWDEX can assist any organization or individual in identifying and locating needed water data and referring the requestor to the organization that retains the data required. To accomplish this service, NAWDEX maintains a computerized Master Water Data Index (fig. XV3-2), which identifies sites for which water data are available, the type of data available for each site, and the organization retaining the data. A Water Data Sources Directory (fig. XV.3-3) also is maintained that identifies organizations that are sources of water data and the locations within these organizations from which data may be obtained. In addition, NAWDEX has direct access to some large water-data bases of its members and has reciprocal agreements for the exchange of services with others.

Charges for NAWDEX services are assessed at the option of the organization providing the requested data or data service. Search assistance services are provided free by NAWDEX to the greatest extent possible. Charges are assessed, however, for those requests requiring computer cost, extensive personnel time, duplicating services, or other costs encountered by NAWDEX in the course of providing services. In all cases, charges assessed by NAWDEX Assistance Centers will not exceed the direct costs incurred in responding to the data request. Estimates of cost are provided by NAWDEX upon request and in all cases where costs are anticipated to be substantial.

For additional information concerning the NAWDEX program or its services contact:

Program Office
National Water Data Exchange (NAWDEX) U.S. Geological Survey
421 National Center 12201 Sunrise Valley Drive
Reston, VA 22092
Telephone: (703) 860-6031
FTS-938-6031 Hours: 7:45-4:15 Eastern Time

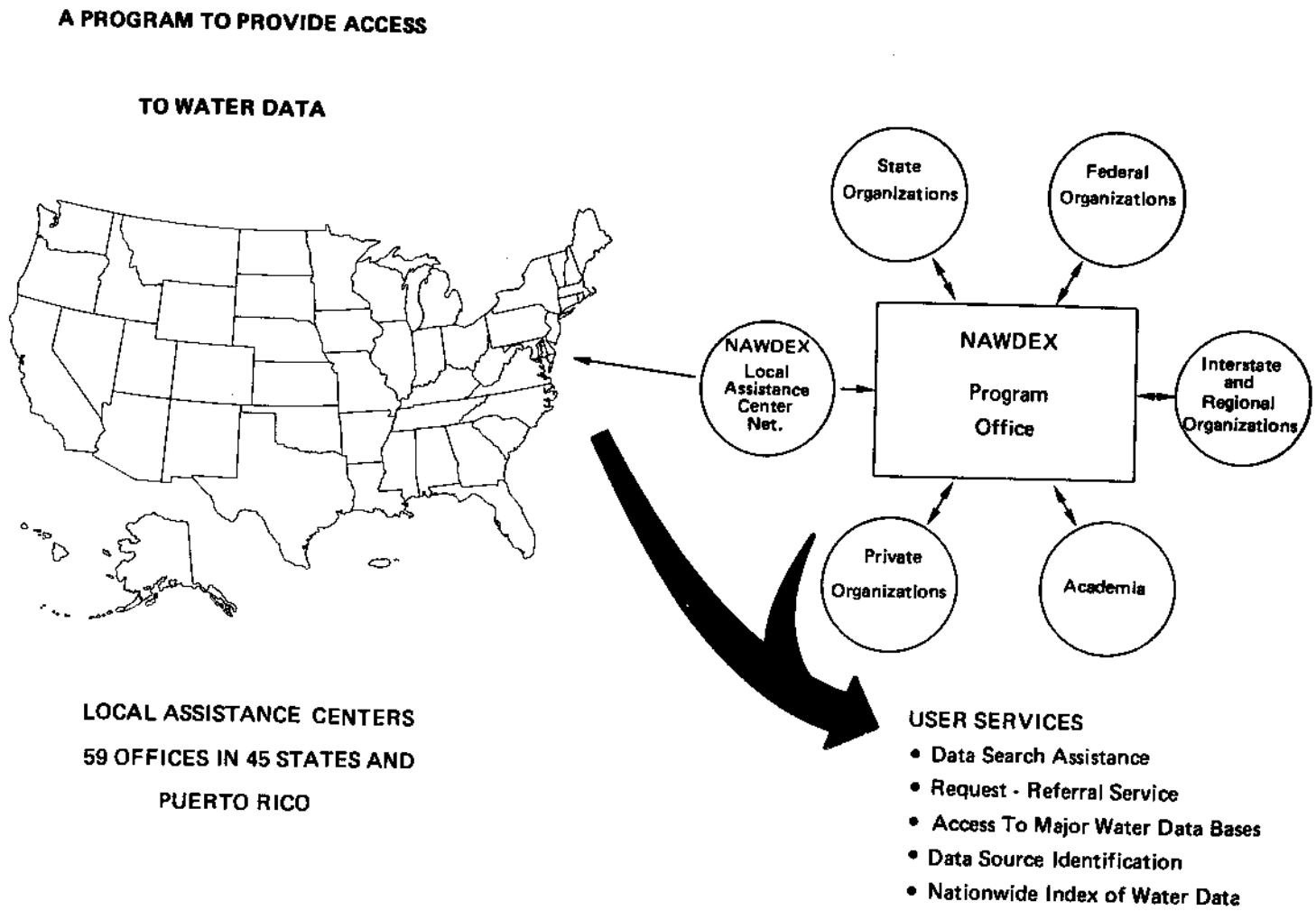


Figure XV-3-1.—Access to water data.

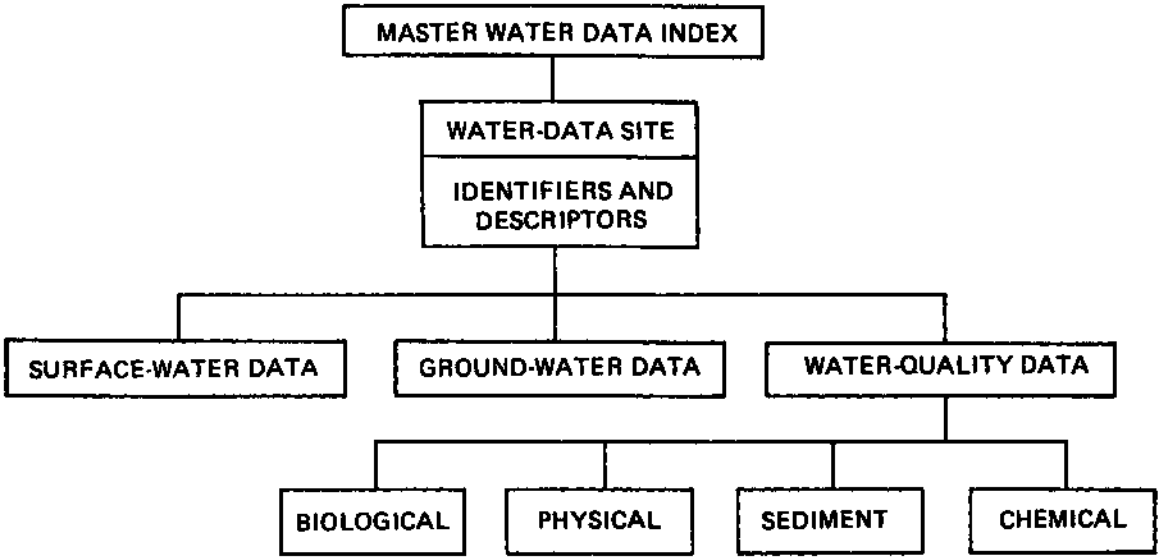


Figure XV-3-2.— Master water-data index

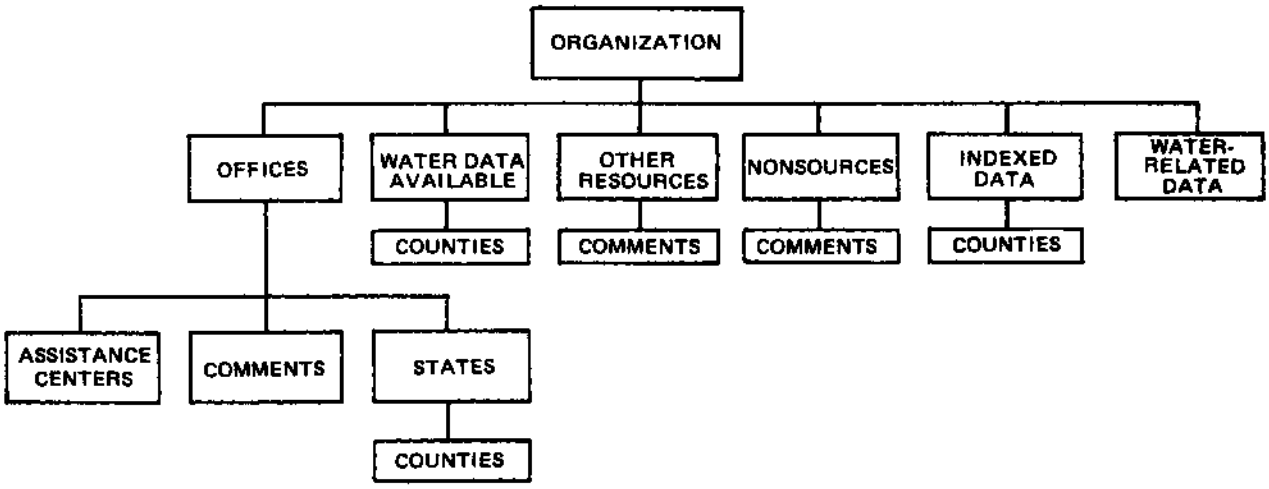


Figure XV-3-3.— Water-data sources directory.

4. National Water Data Storage and Retrieval System (WATSTORE)

The following description of WATSTORE is from Roth and Cooper (1984) report on coal area 11.

The National Water Data Storage and Retrieval System (WATSTORE) was established in November 1971 to computerize the U.S. Geological Survey's existing water-data system and to provide for more effective and efficient management of its data-releasing activities. The system is operated and maintained on the central computer facilities of the Survey at its National Center in Reston, Va.; however, data may be entered into and retrieved from WATSTORE at a number of locations that are part of a nationwide telecommunication network. General inquiries about WATSTORE may be directed to U.S. Geological district office or to:

WATSTORE Program Office
U.S. Geological Survey
437 National Center
Reston, VA 22092

The Geological Survey currently (1983) collects data at approximately 17,000 stage- and discharge-gaging stations, 5,200 surface-water quality stations, 27,000 water-level observations wells, and 7,400 ground-water quality wells. Each year many water-data collection sites are added and others are discontinued; thus, large amounts of diversified data, both current and historical, are amassed by the Survey's data-collected activities.

The WATSTORE system consists of several files in which data are grouped and stored by common characteristics and data-collected frequencies. The system also is designed to allow for the inclusion of additional data files as needed. Currently, files are maintained for the storage of: (1) Surface-water, quality-of-water, and ground-water data measured on a daily or continuous basis; (2) annual peak values for streamflow stations; (3) chemical analyses for surface-and ground-water sites; (4) water parameters measured more frequently than daily; and (5) geologic and inventory data for ground-water sites. In addition, an index file of sites for which data are stored in the systems is also maintained (fig. XV 4-1). A brief description of each file is as follows:

Station Header File: All sites for which data are stored in the Daily Values, Peak Flow, Water-Quality, and Unit Values files of WATSTORE are indexed in this file. It contains information pertinent to the identification, location, and physical description of nearly 220,000 sites.

Daily Values File: All water-data parameters measured or observed either on a daily or on a continuous basis and numerically reduced to daily values are stored in this file. Instantaneous measurements at fixed-time intervals, daily mean values, and statistics such as daily maximum and minimum values also may be stored. This file currently contains over 200 million daily values including data on streamflow, river stages, reservoir contents, water temperatures, specific-conductance, sediment concentrations, sediment discharges, and ground-water levels.

Peak Flow Pile: Annual Maximum (peak) streamflow (discharge) and gage height (stage) values at surface-water sites comprise this file, which currently contains over 400,000 peak observations.

Water Quality File: Results of over 1.4 million analyses of water samples that describes the chemical, physical, biological, and radiochemical characteristics of both surface and ground waters are contained in this file. These analyses contain data for 185 different constituents.

Unit Values File: Water parameters measured on a schedule more frequent than daily are stored in this file. Rainfall, stream discharge, and temperature data are examples of the types of data stored in the Unit Values File.

Ground-Water Site-Inventory: This file is maintained within WATSTORE independent of the files discussed above, but it is cross-referenced to the Water-Quality File and the Daily Values File. It contains inventory data about wells, springs, and other sources of ground water. The data included are site location and identification, geohydrologic characteristics, well-construction history, and one-time field measurements such as water temperature. The file is designed to accommodate 225 data elements and currently contains data for nearly 700,000 sites.

Remote Job Entry Sites: Almost all of the Water Resources Division's district offices are equipped with high-speed computer terminals for remote access to the WATSTQRE system. These terminals allow each site to put data into or retrieve data from the system within several minutes to overnight, depending upon the priority placed on the request. The number of remote job entry sites is increased as the need arises.

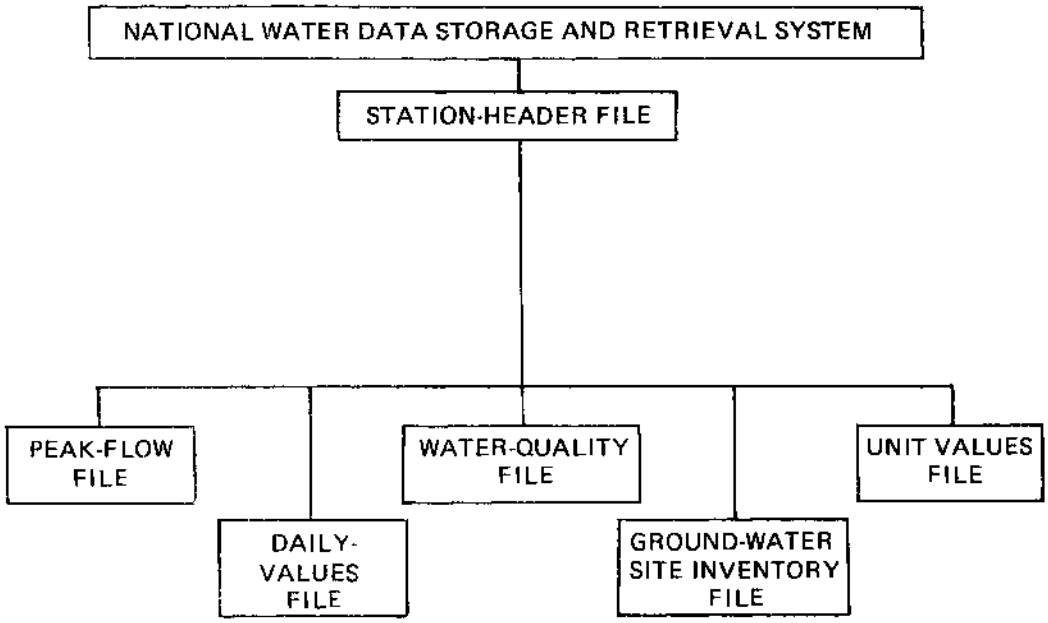


Figure XV-4-1.—index file of stored data (WATSTORE).

Digital Transmission Sites: Digital recorders are used as many field locations to record values for parameters such as river stages, conductivity, water temperature, turbidity, wind direction, and chlorides. Data are recorded on 16-channel paper tape, which is removed from the recorder and transmitted over telephone lines to the receiver at Reston, Va. The data are recorded on magnetic tape for use on the central computer. Extensive testing of satellite delta collection platform indicates their feasibility for collection real-time hydrologic data on a national scale. Battery-operated radios are used as the communication link to the satellite. About 500 data relay stations are being operated currently (1983) by the Water Resources Division.

Central Laboratory Systems: The Water Resources Division's two Welter-quality laboratories, located in Denver, Colorado, and Atlanta, Georgia, analyze more than 150,000 water samples per year. These laboratories are equipped to automatically perform chemical analyses ranging from determinations of simple inorganic compounds, such as chloride, to complex organic compounds, such as pesticides. As each analysis is completed, the results are verified by laboratory personnel and transmitted via a computer terminal to the central to the central computer facilities to be stored in the Water -Quality of File of WATSTORE.

Computer-Printed Tables: Users most often request data from WATSTORE in the form of tables printed by the computer. These tables may contain lists of actual data or condensed indexes that indicate the availability of data stored in the files. A variety of formats is available to display the many types of data.

Computer-Printed Graphs: Computer-printed graphs for the rapid analysis or display of data are another capability of WATSTORE. Computer programs are available to produce bar graphs (histograms), line graphs, frequency distribution curves, X-Y point plots, site-location map plots, and other similar items hy means of line printers.

Statistical Analyses: WATSTORE interfaces with a proprietary statistical package called the Statistical Analysis System (SAS)[1] (SAS Institute, 1982) to provide extensive analyses of data such as regression analyses, the analysis of variance, transformations, and correlations.

Digital Plotting: WATSTORE also make use of software systems that prepare data for digital plotting on peripheral offline plotters available at the central computer site. Plots that can be obtained include hydrographs, frequency-distribution curves, X-Y point plots, contour plots, and three-dimensional plots.

Data in Machine-Readable Form: Data stored in WATSTORE can be obtained in machine-readable form for use on other computers or for use as input to user-written computer programs. These data are available in the standard format of the WATSTORE system or in the form of punched cards or card images on magnetic tape.

[1] The use of trade names in this report is for identification purposes only and does not imply endorsement by the U. S. Geological Survey.

5. Index to Water-Data Activities in Coal Provinces

The following description of the "Index to Water-Data Activities" is from Roth and Cooper (1984) report of coal area 11.

The "Index to Water-Data Activities in Coal Provinces of the United States" was prepared to assist those involved in developing, managing, and regulating the Nation's coal resources by providing information on the availability of water-resources data in the major coal provinces of the United States. It is derived from the "Catalog of Information on Water Data" which is a computerized information file about water-data acquisition activities in the United States, and its territories and possessions, with some international activities included.

This special index consists of five volumes (figure XV5-1) Volume 1, Eastern Coal province; volume II, Interior Coal province, volume III, Northern Great Plains and Rocky Mountain Goal provinces; volume IV, Gulf Coast Coal provinces; and volume V, Pacific Coast and Alaska Coal provinces. The information presented will aid the user in obtaining data for evaluating the effects of coal mining on water resources and in developing plans for meeting additional water-data needs. The report does not contain the actual data; rather, it provides information that will enable the user to determine if needed data are available.

Each volume of this special index consists of four parts; Part A, Streamflow and Stage Stations; Part B, Quality of Surface-Water Stations; Part C, Quality of Ground-Water Stations; and Part D, Areal Investigations and Miscellaneous Activities. Information given for each activity in Parts A-C includes: (1) The identification and location of the station, (2) the major types of data collected, (3) the frequency of data collection, (4) the form in which the data are stored, and (5) the agency or organization reporting the activity. Part D summarizes areal hydrologic investigations and water-data activities not included in the other parts of the index. The agencies that submitted the information, agency codes, and the number of activities reported by type are shown in a table.

Those who need additional information from the Catalog file or who need assistance in obtaining water data should contact the National Water Data Exchange(NAWDEX). (See chapter XV. 3)

Further information on the index volimes and their availability may be obtained from:

Office of Water Data Coordination
U.S. Geological Survey
National Center Mail Stop 417
Reston, Virginia 22092
Telephone: (703) 860-6931

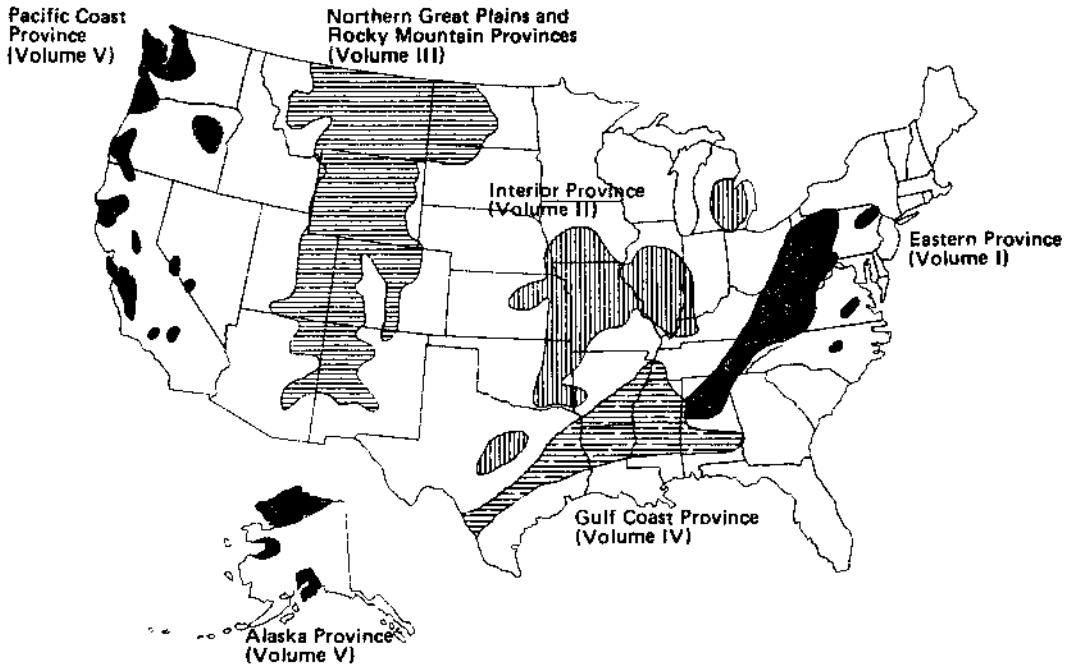


Figure XV-5-1.—Index volumes to water-data activities in coal provinces.

6. U.S. Geological Survey Annual Water Resources Reports

Records of discharge and stage of streams and contents or stage of lakes and reservoirs were first published in a series of U.S. Geological Survey water-supply papers titled "Surface Water Supply of the United States." Through September 30, 1960, these water-supply papers were published in an annual series and then during 1961–65 and 1966–70 in a 5-year series. Records of chemical quality, water temperatures, and suspended sediment were published from 1941 thru 1970 in an annual series of water-supply papers titled, "Quality of Surface Waters of the United States." Records of ground-water levels were published from 1944 thru 1973 in a series of water-supply papers entitled, "Ground-Water Levels in the United States."

Since the 1961 water year the U.S. Geological Survey has released streamflow data on a State-boundary basis, in annual reports in a series titled "Water Resources Data for (state)". Water-quality records beginning with the 1964 water year and ground-water data sīnc̄ ēthē 1971 water year have been similarly released either in separate volumes or in conjunction with streamflow records. These reports provide rapid release of preliminary water data shortly after the end of the water year. The final data are then released in the water-supply paper series mentioned above.

Since the 1975 water year, water data have been released on a State-boundary basis in final form and are not republished in the water-supply paper series. These reports make up an annual series that carry an identification number consisting of the two-letter State abbreviation and the last two digits of the water year.

Reports in the annual series contain records of stage, discharge, and water quality of streams; stage and volume of lakes; and water levels and water quality of wells and springs. They also include daily discharge records for stream-gaging stations; stage and (or) volume of lakes and reservoirs; and data for crest-stage and low-flow partial-record stations. They also include water-quality data from National Stream Quality Accounting Network Stations (NASQAN) and coal-hydrology stations. Some reports in the series may contain daily temperatures records, daily specific conductance, and miscellaneous tanperature and specific conductance determinations for special purpose (project) stations. Suspended sediment data for some special study stations are also given. Ground-water levels and, for seme States, data on the quality of ground water, are published in separate reports. These data represent that part of the National Water Data Systems operated by the U. S. Geological Survey and cooperating State and Federal agencies.

These reports are for sale to the public for a nominal fee from the National Technical Information Service, U.S. Department of Connerce, Springfield, VA 22161.

7. Regional Aquifer Systems Analyses (RASA)

Regional Aquifer System Analyses (RASA) have been formed to examine the hydrology of the major aquifer systems of the united States on a regional scale. These studies develop quantitative appraisals of the major ground-water systems through the use of digital computer modeling. The areal extent of the RASA studies is shown on figure XV-7-1. Coal-permit areas within these RASA areas therefore have additional hydrologic data available for analysis and inclusion in permit applications.

Digital ground-water computer models are constructed to provide information on the nature of ground-water systems, how they function, and hew they respond to hydraulic or chemical stresses, and to identify the need for additional data. The models are constructed by defining the limit of the aquifer system, the spatial variation of aquifer properties, and the stresses to be imposed.

As stated by the U.S. Water Resources Council (1980), the principal data requirements for ground-water analysis and modeling (table XV-7-1) include:

(1) physical framework: the time and space variation of the aquifer characteristics—transmissivity, storativity(storage coefficient), and specific yield (chapter X), and definition of the hydrologic boundaries (chapter X-2.7);

(2) hydrologic stresses: the time and space variation of the flow rates (discharges and recharges) to the aquifer system—ground-water pumpage, precipitation, infiltration from precipitation, evapotranspiration, induced streamflow infiltration, and ground-water discharge as base flow (chapters VII, XI); and,

(3) model calibration: the time and space variation of water levels (chapter IX) in the aquifer, which are used to test and to calibrate, the components of the model.

Compilations of these data for the RASA studies are available to the public.

The reliability of the model output, such as predicted water-level declines due to projected surface-mining operations, depends directly upon the quantity and quality of the hydrologic data input to the model.

Additional information on available ground-water models can be obtained from the Clearinghouse for Ground-Water Models, Holccmb Research Institute, Butler University, Indianapolis Indiana 46208. Information on the Clearing House and its services may be obtained from the Director of the Institute.

In 1984, the U.S. Geological Survey published a report titled "A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model", Open File Report 83-875. Copies can be purchased from:

Open-File Services Section
Western Distribution Branch
Box 25425, Federal Center
Denver, Colorado 80225
Telephone: (303) 234-5888

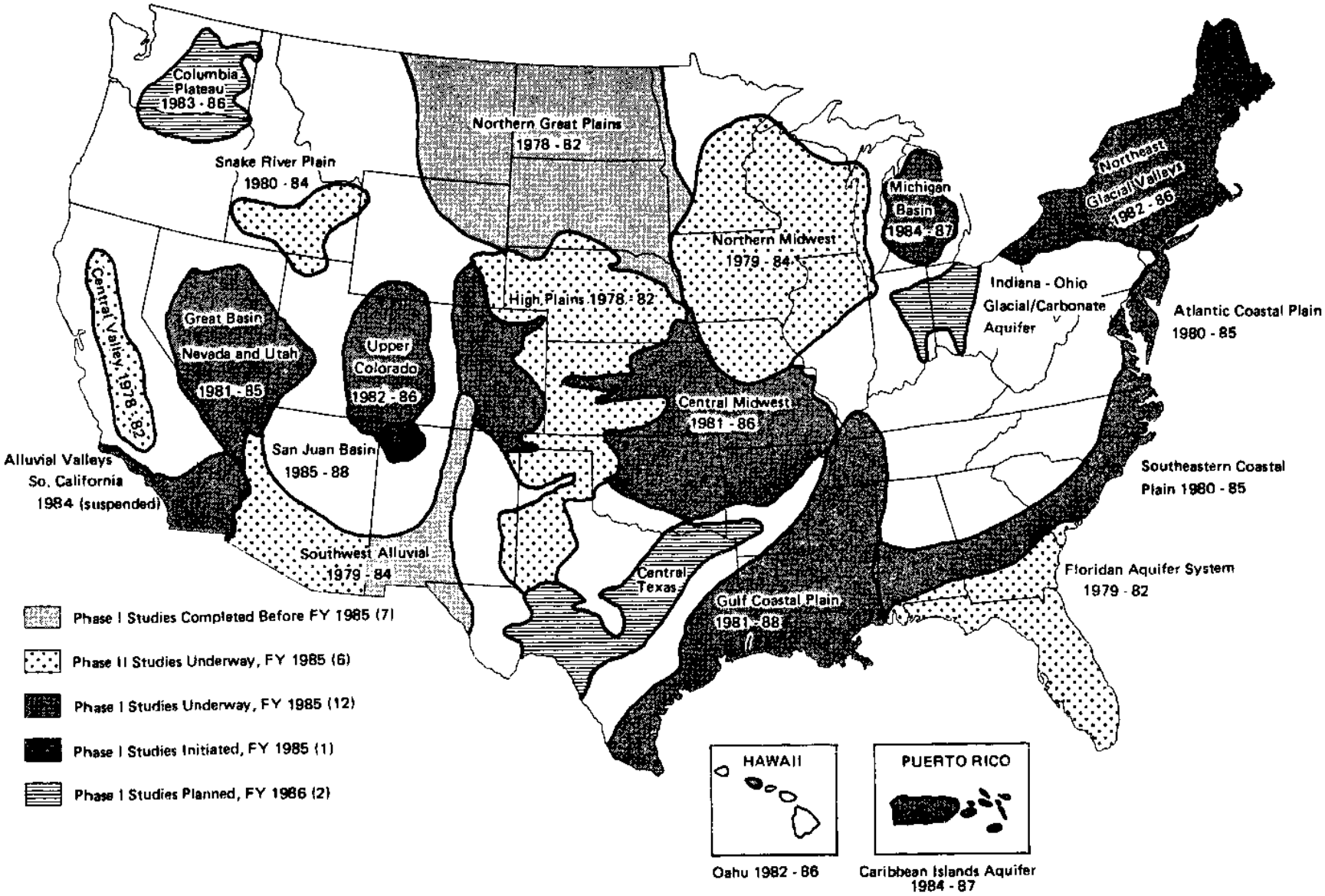


Figure XV-7-l.— Areal extent of regional aquifer-system analyses.
(From U.S. Geological Survey, Ground-Water Branch, personal communication)

Table XV 7-1.– Principal data requirements for ground-water analysis and modeling (From U.S. Water Resources Council, 1980, p. 21.)

Physical Framework	Hydrogeologic maps showing extent and boundaries of all aquifers and non -water -bearing rocks. Topographic map showing surface-water bodies and land forms. Water-table, bedrock-configuration, and saturated-thickness maps. Transmissivity maps showing aquifers and boundaries. Map showing variations in storage coefficient. Relation of saturated thickness to transmissivity. Hydraulic connection of streams to aquifers .
Hydrologic Stresses	Type and extent of recharge areas (irrigated areas, recharge basins, recharge wells, natural recharge areas). Surface-water diversions. Ground-water pumpage (distribution in time and space). Precipitation. Areal distribution of water quality in aquifer. Streamflow quality (distribution in time and space). Geochemical and hydraulic relations of rocks, natural water, and artificially introduced water or waste liquids.
Model Calibration	Water-level change maps and hydrographs. Streamflow, including gain and loss measurements. History of pumping rates and distribution of pumpage.
Prediction and Optimization Analysis	Economic information on water supply and demand. Legal and administrative rules. Environmental factors. Other social considerations.

XVI. STAGES OF A GOAL EXPLORATORY PROGRAM AS RELATED TO GEOLOGY AND HYDROLOGY INFORMATION

Pertinent 30CFR[1] Sections:
- Maps
- Operation Plan

Mining companies collect geologic, hydrologic, and geochemical data on pre-mining conditions in a proposed permit area to:

1. define the quality and quantity of the coal resources,
2. determine how to minimize unexpected ground-water inflows to the proposed mining excavation,
3. provide information for the water-supply design for the mining and plant operations and support facilities, and,
4. satisfy the requirements of the regulatory authority to predict the potential geohydrologic impacts of the mining operation on the ground-water flow system(s) of the general area, by quantitative analysis, and (or) by ground-water modeling.

The four stages of a coal-mining exploratory program include mine feasibility, information evaluation, mine design, and mine operations (Coates and Yu, 1977). At the conclusion of mining, ground-water quantity and quality data are monitored to satisfy the requirements of the regulatory authority until bond release, which is granted when the monitoring data indicate the quality of the ground water and base flow are suitable to support the approved postmining land uses and that the water rights of other users have been protected or replaced (as described in chapter II herein).

1. Feasibility

The mine-feasibility stage starts with regional and local studies to collect geologic, hydrologic, and geochemical information. The first step is a comprehensive literature search (as described in chapter XV) and an examination of topographic maps, geologic maps, and aerial photographs of the general area. (These photographs are generally available from various Federal and State agencies.) From the information, the geologic setting (chapter IV) and hydrologic setting (chapter VI) can be estimated.

The maps and recent aerial photographs show the water and terrain features near and within the permit area that might influence the economic success of a mining venture. The water features include reservoirs, lakes, rivers, creeks, and swamps. If these features are adjacent to the permit area and are at a higher elevation than the coal bed(s) to be mined, inflow of water into the mining excavation is possible. Conversely, mining operations higher than surface-water features have a potential for surface-water contamination. Terrain features include active mine operations, abandoned mine areas, and landslides. If these features are adjacent to the permit area, water-quality problems and geologic hazards are possible.

[1]CFR = Code of Federal Regulations

2. Evaluation of geohydrologic information

The second stage in the initial investigations of the exploratory program for mining is the detailed evaluation of the information collected in stage 1, within the general area, which also includes a field-reconnaissance trip. This step includes:

1. verification of the information compiled,
2. an examination of geologic and hydrologic activities within the general area, such as active mining, petroleum exploration and development, water-resource development (wells and reservoirs for water supplies), and water-treatment facilities, and,
3. a preliminary determination of water quantity and quality.

Other activities include:

1. Location of water wells and oil or gas wells and spotting then on the topographic maps. With this information, additional geologic and hydrologic data such as driller's logs (chapter VIII), and maps showing the occurrence of coal (section III) and ground water (chapter VI) can be obtained from State and Federal agencies.
2. Examination of outcrops to determine rock types, the presence of acid-forming minerals (pyrite, marcasite, siderite), neutralizing rocks (limestone and dolomite), and geologic structures (such as dipping beds, folds, faults, and fracture zones). This information, together with the drillers logs, forms a basis for a. preliminary geologic map and geologic cross sections.
3. Planning and implementation of:
   (a) a drilling program including the layout of exploratory test-hole sites,
   (b) the siting of geophysical survey lines, and
   (c) the siting of hydrologic monitoring stations upgradient and downgradient of the proposed permit area.

   If little or no hydrologic information is available, the drilling program and the geophysical surveying will be necessary to determine the geologic setting (chapter IV), the hydrologic setting (chapter VI), and the feasibility of the proposed mining.
4. Collecting and chemically analyzing ground-water samples and base flow samples (chapter XII) at the monitoring stations. This provides information on the chemical character of ground water.
5. Water-level monitoring (chapter IX) and aquifer testing (chapter X-2). Ground-water samples are collected and analyzed along with this testing.

The geohydrologic tasks of an exploratory program are listed in table XVI-1. The completion of these tasks is mandatory to satisfy ground-water regulations of the State regulatory authority for the proposed permit application. The end of the feasibility and information evaluation stages is determined by a management decision on the economic soundness of the proposed mining venture.

3. Design

This stage includes the collection and analysis of additional geologic and hydrologic field data, which are necessary to:

1. refine the coal-reserves estimate,
2. define the water-inflow problems (if any),
3. finalize the water-supply design, and,
4. quantify the impact of the mining operation on the aquifer systems and thereby satisfy the regulation requirements.

Activities in this stage include:

1. Aquifer testing in selected exploratory test holes within the permit area and adjacent area (chapter X-2).
2. Borehole geophysical logging to aid in aquifer delineation.
3. Interpretation of hydraulic properties for the impacted aquifer systems within the permit and adjacent area (chapter X-l), in terms of the above activities.
4. Delineation of confining beds adjacent to the coal seams to be mined.
5. Chemical analysis of water samples from base-flow sites and wells and springs (chapter XII).
6. Detailed well and spring inventory in the general area, which includes the investigation of ground-water pumpage and use (chapter VII).
7. Establishment of base-flow sites upgradient and downgradient of the permit site. Low-flow measurements are made within the permit area and adjacent area (chapter XI).
8. Drafting and implementation of ground-water monitoring plan in the permit area and adjacent area, including selected springs (if any), selected exploratory test holes for observation wells, and selected suitable inventoried wells.
9. Final water-supply design for the mine-plant operations and the support facilities.
10. Estimation of the potential hydrologic impacts (chapter XIII) of mining on the aquifer systems within the adjacent area through quantitative analysis and (or) digital computer ground-water-model analysis (chapter XV-7).
11. Completion of the products listed in table XVI-1 and as required by the State regulatory authority (chapter II).

4. Operations

At this stage, the mining-operations strategy has been resolved, the orientation of the adits has been defined, the water-supply facility has been constructed, the ground-water monitoring plan is operational, and the potential impact of the operations on the aquifer systems has been estimated.

The hydrologic data obtained from the monitoring system are compiled and submitted to the regulatory authority at least every 3 months, or more frequently if required. The authority may also require additional monitoring stations (chapter II), such as the conversion of core-test holes into observation wells. Additional observation wells will also need to be installed within and adjacent to waste-disposal (spoil) piles.

As the exploratory program continues to refine the coal-reserve estimates before mining the geohydrologic tasks (listed in table XVI-1) are also performed and refined on a continuing basis. Engineering evaluations include:

1. comparison of predicted water-level changes in the adjacent area against the observed water-level changes;
2. comparison of predicted ground-water pumpage from mine-dewatering operations against the actual pumpage; and,
3. comparison of predicted precipitation against actual precipitation data.

If the comparisons show little difference, the assessment of probable hydrologic impacts is satisfactory. If the estimates differ from the observed values by orders of magnitude, however, additional aquifer testing and computer-model analyses are necessary. Additional aquifer testing will improve the hydraulic properties data array in the ground-water model, and corrected pumpage data will also improve the results. The addition of updated hydrologic data in the model will yield a new estimate of the hydrologic impacts of mining. The regulatory authority should be kept informed of the changing projected conditions from the analytical or model runs.

Table XVI.-1– Geohydrologic investigation tasks for exploratory program, and resulting products and digital-computer modeling.

	Reference Chapter	Product
Geologic Information		
determination of Geologic Setting	IV	
literature search and bibliographic reference listing	XV	list of references
outcrop mapping for geologic map	XIX	map
underground/subsurface mapping for selected subsurface maps		map
measuring geologic sections to be shown on geologic map	VIII	cross section
and cross section	XIX	cross section
surficial geophysical very low surveying - shallow seismic frequency		map
electrical resistivity techniques for definition of buried channels in bedrock (glacial terrain)		
downhole geophysical logging - contributing to geologic cross section		cross section
analysis of driller's logs borings test holes and cores for	VIII	map
geologic cross section (s); also defines presence of pyrite and	XIX	cross section
carbonate minerals in overburden	XIX	cross section
photogeologic analysis of structural geologic features	IV	map
(faults fracture traces folds and lineaments)		cross section
'well sitting for the collection and analysis of driller's samples identifying	VIII	cross section
aquifers and confining beds relative to the coal seams to	VI	cross section
be mined		
Hydrologic Information		
determination of Hydrologic Setting	VI	
literature search and bibliographic reference listing	XV	list of references
compilation of water-level data from driller's logs borings test	IX	cross section table
holes downhole geophysical logging and 'well sitting' information.		
definition of potentiometric surfaces for individual aquifers	IX	map
water well and table spring inventory for well and spring location map	VII	map
streamflow monitoring information (hydraulic boundary)* -	X	map
existing streamflow information	XI	graph, table
base flow determination from existing information or from	XI	graph, table
temporary gaging stations.		
losing streams determined from seepage measurements	XI	map, table
demands for existing water supplies (surface-water use)		table
surface-water diversions such as for irrigation purposes		map
precipitation*		graph, table
define aquifers and confining beds	VI	cross section
aquifer recharge areas (hydraulic boundary)*	X	map
hydraulic properties of aquifers* from aquifer tests	X	table
laterally and vertically	X	table
ground-water use* including irrigation, industrial, commercial,	VII	map, table
domestic stock		
ground-water pumpage-rate inventory* including historical and	VII	table
time and space distribution		
ground-water monitoring plan (observation-well network) from		
existing hydrograph information* (for model calibration) and	XIV	map
nested piezometers in borings	IX	graph, table
active- and abandoned-mine water discharge and mine pool information *		table
digital computer ground-water model analysis with input data	XV(7)	
tabulated for estimation of probable hydrologic consequences of		tables
proposed mining		cross section
Geochemical Information		
determination of water quality in time and space		
literature search - bibliographic reference listing	XV	list of references
water well and spring sampling	XII	map, table
stream base -flow sampling	XII	map, table
determination of alkalinity and acidity	XII	map, table
active- and abandoned-mine discharge water quality table information	XII	map, table
ground-water monitoring plan analysis of existing water quality	XIV	map
overburden analyses - analysis of acid-forming minerals	XIX	table
		cross section

* hydrologic data input for digital computer ground-water modeling, for areal drawdown effects.

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XVIII. GLOSSARY OF GEOHYDROLOGIC TERMS USED IN THIS MANUAL.

Numbers at the end of the definitions, in parentheses, indicate the source. References for the glossary terms are listed at the end of this chapter. Definitions by U.S. Department of the Interior, Office of Surface Mining, Permanent Regulatory Program (Title 30, Chapter VII, Part 701) have priority over other available definitions, are quoted from the regulations, and are indicated by (9). Almost all other definitions are directly quoted from the source. Minor rewriting exists for greater clarity.

Acid-base accounting - A criterion to evaluate the potential toxicity of overburden materials, which consists of two measurements: (1) total or pyritic sulfur and (2) neutralization potential. (6)

Acidity - The capacity of a water solution to neutralize basic or alkaline solutions. Acidity in water is due to the presence of excess hydrogen ions. (5)

Acid drainage - Water with a pH of less than 6.0 and in which total acidity exceeds total alkalinity, discharged from an active, inactive or abandoned surface coal mine and reclamation operation or from an area affected by surface coal mining and reclamation operations. (9)

Acid-forming materials - Earth materials that contain sulfide minerals or other materials, which if exposed to air, water, or weathering processes, forms acids that may create acid drainage. (9)

Acid mine drainage - Water discharged from mines and mine wastes with a pH range of 2.0 to 4.5. Acidity results from the oxidation of sulfides exposed during mining, which produces sulfuric acid and sulfate salts. The acid dissolves minerals in the rocks, further degrading the quality of the drainage water. (8)

Adit - A horizontal passage from the land surface into a mine. Sometimes called a tunnel. (8)

Adjacent area - The area outside the permit area where a resource or resources, determined according to the context in which adjacent area is used, are or reasonably could be expected to be adversely impacted by proposed mining operations, including probable impacts from underground workings. (9)

Affected area - Any land or water surface which is used to facilitate, or is physically altered by surface coal mining and reclamation operations. It includes the disturbed area; any area upon which surface coal mining and reclamation operations are conducted; any adjacent lands the use of which is incidental to surface coal mining and reclamation operations; ... any areas upon which are sited structures, facilities, or other property material on the surface resulting from, or incident to surface coal mining and reclamation operations; and the area located above underground workings. (9)

Alkalinity - The capacity of a water solution to neutralize acid solutions. This property is attributed largely to the presence of the bicarbonate ion ($H\ CO_3^-$) in solution; other ions such as carbonate (CO_3^-) and hydroxyl (OH^-), may contribute to this property. (5)

Alluvial valley floors - The unconsolidated stream-laid deposits holding streams with water availability sufficient for subirrigation or flood irrigation agricultural activities but does not include upland areas which are generally overlain by a thin veneer of colluvial deposits composed chiefly of debris from sheet erosion, deposits formed by unconcentrated runoff or slope wash, together with talus, or other mass-movement accumulations, and windblown deposits. (9)

Alluvial aquifer - An aquifer within unconsolidated stream deposits of comparatively recent time. (10)

Alluvium - A general term for clay, silt, sand, gravel, or other similar material deposited in a streambed, on a flood plain, delta, or at the base of a mountain during comparatively recent geologic time. (14)

Anion - A negatively charged ion; for example, CL^-(chloride) and $S0_4^-$(sulfate). (10)

Anisotropy - A condition of having different properties in different directions; example: a geologic stratum that transmits ground water at different velocities in the vertical direction than in the horizontal direction. (8)

Anthracite - Coal of the highest metamorphic rank, in which fixed-carbon content is between 92% and 98% (on a dry, mineral-matter-free basis). It is hard and black, and has a semimetallic luster and semiconchoidal fracture. (8)

Anticline - An upfold or arch of stratified rock, generally convex upward, whose core contains the stratigraphically older rocks. (8)

Apparent specific yield - The specific yield determined near the beginning of the pumping period (the first day) of an aquifer test of a water-table aquifer. This determined value would be lesser than the maximum specific yield obtained from a long-term pumping test period, for example, several weeks.

Aquifer - A zone, stratum, or group of strata that can store and transmit water in sufficient quantities for a specific use. (9)

Aquifer boundaries - recharge (positive) and impermeable (negative) boundaries modify ground-water flow conditions:

–Recharge boundary is a boundary in which there is significant increase in transmissivity; for example, where a permeable material is in direct connection with a surface body of water or a permeable material is faulted against a more permeable material.This boundary influences a discharging well by retarding drawdown or stopping the expansion of the cone of depression; increases specific capacity at the well; the drawdown stabilizes between the well and the boundary. (13)

–Impermeable boundary is a boundary in which there is significant reduction in transmissivity; for example, where a permeable material abuts against a buried valley wall of impermeable granite or shale. This boundary influences a discharging well by retarding or stopping the expansion of the cone of depression, which results in increased drawdown between the well and the boundary; decreases specific capacity at the well. (13)

Aquifer system - a heterogeneous body of intercalated (interbedded) permeable and less permeable material that acts as a water-yielding hydraulic unit of regional extent. (8)

Aquifer test - A test or controlled field experiment involving either the withdrawal of measured quantities of water from, or addition of water to, a well (or wells) and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition. (7)

Artesian aquifer - see confined aquifer.

Artesian water - Ground water that has artesian pressure head; ground water that is under sufficient pressure to rise above the zone of saturation. (3)

Artesian well - A well deriving its water from an artesian or confined aquifer. The water level in an artesian well stands above the top of the artesian aquifer tapped by the well. (1)

Backwater - At a stream site, backwater is the difference in elevation between the observed stage and the stage that should exist at the site for the discharge measured, as indicated by the stage-discharge relation (which applies to normal or natural flow conditions). Backwater, or the backing up of stream water, can be caused by temporary obstructions such as ice, uprooted trees and trash blocking a bridge opening or caught on the stream reach control. (2)

Base flow (or base runoff) - Sustained or fair-weather flow in a stream composed largely of ground-water discharge. (10)

Bedding - The arrangement of a sedimentary rock in beds or layers of varying thickness and character; the general physical and structural character or pattern of the beds and their contacts within a rock mass, such as cross bedding and graded bedding; a collective term denoting the existence of beds. (8)

Bedding plane - (a) A planar or nearly planar bedding surface that visibly separates each successive layer of stratified rock (of the same or different lithology) from the preceding or following layer; a plane of deposition. (8)

Bedrock - A general term for the rock, usually solid, that underlies soil or other unconsolidated surficial material. (8)

Brackish water - Water having a dissolved material content in the range of 1,000 to 30,000 mg/L (milligrams per liter), but not necessarily corresponding to ocean water with respect to ionic ratios. (4)

Brine - Water having more than 30,000 mg/L dissolved material, but not necessarily corresponding to ocean water with respect to ionic ratios. (4)

Cation - A positively charged ion; for example, Na^+(sodium) and K^+(potassium). (10)

Clastic - Pertaining to a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals and that have been transported some distance from their places of origin. (8)

Clastic dike - A sedimentary dike consisting of a variety of clastic materials derived from underlying or overlying beds. (8)

Clay - A rock or mineral particle in the soil, having a diameter less than 0.002 mm (2 microns). (8)

Clay vein - A body of clay, usually roughly tabular in form like a dike or vein, that fills a crevice in a coal seam. (8)

Cleat - In a coal seam, a joint or system of joints along which the coal fractures. There are usually two cleat systems developed perpendicular to each other. (8)

Coal - A readily combustible rock containing more than 50 percent by weight and more than 70 percent by volume of carbonaceous material, including inherent moisture, formed from compaction and induration of variously altered plant remains similar to those in peat. (8)

Coal classification - (a) The analysis or grouping of coals according to a particular property, such as degree of metamorphism (rank), constituent plant materials (type), or degree of impurity (grade); (b) the analysis or grouping of coals according to the percentage of volatile matter, caking properties, and coking properties. (8)

Coal cleat - A joint, or system of joints, along which the coal fractures. (9)

Coal well - A well that receives ground water from a coal bed.

Coefficient of permeability - see hydraulic conductivity.

Coefficient of storage - see storativity.

Coefficient of transmissibility - see transmissivity.

Colluvium - Any … incoherent mass of soil material and (or) rock fragments deposited by rainwash, sheetwash, or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides. (8)

Columnar section - see geologic column.

Cone of depression - A depression in the potentiometric surface of a body of ground water that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines the "area of influence" of a well. The shape of the depression is due to the fact that the water must flow through progressively smaller cross sections as it nears the well, and hence the hydraulic gradient must be steeper. (8)

Confined aquifer - An aquifer bounded above and below by impermeable beds, such as clay or unfractured shale, or by beds of distinctly lower permeability than that of the aquifer itself; an aquifer containing confined ground water. (8)

Confined ground water - Ground water under pressure significantly greater than that of the atmosphere. Its upper surface is the bottom of an impermeable bed or a bed of distinctly lower permeability than the material in which the water occurs. (8)

Confining bed - A body of "impermeable" material stratigraphically adjacent to one or more aquifers. The hydraulic conductivity of the confining bed is distinctly lower than that of the adjacent aquifers. This term supplants the terms aquiclude, aquitard, and aquifuge. (1)

Connate water - Water entrapped in the interstices of sedimentary rock at the time of its deposition. (8)

Consolidation - (a) Any process whereby loosely aggregated soft or liquid earth materials become firm and coherent rock; … the lithification of loose sediments to form a sedimentary rock. (8)

Contaminant - Any physical, chemical, biological, or radiological substance in water. (9)

Cumulative hydrologic impact assessment (CHIA) - A premining analysis of the probable cumulative hydrologic impacts of the proposed operation and all anticipated mining upon the surface- and ground-water systems within the cumulative impact area; and prepared by the regulatory authority. - An assessment sufficient to determine, for purposes of permit approval, whether the proposed (mining) operation has been designed to prevent material damage to the hydrologic balance outside the permit area. (9)

Cumulative impact area - The area, including the permit area, within which impacts resulting from the proposed operation may interact with the impacts, of all other nearby mining, on surface- and ground-water systems. (9)

Dip (structural geology) - The angle that a structural surface, such as a bedding or fault plane, makes with the horizontal, measured perpendicular to the strike of the structure and in the vertical plane. (8)

Discharge - Outflow, or rate of flow, measured in volume per time unit, such as cubic feet per second, that describes the flow of water from a pipe, a mine entry, a drainage basin, or at a stream site. (2)

Discrete ground-water zones - The occurrence of ground water in distinct and separate zones within an anisotropic and heterogeneous media.

Dissolved material - All material which passes through filter having a pore size of 0.45 urn. (4)

Dissolved solids - A term that expresses the quantity of dissolved material in a sample of water, "either the residue on evaporation, dried at 180° C, or, for many waters that contain more than about 1000 parts per million, the sum of determined constituents", generally reported in milligrams per liter. (8)

Disturbed area - An area where vegetation, topsoil, or overburden is removed or upon which topsoil, spoil, coal processing waste, underground development waste, or noncoal waste is placed by surface coal-mining operations. (9)

Divide (ground water) - A ridge in the water table or other potentiometric surface from which the ground water represented by that surface moves away in both directions. (8)

Divide (stream) - (a) The line of separation, or the ridge, summit, or narrow tract of high ground that marks the boundary between two adjacent drainage basins or dividing the surface waters that flow naturally in one direction from those that flow in the opposite direction; the line forming the rim of, or enclosing a drainage basin; a line across which no water flows. (8)

Drainage area, (of a stream at a specific stream site) - That area, measured in a horizontal plane, enclosed by a drainage divide. (8)

Drainage basin - A region or area bounded by a drainage divide and occupied by a drainage system; specifically, the tract of country that gathers water originating as precipitation and contributes it to a particular stream channel or system of channels, or to a lake, reservoir, or other body of water. (8)

Drawdown - (a) The lowering of the water level in a well as a result of withdrawal, (b) the difference between the height of the water table and that of the water in a pumped well, (c) the reduction of the pressure head as a result of the withdrawal of water from a well. (8)

Draw slate - In coal mining, shale that occurs above a coal seam and collapses during or shortly after removal of the coal. (8)

Drift (glacial) - A general term applied to all rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by, or from the ice, or by running water emanating from a glacier. (8)

Drift (mining) - A horizontal or nearly horizontal underground opening driven along a vein. (8)

Drift mining - (b) The extraction of near-surface coal seams by underground inclined tunneling rather than by open cut mining or vertical-shaft methods. (8)

Effective porosity - The amount of interconnected pore space available for fluid transmission. (1)

Effluent stream - see gaining stream.

Ephemeral Stream - A stream which flows only in direct response to precipitation in the immediate watershed or in response to the melting of a cover of snow and ice, and which has a channel bottom that is always above the local water table. (9)

Equipotential line - A contour line on a potentiometric-surface map; a line along which the pressure head of ground water in an aquifer is the same. (8)

Essential hydrologic functions - The role of the alluvial -valley floor in:

- collecting water, storing water, regulating flow, and making the natural flow of surface water or ground water, or both, usefully available for agricultural activities...
- collecting water includes accumulating runoff and discharge from aquifers in sufficient amounts to make the water available at the alluvial valley floor greater than the amount available from direct precipitation.
- storing water involves limiting the rate of discharge of surface water, holding moisture in soils, and holding ground water in porous materials.
- regulating the natural flow of ground water results from the properties of the aquifers which control inflow and outflow.
- making water usefully available for agricultural activities results from the existence of flood plains and terraces where surface and ground water can be provided in sufficient quantities to support the growth of agriculturally useful plants. (9)

Evapotranspiration - Water withdrawn from a land area by evaporation from water surfaces and from moist soil and by plant transpiration. (2)

Face cleat - The major cleat system or jointing in a coal seam. (8)

Facies - (a) The aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin, (b) a mappable, areally restricted part of lithostratigraphic body, differing in lithology or fossil content from other beds deposited at the same time and in lithologic continuity, (c) A distinctive rock type, broadly corresponding to a certain environment or mode of origin. (8)

Facies map - A map showing the gross areal variation or distribution (in total or relative content) of observable designated stratigraphic unit, without regard to the position or thickness of individual beds in the vertical succession. (8)

Fault - A fracture or a zone of fractures along which there has been displacement of sides relative to one another parallel to the fracture. (8)

Fault breccia - (a) A "tectonic breccia" composed of angular fragments resulting from the crushing, shattering, or shearing of rocks during movement on a fault, from friction between the walls of the fault, or from distributive ruptures associated with a major fault. (8)

Fault gouge - Soft, uncemented pulverized clayey or claylike material, commonly a mixture of minerals in finely divided form, found along some faults or between the walls of a fault, and filling or partly filling a fault zone; a slippery mud that coats the fault surface or cements the "fault breccia." (8)

Fault plane - A fault surface that is more or less planar. (8)

Fault surface - In a fault, the surface along which displacement has occurred. (8)

Fence diagram - A drawing in perspective of three or more geologic sections showing their relationship to one another. (8)

Fissility - A general term for the property possessed by some rocks of splitting easily into thin layers along closely spaced, roughly planar, and approximately parallel surfaces, such as bedding planes in shale ... (8)

Flow-duration curve - A cumulative frequency curve that shows the percentage of time that specified discharges (generally stream flow) are equaled or exceeded. (2)

Flowing well - (a) A well that yields water at the land surface without pumping. (8)

Flow line - The path that a particle of water follows in its movement through saturated, permeable material (soil or rock). (7)

Formation - (a) A body of rock strata, of intermediate rank in the hierarchy of "lithostratigraphic units," which is unified with respect to adjacent strata by consisting dominantly of a certain lithologic type or combination of types or by possessing other unifying lithologic features. (8)

Fracture (structural geology) - A general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. A fracture includes cracks, joints, and faults. (8)

Fracture trace - A natural linear feature less than one mile long and best seen on aerial photographs (scale 1:20,000 or smaller); a surface manifestation of subsurface fracture zones, or almost vertical zones of fracture concentrations; identified by dark or light tonal lines (on aerial photographs) in the soil, alignments of vegetation, topographic sags, aligned gaps in ridges, and (or) other similar features. (17)

Fresh water - Water having less than 1,000 milligrams per liter dissolved material. (4)

Gaging station - A particular site on a stream, canal, lake, or reservoir, where systematic streamflow measurements and other hydrologic data are obtained. (10)

Gaining stream - A stream, or reach of stream, whose flow is being increased by the inflow of ground water. (1)

Geohydrologic system - A system which includes: aquifer thickness and extent, aquifer boundaries, variations and approximate values of transmissivity and storage coefficient, and magnitude of control to be imposed on the aquifer(s), such as change in discharge or head. (6)

Geohydrologic unit - An aquifer, a confining unit (aquiclude or aquitard), or a combination of aquifers and confining units, comprising " framework for a reasonably distinct hydraulic system." (8)

Geologic column - (a) A composite diagram that shows in a single column the subdivisions of part, or all, of geologic time, or sequence of stratigraphic units of a given locality, or region (the oldest at the botton and the youngest at the top, with dips adjusted to the horizontal), so arranged as to indicate their relations to the subdivisions of geologic time and their relative positions to each other. (8)

Gob - Materials which are separated and wasted from the coal during cleaning, concentrating, or other processing or preparation of coal. (9)

Graben - An elongate, relatively depressed crustal unit, or block, that is bounded by faults on its long sides. (8)

Grid - (a) A network composed of two sets of uniformly spaced parallel lines, usually intersecting at right angles and forming squares (or rectangles), superimposed on a map, chart, or aerial photograph, to permit identification of ground locations by means of a system of coordinates and to facilitate computation of distance and direction, (b) a systematic array of points or lines. (8)

Ground water - Subsurface water that fills available openings in rock or soil materials to the extent that they are considered water saturated. (9)

Ground-water budget - see hydrologic budget.

Ground-water barrier - A natural or artificial obstacle, such as a dike or fault gouge, to the lateral movement of ground water, not in the sense of a confining bed. It is characterized by a marked difference in the level of the ground water on opposite sides. (8)

Ground-water basin - (a) A subsurface structure having the character of a basin with respect to the collection, retention, and outflow of water, (b) an aquifer or system of aquifers, whether basin-shaped or not, that has reasonably well defined boundaries and more or less definite areas of recharge and discharge.(8)

Ground-water discharge - (a) Release of water from the zone of saturation. (8)

Ground-water divide - see divide (ground water)

Ground-water model - Simulated representation of a ground-water system to aid in the understanding of the behavior of the system when stressed hy discharges and recharges and to aid in decision making for ground-water resources management. (7)

Ground-water reservoir - All rocks in the zone of saturation; same as aguifer, or aquifer system, or ground-water system. (7)

Ground-water runoff - That part of the runoff which has passed into the ground, has become ground water, and has been discharged into a stream channel as spring or seepage water. (2)

Ground-water storage - Water in the zone of saturation.

Ground-water system - A ground-water reservoir and its contained water.

Group - (a) The formal lithostratigraphic unit next in rank above formation. A group includes two or more contiguous or associated formations with significant lithologic features in common. (8)

Hardness - A property of water, that causes formation of an insoluble residue when the water is used with soap and a scale in vessels in which water has been allowed to evaporate. It is primarily due to the presence of ions of calcium and magnesium, but also to ions of other alkali metals, other metals (such as iron), and even hydrogen. Harness of water is generally expressed as parts per million as $CaCO_3$ (40 ppm Ca produces a hardness of 100 ppm as $CaCO_3$); also as milligrams per liter; and as the combination of carbonate hardness and noncarbonate hardness. (8)

Head (static) - The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. (1)

Headwater - (a) The source (or sources) and upper part of a stream, especially of a large stream or river, including the upper drainage basin. (8)

Heavy metals - metallic elements with high molecular weights generally toxic in low concentrations to plants and animal life; such metals exhibit biological accumulation. (16)

Highwall - The face of exposed overburden and coal in an open cut of a surface coal-mining activity or for entry to underground mining activities. (9)

Homogeneous aquifer - Hydraulic properties throughout the aquifer are identical everywhere. (1)

Hydraulic conductivity - The volume of fluid, at the existing kinematic viscosity, that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. (1)

- Describes the ability of aguifer material to transmit water and values for horizontal and vertical flow through the same material may differ.

Hydraulic diffusivity - The hydraulic parameter of transmissivity divided by storage coefficient (storativity); the conductivity of the saturated median when the unit volume of water moving is that involved in changing the head a unit amount in a unit volume of median. (1)

Hydraulic discharge - see ground-water discharge.

Hydraulic gradient - (a) In an aquifer, the rate of change of 'total head' per unit of distance of flow at a given point and in a given direction. (8)

Hydraulic head - (a) The height of the free surface of a body of water above a given subsurface point. (8)

Hydraulic permeability - The ability of a rock or soil to transmit water under pressure. It may vary according to direction; see hydraulic conductivity. (8)

Hydrograph - A graph of stream stage, discharge, water level, velocity, or other property of water with respect to time. (2)

Hydrologic balance - The relationship between the quality and quantity of water inflow to, water outflow from, and water storage (changes in storage) in a hydrologic unit, such as a drainage basin, aquifer soils zone, lake, or reservoir.

- A water budget that encompasses the dynamic relationships among precipitation, surface runoff, evaporation, and changes in ground- and surface-water storage. (9)

Hydrologic budget - An accounting of the inflow to, outflow from, and changes in storage in a hydrologic unit such as a drainage basin, aquifer, soil zone, lake, reservoir, or irrigation project. (2)

Hydrologic cycle - The constant circulation of water from the sea, through the atmosphere, to the land, and its eventual return to the atmosphere by way of transpiration and evaporation from the sea and the land surface. (8)

Hydrologic properties - Those properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water, for example, porosity, effective porosity, specific retention, permeability, and direction of maximum and minimum permeability. (8)

Hydrologic regime - The entire state of water movement in a given area.

- A function of the climate and includes the phenomena by which water first occurs as atmospheric water vapor, passes into a liquid or solid form, falls as precipitation, moves along or into the ground surface, and returns to the atmosphere as vapor by means of evaporation and transpiration. (9)

Hydrologic unit - A geographic area representing part or all of a surface drainage basin or distinct hydrologic feature, ejs delineated by the Office of Water Data Coordination (U.S. Geological Survey) on the State Hydrologic Unit Maps. (10)

Hydrostatic head - The height of a vertical column of water whose weight, if of unit cross section, is equal to the hydrostatic pressure at a given point; "static head" as applied to water. (8)

Hydrostatic level - The level to which the water will rise in a well under its full pressure head. It defines the potentiometric surface. (8)

Hydrostatic pressure - The pressure exerted by the water at any given point in a body of water at rest. The hydrostatic pressure of ground water is generally due to the weight of water at higher levels in the zone of saturation. (8)

Hydrostratigraphic unit - A body of rock having considerable lateral extent and forming "a geologic framework for a reasonably distinct hydrologic system." (8)

Impermeability - The condition of a rock, sediment, or soil that renders it incapable of transmitting fluids under pressure. (8)

Induced infiltration - Recharge to ground water by infiltration, either natural or manmade, from a body of surface water as a result of the lowering of the ground-water head below the surface-water level. (8)

Induced recharge (aquifer) - Recharge to an aquifer by inflow of surface water, generally caused by the cone of depression intersecting the surface-water body.

Indurated - A condition of a rock or soil hardened or consolidated lay pressure, cementation, or heat. (8)

Influent flow - Flow of water into the ground from a body of surface water; for example, the seepage of water from an influent stream to the zone of saturation. (8)

Influent stream - (a) A stream or reach of a stream that contributes water to the zone of saturation and develops bank storage; its channel lies above the water table (8); synonymous term is losing stream.

Instantaneous discharge - The discharge at a particular instant in time. (10)

Insulated stream - A stream or reach of a stream that is separated from the zone of saturation by an impermeable bed and neither contributes water to the zone of saturation nor receives water from it. (8)

Integrated drainage - The drainage developed where various higher local base levels of small basins are incorporated into a large basin which has a single lower base level. (8)

Intermittent stream - (a) A stream or reach of stream that drains a watershed of at least one square mile, or (b) A stream or reach of stream that is below the local water table for at least some part of the year, and obtains its flow from both surface runoff and ground-water discharge. (9)

Ion - An atom, group of atoms, or molecule that has acquired a net electrical charge. (10)

Isopach - A line drawn on a map through points of equal true thickness of a designated stratigraphic unit or group of stratigraphic units. (8)

Isopach map - A map that shows the thickness of a bed, formation, sill, or other tabular body throughout a geographic area by means of isopachs at regular intervals. (8)

Isotropy - A condition of having properties that are uniform in all directions. (8)

Joints - System of fractures in rocks along which no movement parallel to the fracture surface has occurred (as opposed to faults). In coal, joints and fractures may be termed "cleats ". Joints and fractures are some of the most important water-bearing and transmitting openings in rock formations, and provide secondary hydraulic conductivity (secondary permeability). (1)

Key bed - (a) A well-defined, easily identifiable stratum or body of strata that has sufficiently distinctive characteristics (such as lithology or fossil content) to facilitate correlation in field mapping or subsurface work, (b) a bed, the top or bottom of which is used as a datum in making structure-contour maps. (8)

Land Surface Datum (LSD) Correction - The vertical distance from the measuring point (MP), usually from the top of the well (or casing) to the land surface. (6)

Leachate - A solution obtained by leaching; such as water that has percolated through soil containing soluble substances and that contains certain amounts of these substances in solution. (8)

Leaching - (a) Separation, selective removal, or dissolving-out of soluble constituents from a rock, or orebody, by the natural action of percolating water, (b) The removal in solution of nutritive or harmful constituents (such as mineral salts and organic matter) from an upper to a lower soil horizon by the action of percolating water, either naturally (by rainwater) or artificially (by irrigation). (8)

Lignite - (a) A brownish-black coal that is intermediate in coalification between peat and subbituminous coal; consolidated coal with a calorific value less than 8300 BTU per pound on a moist, mineral-matter-free basis. (8)

Limestone - (a) A sedimentary rock consisting chiefly (more than 50 percent by weight or by areal percentages under the microscope) of calcium carbonate, primarily in the form of the mineral calcite, and with or without magnesium carbonate; specifically, a carbonate sedimentary rock containing more than 95 percent calcite and less than 5 percent dolomite. (8)

Lineaments - Linear features on aerial photographs or imagery formed by the alignment of stream channels or tonal features in soil, vegetation, or topography. (15)

Linear (adj.) - Arranged in a line or lines; pertaining to the line-like character of some object or objects. (8)

Lithification - The conversion of a newly deposited, unconsolidated sediment into a coherent, solid rock, involving processes such as cementation, compaction, desiccation, crystallization. It may occur concurrent with, soon after, or long after deposition. (8)

Lithify - To change to stone, or to petrify; especially to consolidate from a loose sediment to a solid rock. (8)

Lithofacies map - A "facies map" based on lithologic attributes, showing areal variation in the overall lithologic character of a given stratigraphic unit. (8)

Lithologic map - A type of geologic map showing the rock types of a particular area. (8)

Lithology - (a) The description of rocks, especially in the hand specimen and in outcrop, based on such characteristics as color, mineralogic composition, and grain size. (8)

Lithostratigraphic unit - A body of rock that is unified by consisting dominantly of a certain lithologic type or combination of types, or by possessing other unifying lithologic features. (8)

Losing stream - A stream, or reach of a stream, that is losing water into the streambed and recharging the underlying aquifer. (1)

Low flow - The flow of a stream when less than an average minimum flow occurs for an indicated period of days, see base flow.

Low-flow frequency curve - A graph showing the magnitude and frequency of minimum flows for a time period of a given length. The frequency is generally expressed as the average interval, in years, between recurrences of an annual minimum flow equal to or less than shown by the magnitude scale. (2)

Marker bed - (a) A geologic formation serving as a marker, (b) "key bed." (8)

Materially damage the quantity or quality of water - With respect to alluvial valley floors, to degrade or reduce by surface coal mining and reclamation operations the water quantity or quality supplied to the alluvial valley floor to the extent that resulting changes would significantly decrease the capability of the alluvial valley floor to support agricultural activities. (9)

Mean discharge - The arithmetic mean of individual discharges during a specific period of time. (10)

Member - A lithostratigraphic unit of subordinate rank, comprising some specifically developed part of a formation. It may be formally defined and named, informally named, or unnamed. (8)

Micromho - The unit used in reporting specific conductance of water per centimeter at 25˚ C. (15)

Micron (un) - A unit of length that is equal to one-millionth of a meter; it is also known as a micrometer. (5)

Mine drainage - Surface-water and ground-water drainage from mines. Mine plan area - The area of land and water within the boundaries of all permit areas during the entire life of the surface coal mining and reclamation operations. (9)

Monocline - A local steepening in an otherwise uniform gentle dip. (8)

Node - A point within a digital ground-water model at which hydraulic properties, boundary conditions, and hydraulic head can be fixed, or referenced, in space.

Observation well - A special well installed in a selected location for the purpose of observing hydrologic variables, such as water levels, pressure changes, ground-water quality. (8)

Open-hole well - A well that is drilled and does not contain any casing, grouting, or other well construction features.

Overburden - Material of any nature, consolidated or unconsolidated, that overlies a coal deposit, excluding topsoil. (9)

Paludal - pertaining to a marsh. (8)

Particulate material - Material that is retained by a filter having a pore size of 0.45 micron. (4)

Perched ground water - Unconfined ground water that is separated from an underlying body of ground water by an unsaturated zone and by a confining bed (also called the perching bed).

–The perched zone of saturation may be either permanent, where recharge is frequent enough to maintain a saturated zone above the perching bed, or temporary where recharge is insufficient to prevent the perched water from disappearing as a result of drainage over the edge of or through the confining or perching bed. (1)

Perched water table - The water table of a body of perched ground water. (8)

Perching bed - A body of rock, generally having the form of a layer, bed, or stratum, that supports a body of perched ground water. Its permeability is sufficiently low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure. (8)

Percolation - The movement, under hydrostatic pressure, of water through the interstices of a rock or soil. (Does not include movement through large openings such as caves. (2)

Perennial stream - A stream, or part of stream, that flows continuously during year as a result of ground-water discharge or surface runoff. (9)

Permeability (intrinsic) - A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. (1)

Permit area - The area of land indicated on the approved map submitted by the operator with his or her application, required to be covered by the operator's performance bond …which shall include the area of land upon which the operator proposes to conduct surface coal mining and reclamation operations under the permit, including all disturbed areas,…(9)

Permittee - A person holding or required by the Act …to hold a permit to conduct surface coal mining (and underground mining) and reclamation operations issued by a State regulatory authority pursuant to a State program, by the Director pursuant to a Federal program, by the Director pursuant to a Federal lands program,… (9)

pH - A standard unit for expressing the hydrogen-ion concentration. It is defined as the negative logarithm to the base 10 of the hydrogen-ion concentration in gram-moles per liter. A pH of 7 is neutral, whereas values below 7 are acidic and values above 7 to the theoretical maximum of 14 are alkaline. More precisely, pH meters measure chemical activity rather than concentration of the hydrogen-ions; however, activity is equal to or nearly equal to concentration in dilute solutions. (5)

Phreatic water - A term that originally was applied only to water that occurs in the upper part of the zone of saturation under water-table conditions, but has come to be applied to all water in the zone of saturation. (8)

Phreatophyte - A plant that obtains its water from the zone of saturation or through the capillary fringe and is characterized by a deep root system. (8)

Porosity - The percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected. (8)

Potentiometric map - A map showing the altitude of a potentiometric surface of an aquifer by means of contour lines or other symbols. (8)

Potentiometric surface - An imaginary surface representing the total head of ground water and defined by the level to which water will rise in a tightly cased well. (8)

- The water table of an unconfined aquifer is a particular potentiometric surface. (1)

Precipitation - All forms of water particles, liquid or solid, that fall from the atmosphere and reach the ground. (8)

Precipitation event - A quantity of water resulting from drizzle, rain, snow, sleet, or hail, in a limited period of time; …also includes that quantity of water emanating from snow cover as snow melt in a limited period of time. (9)

Primary porosity - The "porosity " that developed during the final stages of sedimentation or that was present within sedimentary particles at the time of deposition. (8)

Probable hydrologic consequences (PHC) determination - A premining predictive estimate (by the operator) of the hydrologic impacts of the proposed mining operation.

- An analysis of the potential impacts of the proposed mining operation on the quantity and quality of ground water and surface yater under seasonal flow in the permit and adjacent areas.
- A predictive estimate of the potential impacts on the hydrologic balance. (9)

Public-water system - A system for the provision to the public of piped water for human consumption, if such system has at least 15 service connections or regularly serves an average of at least 25 individual daily at least 60 days out of the year. (9)

Pumpage - (a) The quantity or discharge of water, or other liquid, pumped, such as ground water. (8)

Pumping level - The water level in a discharging well.

Pumping test - see aquifer test.

Radius of influence - The radial distance from the center of a well bore to the edge of its area of influence. (8)

Rank (coal) - A generalized classification of coals according to degree of metamorphism, or progressive alteration, in the natural series from lignite to anthracite. (11)

Rating curve - See stage-discharge curve.

Recharge - The process involved in the absorption and addition of water to the zone of saturation; also, the amount of water added. (8)

Recharge area - An area in which water is absorbed that eventually reaches the zone of saturation in one or more aquifers. (8)

Recharge capacity - The ability of the soils and underlying materials to allow precipitation and runoff to infiltrate and reach the zone of saturation. (9)

Regolith - A general term for the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers the bedrock. (8)

Rib - The side wall of an outside entry in a coal mine. (11)

Rider coal - A thin, unminable coal found closely above a thicker, minable coal bed. Normally only a few inches thick. (11)

Rose diagram - A circular or semicircular star-shaped graph indicating values or quantities in several bearing directions, consisting of radiating rays drawn proportional in length to the value or quantity; some examples include a structural diagram for plotting strikes of planar features, or a 'histogram' of orientation data. (8)

Runoff - That part of the precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversions, storage, or other works of man in or on the stream channels. (2)

Salinity - A term describing water solutions containing dissolved mineral solids. The U.S. Geological Survey has assigned terms for degrees of salinity for waters with the following dissolved-solids concentration ranges (5):
slightly saline = 1,000 to 3,000 mg/L (milligrams per liter)
moderately saline = 3,000 to 10,000 mg/L
very saline = 10,000 to 35,000 mg/L
briny = over 35,000 mg/L

Sandstone - (a) A medium-grained clastic sedimentary rock composed of abundant rounded or angular fragments of sand size ($^1/_{16}$ to 2 mm) set in a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material (commonly silica, iron oxide, or calcium carbonate). The consolidated equivalent of sand, intermediate in texture between conglomerate and shale. (8)

Sandstone channel - A sandstone body that ranges in thickness from several inches to many feet and in length up to several miles and that cuts across structure and bedding of the enclosing rocks. Also called a clastic dike. (11)

Saturated thickness - see zone of saturation.

Secondary permeability - The permeability developed in a rock after its deposition or emplacement through such processes as solution or fracturing. (8)

Seepage measurements - Flow measurements made at various locations along a stream to determine whether or not a stream is losing or gaining water. (15)

Semiperched ground water - Unconfined ground water separated from a body of confined water whose hydrostatic level is below the water table by a low-permeability, but saturated, bed. (8)

Shale - A fine-grained detrital sedimentary rock, formed by the consolidation (especially by compression) of clay, silt, or mud. It is characterized by finely laminated structure that imparts a fissility approximately parallel to the bedding, along which the rock breaks readily into thin layers and that is commonly most conspicuous on weathered surfaces, and by an appreciable content of clay minerals and detrital quartz; a thinly laminated or fissile claystone, siltstone, or mudstone. (8)

'Shut-in' well - a tightly cased well is 'shut-in' when a valve, or other flow restricting device, is closed preventing discharge of fluids. A well is 'shut-in' to measure fluid pressures, which can be related to hydraulic properties of the aquifers tapped by the well.

Slug test - An aquifer testing method where a known solid volume—a slug of water or a sand filled pipe—is instantaneously injected into (or removed from) a well, and the decline of (or recovery of) the water level is measured at closely spaced intervals to determine hydraulic characteristics of the rocks penetrated by the well.

Sole-source aquifer - An aquifer that supplies 50 percent or more of the drinking water of an area, as defined by the U.S. Environmental Protection Agency. (14)

Solute - Any substance derived from the atmosphere, vegetation, soil, or rocks and is dissolved in water. (10)

Specific capacity - The rate of discharge of a well divided by the drawdown of the well; expressed as gallons per minute per foot of drawdown. Specific capacity is roughly proportional to transmissivity. (1)

Specific conductance - A measure of the ability of a water to conduct an electrical current. It is the reciprocal of the electrical resistance in ohms measured between opposite faces of a centimeter cube of an aqueous solution at a specific temperature. The standard measurement is expressed in microsiemens per centimeter at 25 degrees Celsius (°C), abbreviated uS/cm. The old units for specific conductance were micromhos per centimeter at 25 degrees Celsius, abbreviated µmhos/cm at 25°C. Specific conductance is related to the type and concentration of ions in solution and can be used to approximate the dissolved-solids concentration in water. Estimates of the dissolved-solids concentration, in milligrams per liter (mg/L), range from 60 to 85 percent of the specific-conductance value in uS/cm at 25°C. (5)

- For sulfate-type waters, the estimated range of dissolved solids concentration in milligrams per liter is from 90 to 100 percent of the specific-conductance value.

Specific discharge - The rate of discharge of ground water per unit area of porous media measured at right angles to the direction of flow. (1)

Specific storage - The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. (1)

Specific yield - The yield, or storage coefficient, of an unconfined aquifer, defined as the ratio of the volume of water which saturated rock or soil will yield by gravity to the total volume of the saturated rock or soil. (1)

Spoil - The overburden or non-coal material removed in gaining access to the coal or mineral material in surface mining. (9)

Spring - A place where ground water flows from a rock or soil upon the land or into a body of surface water. (3)

Stage-discharge curve (rating curve) - A graph showing the relation between the gage height, usually plotted as ordinate, and the amount of water flowing in a channel, expressed as volume per unit of time, plotted as abscissa. (2)

Static water level - The water level in a well which is in equilibrium with the ground-water flow conditions of the aquifer at the well; that is, when no water is being, or recently has been, taken from the aquifer either by pumping or by free flow. It is generally expressed as the distance from the ground surface (or from measuring a point near the ground surface) to the water level in the well; also, static head (12)

Steady flow - Occurs when, at any point, the magnitude and direction of the specific discharge are constant in time. (1)

Storage - In ground-water hydrology, storage refers to water naturally detained in a ground-water reservoir, to artificial impoundment of water in ground-water reservoirs, and to the water so impounded. (7)

Storage coefficient - see storativity.

Storativity - The hydraulic property of an aquifer that measures the volume of water an aquifer releases from or takes into storage per unit of surface area of the aquifer per unit change in head. (1) and (10)

- The storage capacity of an aquifer as described by the terms specific yield, effective porosity, coefficient of storage, and storage coefficient. (15)

Strata - plural of stratum. (8)

Stratigraphic classification - The arbitrary but systematic arrangement, zonation, or partitioning of the sequence of rock strata of the earth's crust into units with reference to any or all of the many different characters, properties, or attributes that the strata may possess. (8)

Stratigraphic map - A map that shows the aerial distribution, configuration, or aspect of a Stratigraphic unit or surface. (8)

Stratigraphic column - see geologic column. Stratigraphic section - see geologic column.

Stratigraphic sequence - A chronological succession of sedimentary rocks from older below to younger above, essentially without interruption. (8)

Stratigraphy - (a) The science of rock strata. It is concerned not only with the original succession and age relations of rock strata but also with their form, distribution, lithologic composition, fossil content, geophysical and geochemical properties and other characteristics and attributes of rocks as strata; also their interpretation in terms of environment or mode of origin, and geologic history. (8)

Stratum - A tabular or sheetlike body or layer of sedimentary rock, visually separate from other layers above and below; a bed. (8)

Stream - A general term for a body of flowing water. (2) Stream basin - see drainage basin.

Stream gaging - The process and art of measuring the depths, areas, velocities, and rates of flow in natural or artificial channels. (2)

Stream-gaging station - A location on a stream at which a record of stream discharge is obtained. Within the U.S. Geological Survey, this term is used only for those stream sites where a continuous record of discharge is obtained. (2)

Stream regimen - The system or order characteristics of a stream; … its habits with respect to velocity and volume, form of and changes in channel, capacity to transport sediment, and amount of material supplied for transportation.

- Term also applied to a stream which has reached equilibrium between erosion and deposition. (2)

Strike (structural geology) - The direction (bearing) or trend taken by a structural surface, such as a bedding plane or fault plane as it intersects the horizontal. (8)

Structure (geologic) - (a) The general attitude, arrangement, or relative positions of rock units within an area; the collection of the structural features within an area, reflecting past deformational processes as faulting, folding, and igneous intrusion. (8)

Structure contour - A contour line on a map that indicates the altitude of a structural surface, such as on the base or top of a formation, a formation boundary or a fault. (8)

Structure-contour map - A map that indicates the subsurface configuration by means of structure contour lines. (8)

Structure section - A vertical section that shows the observed geologic structure on a vertical or near-vertical surface, or, more commonly, one that shows the inferred geologic structure as it would appear on a vertical plane cutting through part of the earth's crust. (8)

Subsidence - (a) The sudden sinking or gradual downward settling of the earth's surface with little or no horizontal motion. (8)

- A sinking of part of the Earth's surface, such as may result from soil compaction, collapse of underground mines, or removal of ground water, oil or gas. (15)

Subsidence crack - A crack or joint in the rock formed or widened as a result of subsidence. (15)

Substantially disturbed - For the purposes of coal exploration, to impact significantly upon land, air, or water resources by such activities as blasting, mechanical excavation, drilling or altering coal or water exploratory holes or wells, construction of roads and other access routes, and the placement of structures, excavated earth, or other debris on the surface of the land. (9)

Surface mining activities - Those surface coal mining and reclamation operations incident to the extraction of coal from the earth by removing the materials over a coal seam, before recovering the coal, by auger coal mining, or by recovery of coal from a deposit that is not in its original geologic location. (9)

Surface water - Water on land surface, such as stream and lakes (as opposed to ground water). (2)

Syncline - A fold in which the core contains the stratigraphically younger rocks; it is generally concave upward. (8) Suspended material - see particulate material. (4)

Suspended residue - The material retained by a filter. (4)

Total material - The quantity of a given material present in an unfiltered water sample, regardless of the form or occurrence of the material. (4)

Total recoverable material - The total quantity of all dissolved forms of a given material plus that which is brought into solution and into an analytically determinable form, usually by means of an acid-digestion pretreatment or an acid-oxidation-digestion pretreatment of the sample. The exact conditions of the digestion pretreatment must be specified. (4)

Toxic forming materials - Earth materials or bedrock mine waste which are acted upon by air, water, weathering or microbiological processes and are likely to produce chemical or physical conditions in soils or water that are detrimental to biota or users of water. (9)

Toxic mine drainage - Water that is discharged from active or abandoned mines or other areas affected by coal exploration or surface coal mining and reclamation operations, which contains a substance that through chemical action or physical effects is likely to kill, injure, or impair biota commonly present in the area that might be exposed to it. (9)

Trace element - Any constituent, other than organic, of water that generally occurs in concentrations of less than one milligram per liter. (10)

Transgressive sediments - Sediments deposited during the advance or encroachment of water over a land area or during the subsidence of the land. (8)

Transmissivity - The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. (1)

Transpiration - The process by which water absorbed by plantsf usually through the roots, is evaporated into the atmosphere from the plant surface. (8) Uhconfined aquifer - see water-table aquifer.

Unconfined ground water - Ground water that has a free water table and is not overlain by a confining bed . . . (8)

Unconformity - (a) A substantial break or gap in the geologic record where a rock is overlain by another that is not next in stratigraphic succession, … - (b) The structural relationship between rock strata in contact, characterized by a lack of continuity in deposition and corresponding to a period of non-deposition, weathering, or especially erosion… prior to the deposition of the younger beds, and often (but not always) marked by absence of parallelism between the strata;…(8)

Unconsolidated materials - (a) Sediment that is loosely arranged or unstratified, or whose particles are not cemented together, occurring either at the surface or at depth, (b) Soil material that is in a loosely aggregated form. (8)

Underburden - the barren rock material underlying a mineral deposit; opposite of overburden; underclay is a special type of underburden.

Underclay - a layer of fine-grained detrital material, usually clay, lying immediately beneath a coal bed or forming the floor of a coal seam. (8)

Underground mining activities - A combination of

(a) surface operations incident to underground extraction of coal or in situ processing …
(b) underground operations such as underground construction, operation, and reclamation of shafts, adits, underground support facilities, in situ processing, and underground mining, hauling, storage, and blasting. (9)

Undifferentiated - Not separated into different formations or rock types.

Uniform flow - Specific discharge, at every point in the aquifer, that has the same magnitude and direction at any given instant in time. (1)

Unsaturated zone - The thickness of material between the land surface and the water table. (1)

Unsteady flow - Flow that results if the magnitude or direction of the specific discharge changes with time. (1)

Washout (mining) - A mass of shale, siltstone, or sandstone filling a channel in a coal seam that was cut into the coal swamp during the time of deposit ion. (8)

- A channel cut into or through a coal seam at some time during or after the formation of the seam, and generally filled in later by sand that later lithified into sandstone. (11)

Water budget - see hydrologic budget.

Water table - The upper surface of a zone of saturation where the body of ground water is not confined by an overlying impermeable zone. (9)

Water-table aquifer - An aquifer having a water surface at which the water pressure is atmospheric. (1) (see unconfined ground water.)

Well yield - The quantity of water pumped, or withdrawn, from a well per unit of time; for example, the number of gallons per minute. (7)

Zone of saturation - A thickness of rock or soil material in which all the interstices are filled with water under pressure greater than atmospheric. The upper surface of the zone of saturation is the water table. (7)

References for glossary of ground-water terms

(1) Lohman, S. W., and others, 1972, Definitions of selected ground-water terms - revisions and conceptual refinements: U.S. Geological Survey Water Supply Paper 1988, 21 p.

(2) Langbein, W. B. and Iseri, K. T., 1960, General introductions and hydrologic definitions, Manual of Hydrology: Part 1. General Surface-Water Techniques.: U.S. Geological Survey Water Supply Paper 1541-A, 29 p.

(3) Meinzer, O. E., 1923, Outline of ground-water hydrology with definitions: U.S. Geological Survey Water Supply Paper 494, 71 p.

(4) U. S. Department of the Interior, 1977a, National handbook of recommended methods for water-data acquisition: Geological Survey Office of Water Data Coordination.

(5) Roybal, F. E., and others, 1983, Hydrology of area 60, Northern Great Plains, and Rocky Mountain Goal Provinces, New Mexiso, Colorado, Utah, and Arizona: U.S. Geological Survey Open File Report 83-203, 80 p.

(6) Sobek, A. A., Schuller, W. A., Freeman, J. R., and Smith, R. M., 1978, Field and laboratory methods applicable to overburdens and minesoils: Cincinnati, Ohio, U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory; EPA-600/2-78-054; 204 p.

(7) U.S. Water Resources Council, 1980, Essentials of ground-water hydrology pertinent to water-resources planning: Washington, D.C., Bulletin 16(revised), 38 p.

(8) Bates, R. L., and Jackson, J. A., (eds.), 1980, Glossary of geology (2d): Falls Church, Va., American Geological Institute, 749 p.

(9) Code of Federal Regulations #30 Mineral Resources, March 13, 1979, Permanent Regulatory Program, and subsequent addendums (to March 31, 1984).

(10) Kuhn, Gerhard, Daddow, P. B., Craig, G. S., Jr., and others, 1983, Hydrology of area 54, Northern Great Plains, and Rocky Mountain Coal Provinces, Colorado, and Wyoming: U.S. Geological Survey Open File Report 83-146, 94 p,

(11) Mining engineering texts and U. S. Bureau of Mines references.

(12) Johnson Division, 1975, Ground water and wells(4th ed.): Saint Paul, Minn., Edward F. Johnson, Inc., 440 p.

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(15) Hobba, W. A., Jr., 1981, Effects of underground mining and mine collapse on the hydrology of selected basins in West Virginia: West Virginia Geological and Economic Survey Report of Investigations RI-33, 77 p.

(16) Lapedes, D. N., ed., 1974, Encyclopedia of environmental science: New York, N. Y., McGraw-Hill Book Company, 754 p.

(17) Lattman, L. H. ,and Parizek, R. R., 1964, Relationship between fracture traces and the occurrence of ground water in carbonate rocks: Jour. Hydrology, v. 2, p. 73-91.

XIX. EXAMPLES OF GROUND-WATER INFORMATICS TO BE INCLUDED IN COAL-MINE PERMIT APPLICATIONS

Preface - MANDATORY READING

How does the applicant combine the various types of ground-water information presented in this manual, and listed below, to describe the geohydrologic conditions for the permit area? What are the formats for presenting the information suggested by the regulatory authority including:

- geologic map and cross sections
- driller's logs
- inventory of wells, springs, and streams
- potentiometric and water-table maps
- directions of ground-water flow
- water-level variations in aquifers
- aquifer test - drawdown, recovery, and slug test data
- low-flow stream data
- water-quality chemical results for ground water and streams
- ground-water pumpage information
- ground-water monitoring plan
- ground-water model and projected hydrologic impacts.

This chapter addresses these questions by demonstrating the use of maps, graphs, cross sections, and tables and interpreting the data. These examples supplement the illustrations and tables given in the previous chapters and are similar to documents prepared by the mining company, or its representative, to satisfy the requirements of the regulatory authority for the ground-water aspects of a permit application. The examples are taken from reports on geohydrologic investigations in several coal provinces of the United States; thus, the reader should infer NO relationship between the maps, graphs, cross sections, and tables of the various subunits unless so indicated.

The relationship between the tables and illustrations in this chapter, and other chapters, and the regulation categories and the ground-water investigation activities is shown in table XIX 1.1. The activities column includes the work tasks necessary to define the geologic and hydrologic settings (chapters IV and VI), the potential impacts of the proposed mining operation on the aquifer system(s) (chapter XIII), and the postmining hydrologic monitoring.

Note that strict adherence to the format of these examples DOES NOT GUARANTEE PERMIT APPROVAL by the regulatory authority because regulations differ among the States. Note also that the applicant need not adhere strictly to the size or formats illustrated in this chapter. (The maps and illustrations herein were scaled to publication size, and no attempt was made to address the map-scale requirements of the regulatory authorities.)

Table XIX 1.1 – Illustrations and tables that serve as examples to partially satisfy regulation requirements.
[F= figure; Fs= figures; T=table; Ts=Tables.]

Note: the chapter prefix number XIX has not been included in this table for simplicity, for example, fs.3.4,4.4 refer to figures XIX 3.4 and XIX 4.4; however, other chapter numbers have been included, for example , Ts.VII-2, 3.1 refer to tables VII-2 and Vi-3.1.

GROUND-WATER INVESTIGATION ACTIVITIES (Presentations are in the form of figures and tables.)	REGULATION CATEGORIES						
	Description of hydrology	Ground-water information	Surface-water Information as related to ground water	Alter-native water-supply infor-mation	Cross sections, maps and plans	Protection of hydrologic balance	Operation plan
2. Geologic Setting							
Discussion of Geology and the Occurrence of Coal		f.3.4	f.3.4		fs.3.4,4.4		
Geologic Map and Cross Sections	fs.2.1,2.2				fs.2.1,2.2		
Driller's Log; Stratigraphic Col.	T.2.1				fs.VIII-1,2		
Structural Geology:					fs.X-3.0-2, X-3.0-4,		
Bedrock fractures(joints)					f.IV-7,		
Faults, fracture zones, and fracture traces					fs.XIV-2,3		
3. Hydrologic Setting							
Location, Climate, & Topography	fs.1.1,3.2,3.3	f.3.7					
Occurrence & Movement of Ground Water	f.4.4	T.3.2 f.3.7			f.3.2	T.3.2	
Well & Spring Inventory Table	T.3.1	Ts.VII-2,3.1		T.3.1		T.3.1	
Well & Spring Location Map					fs.VII-1,3.1		
Well Hydrograph		f.3.3				fs.XIII2-4,3.3	
Aquifer Test Information/Hydraulic Properties of Aquifer(s)		T.3.3			f.3.4	f.3.6	f.3.6
- graphical plot & tabulation of data	fs.4.1,4.4	f.3.5					
Base-Flow Discharge		f.3.7	fs.3.7-3.9	f.VII-1	f.3.8	f.3.9	
-tabulation & plotting of data			Ts.3.4,3.5			Ts.3.4,3.5	
Water Quality							
Ground water		Ts.VII-3,XII-2					
Surface water (base flow)			T.XII-2				
- tabulation & plotting of data			fs.3.8,XII-4				
Ground-Water Use		T.3.6		T.3.6	f.VII-1		
Ground-Water Monitoring Plan		Ts.IX-1,3.7 f.XIII 2-4			f.XIV-1	Ts.3.1, XIV-4,XIV-5	fs.XIII 2-4, XIV-1
4. Potential Impacts on Hydrologic System							
- Ground-Water Level Decline	fs.4.1-4.6	fs.4.1-4.6			fs.4.1-4.5	fs.4.1-4.6	
- Change in Ground-Water Storage and Modification of Ground Water-Surface Water Interrelationship					fs.XIII-3-1, XIII-3-2		
- Ground-Water Quality Modification					T.XIII-4-2 f.XIII-4-3		
- Overburden Analysis	f.4.7					f.4.7	f.4.7
5. Postmining Hydrologic Monitoring							
Ground-Water Monitoring plans	fs.5.2-5.4	fs.5.1-5.4			fs.5.1-5.4	fs.5.1,5.4	fs.5.1,5.4

1. INTRODUCTION

The following is selected information that might be included in the introduction chapter of a permit application describing the location of the permit site, the topography, and climate. (The emission of State designation is intentional to give the examples an apolitical unbiased presentation.)

Location

The proposed surface-mine permit area is in the James Fork watershed, which is tributary to the Polk River within Le Flore County and the Roosevelt coal field of the Interior coal province (fig. XIX 1.1). The permit area is also within the Drake gas field. The 96.4 acre tract is 0.6 miles east of the community of Williams and 0.4 miles north of James Pork, within section 14 of Township 1 North and Range 2 West.

Topography

The topography of the permit site is rolling as shown in the geologic map (fig. XIX 2.1) and the geologic sections (fig. XIX 2.2). The local relief within the adjacent area is less than 150 ft, and the area is characterized by narrow hogbacks, or ridges, and irregular hills generally capped with erosion-resistant sandstone. The broad valleys between the hogbacks have been formed by weathering and the erosion of the thick, easily eroded shales.

Climate

The climate in the coal field area is warm and temperate. Spring and autumn are usually mild, and summer is hot. Winter is comparatively mild, although an occasional outbreak of cold air keeps the temperature below freezing for about 7 days each year, on the average. Average annual precipitation ranges from 39 to 45 inches; an average of 35 percent of the year's total moisture falls in the spring, 27 percent in summer, 23 percent in autumn, and 15 percent in winter. January is the driest month, and May is the wettest. The hydrograph in the next section (fig. XIX 3.3) illustrates the correlation between rainfall and water level in an observation well in the permit area. Average annual lake evaporation is about 53 inches.

Much of the rainfall results from short-duration thunderstorms of varying intensity. Although such storms are most common in April, May, and June, they may occur any month of the year because of these storms are localized. Precipitation can vary significantly over short distances.

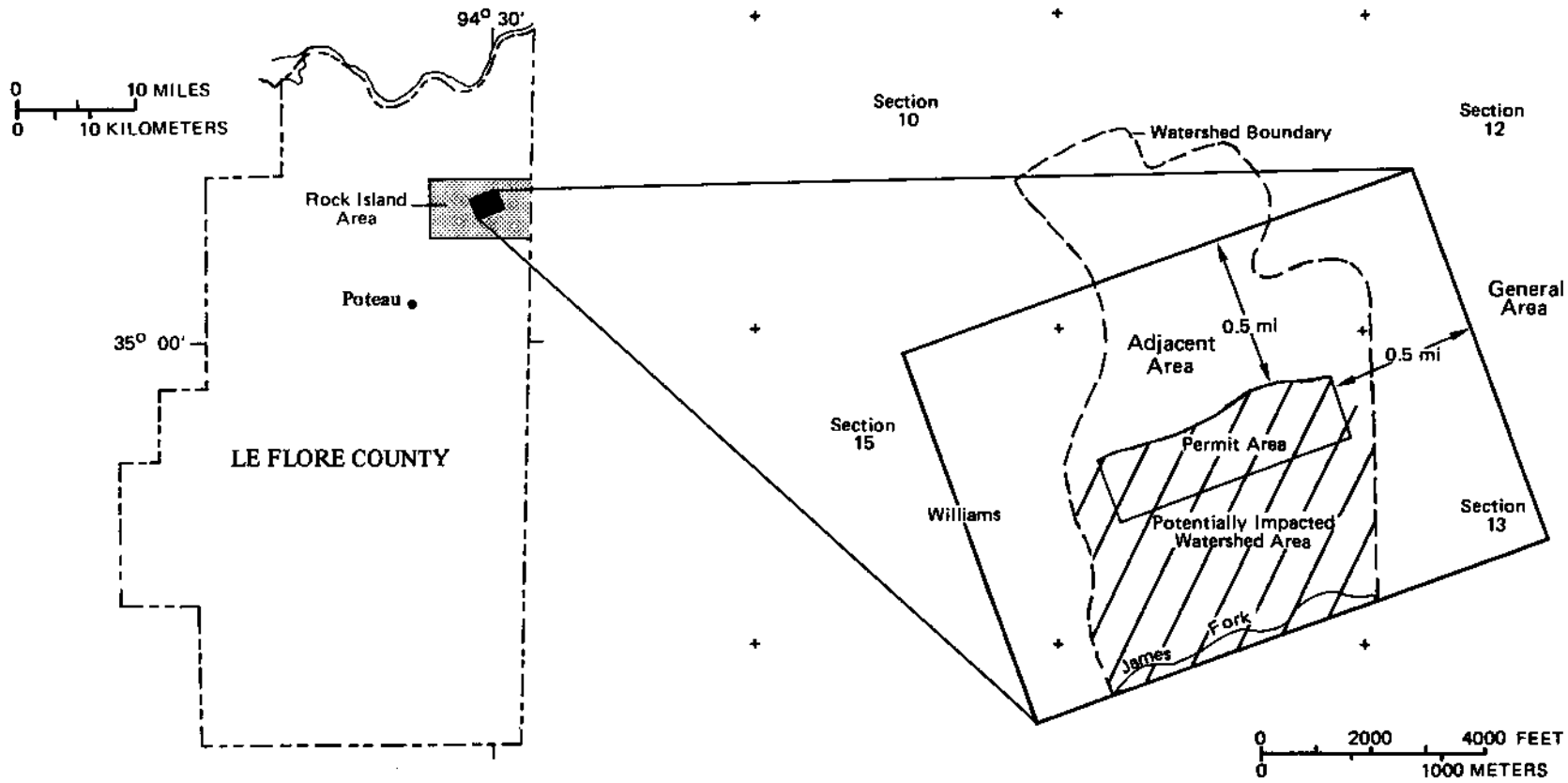


Figure XIX-1.1-1.—Example of permit-area location map.

2. GEOLOGIC SETTING

Geologic information on the general area was compiled from field mapping, log interpretation of the drill/core holes from the exploratory program, water-well information, and results of a geologic literature search.

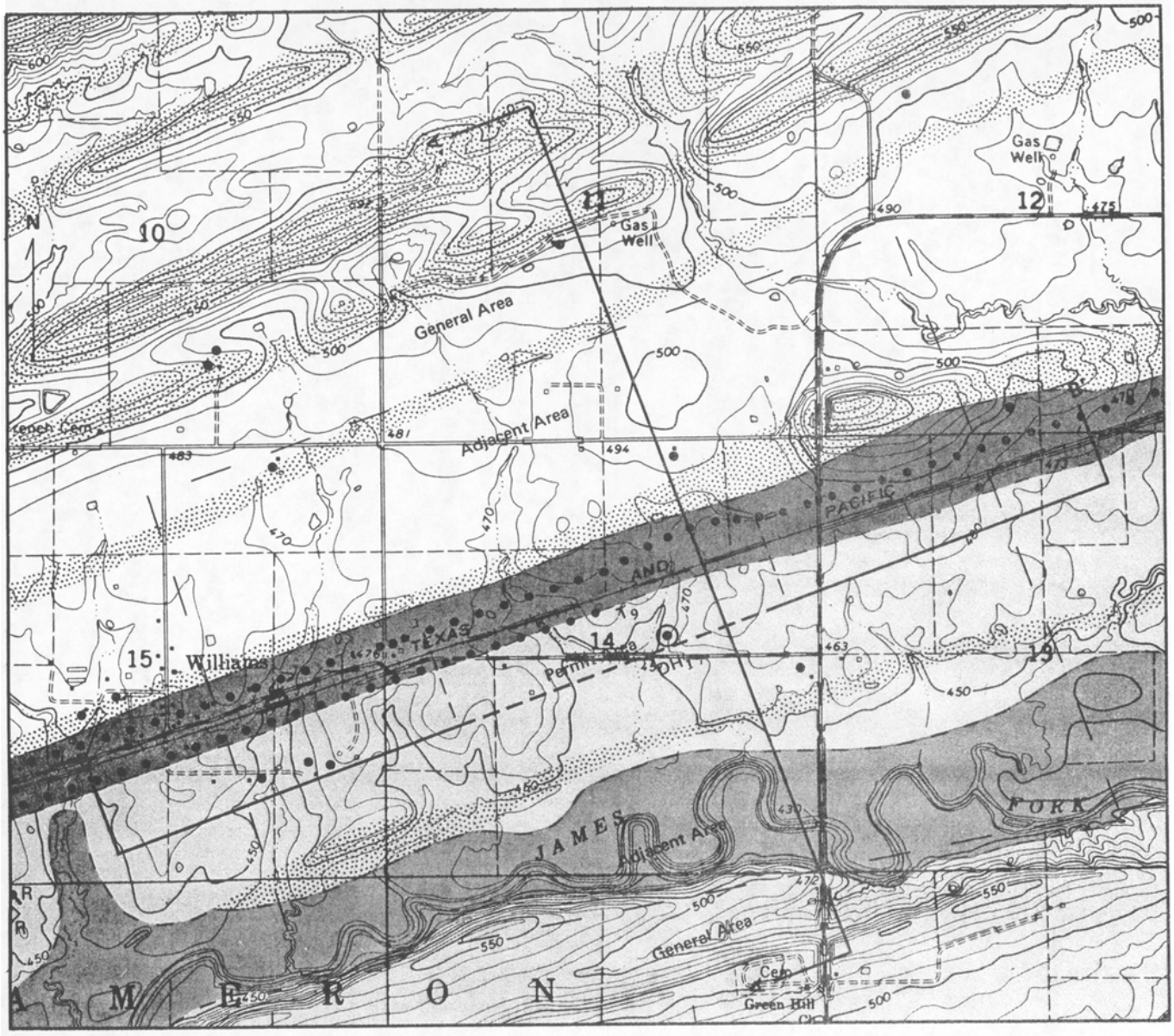
Bedrock in the general area consists of interbedded siltstone, shale, and sandstone units of the McAlester, Hartshorne, and Atoka Formations (fig. XIX 2.1). About 70 percent of the bedrock is shale and siltstone. The Hartshone coal beds occur in the Hartshorne Formation, vary in thickness from 2 to 4 ft, and have potential for surface mining.

The permit area lies on the southern flank of the east-west-trending Backbone anticline, which is broken along its crest 1.8 mi. north of the permit area by the Backbone thrust fault. The rock layers dip to the south. The dip steepens from 5° to 10° near James Fork to 35° to 45° along the crest of Backbone Mountain. The dip of the Hartshorne coal is probably 10° to 15°, as inferred from measurements on the underlying Hartshorne sandstone, shown in the geologic cross sections in figure XIX 2.2. Bedrock fractures parallel and across the bedding and were formed during formation of the anticlinal structure. The depth of the weathered rock is variable and is saturated. Fractures beneath this weathered zone are the major source of ground water to springs and wells. Layers of sandstone are silty, fine grained, and cemented with silica and iron oxide.

The alluvium along James Fork may be as much as 30 ft thick, is absent along some of the reaches, where the stream flows directly on bedrock. The upper part of the alluvium consists of sandy and clayey silt; and the lower part may include beds of silty sand. James Fork in the general area is a gaining stream, that is, the low flow of James Fork is predominantly ground-water discharge.

The geologic setting of the permit area is classified as GS-4 because of the gently dipping (10° to 15°) sedimentary strata, as shown in figure XIX 2.2. Surface mining will proceed until the height of the high wall is about 150 ft. The mining operation will then proceed parallel to the strike of the outcrop.

Exploratory drill hole 17 was drilled in T 1N R 2W section 14 SE¼; the log is presented in table XIX 2.1. This log and other geologic information indicates that the shale beds confine the sandstone aquifer of the Hartshorne Formation. However, the thickness of the shale and siltstone beds are probably insufficient to prevent ground-water discharge into the proposed excavation. (A preliminary estimate of the hydrologic-setting classification for the coal bed is F(l), where the coal bed will act as a confined aquifer since it is probably in hydraulic connection with the underlying confined sandstone aquifer.)

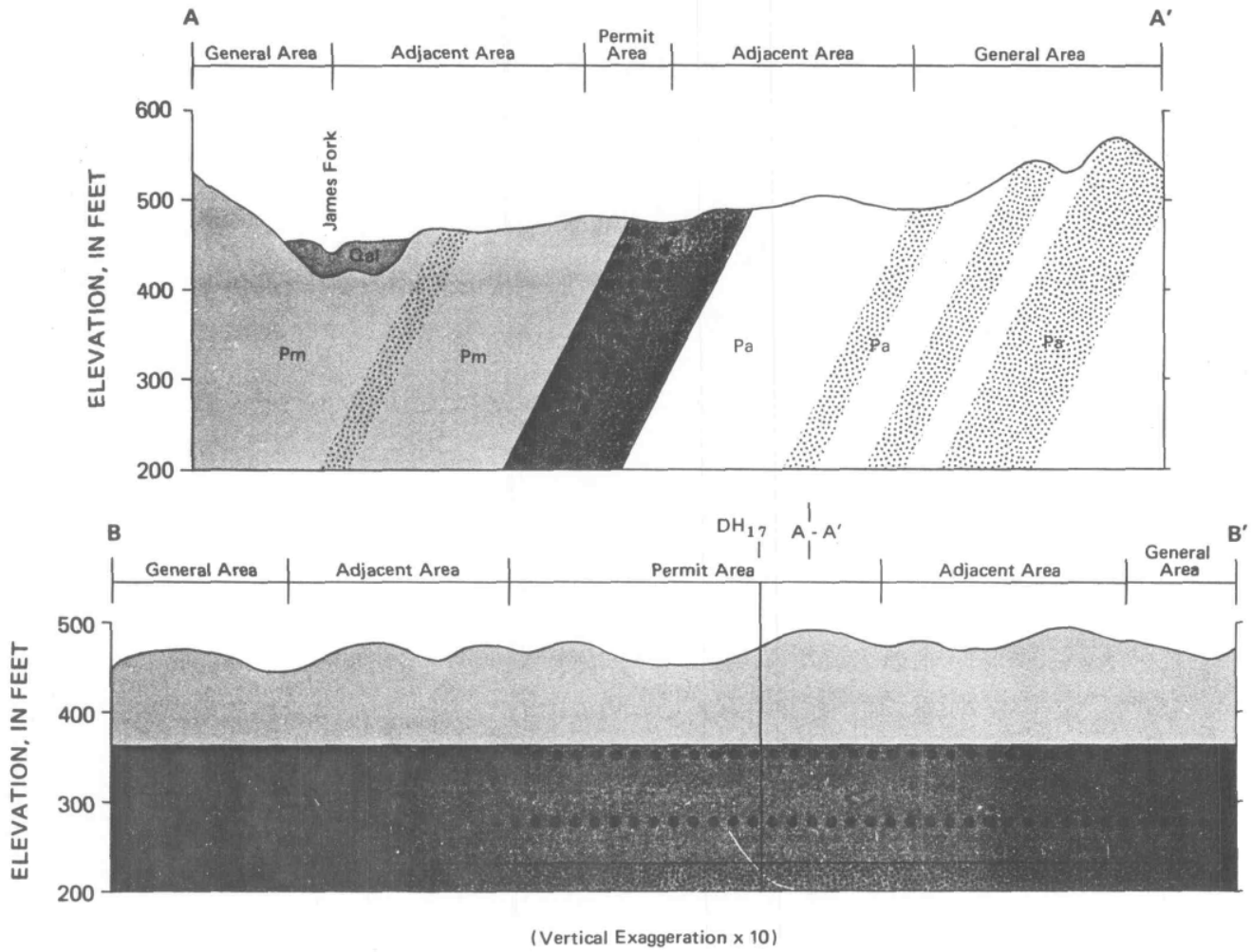


EXPLANATION

Qal	Alluvium - unconsolidated deposits, sandy and clayey silt overlying silty sand.
Pm	McAlester Formation - interbedded sandstone, siltstone, and shale.
Ph	Hartshorne Formation - shale and sandstone with commercial - grade coal - Upper and lower Hartshorne coals shown by dots.
Pa	Atoka Formation - interbedded shale, sandstone and shale.

(Major sandstone units shown by stipple pattern; shale units not patterned.)

Figure XIX-2.1.— Example of geologic map of permit area, adjacent area, and general area. (Modified from Marcher and others, 1983, pl. 1)



EXPLANATION

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Pa	Atoka Formation - interbedded shale, sandstone and shale.
	(Major sandstone units shown by stipple pattern; shale units not patterned.)
——	Geologic contact approximately located
T_9	Direction of strike and number of degrees of dip.

Figure XIX-2.2.— Example of geologic sections through permit area, adjacent area, and general area. (locations are shown in fig. XIX-2.1.)

Table XIX 2.1 - Drillers log of drill hole 17 (DH 17).
(From Marcher, U.S. Geological Survey, 1981, personal communication.)

[ft, feet.]

Latitude:42°42'42"	Aquifer: Hartshorne Formation
Longitude: 100°00'100"	Date Drilled: August 20, 1965
Land-surface altitude(LSD): 461 ft	Well Depth: 277.0 ft
Depth to water below LSD and date of measurement:	10 ft (October 4, 1965)

Lithologic description	Thickness (ft)	Depth (ft)
McAlester Formation		
Shale, decomposed to very intensely weathered	7.5	7.5
(saturated material at base of weathered zone) (no sample)	4.5	12.0
Shale, clayey, 10 to 20 percent silty interbeds	76.7	88.7
Siltstone, 25-35 percent shale interbeds	15.2	103.9
Hartshorne Formation		
Shale, carbonaceous, silty to clayey	11.9	115.8
Siltstone, 25 percent interbedded clayey shale	22.7	138.5
Shale, carbonaceous	0.7	139.2
Siltstone, 25 percent interbedded clayey shale.	52.2	191.4
Shale, carbonaceous	0.4	191.8
Coal	2.7	194.5
Shale, carbonaceous	0.9	195.4
Siltstone, 25 percent interbedded clayey shale	2.7	197.2
Sandstone, fine-grained, 20-30 percent fine grained silty shale. (water encountered during interval 198 to 230 feet and rose to 10 feet below land surface)	31.9	229.1
Shale, silty,20-30 percent fine grained sandstone	22.7	251.8
Sandstone, fine-grained, 5 percent shale	12.1	263.9
Shale, silty, 20-30 percent fine grained sandstone	13.1	277.0

3. HYDROLOGIC SETTING

Ground-Water Hydrologic Data Inventory

For a geographic area that is different than the area shown on figures XIX 2.1 and 2.2, well and spring inventory information were provided by the State Engineer's Office, from the drillers' water well completion reports, by the U.S. Geological Survey, by the State Geological Survey, and by the State Department of Health. Part of these reported data are shown in table XIX 3.1. Other wells within the permit area and general area ware visited and included table XIX 3.1. This table contains information necessary to define the premining hydrologic conditions, such as well depth, depth to water, driller's test well yield, duration of test, specific capacity, length of well casing, and aquifer(s) providing water supply. Other types of well information available on the government completion reports (not included in table XIX 3.1) include latitude and longitude, screened intervals, drilling method, topographic setting, driller's log, minor aquifer(s), depth to bedrock, and depth and yield of individual water-bearing zones.

Wells referred to in table XIX 3.1 are plotted on a planimetric map (fig. XIX 3.1), which also shows the locations of springs, test holes, the permit area, and the surface-water sources (creeks, lakes and reservoirs).

Integrating the ground-water information with the geologic formation information yields a definition of the aquifer groups and the confining beds, such as depicted as a stratigraphic section in figure VIII-2. The upper (first) aquifer group is the bedrock overlying the Lower Freeport coal, which is beneath the hilltops; the second aquifer group is between the Lower Freeport coal and the confining bed (the Logan Formation); and, the third aquifer group is the Black Hand Sandstone Member of the Cuyahoga Formation.

The specific capacity values given in table XIX 3.1 indicate a wide range of water-yielding capability within the aquifer groups. The unconsolidated deposits of the Quaternary alluvium has the greatest ground-water availability, however.

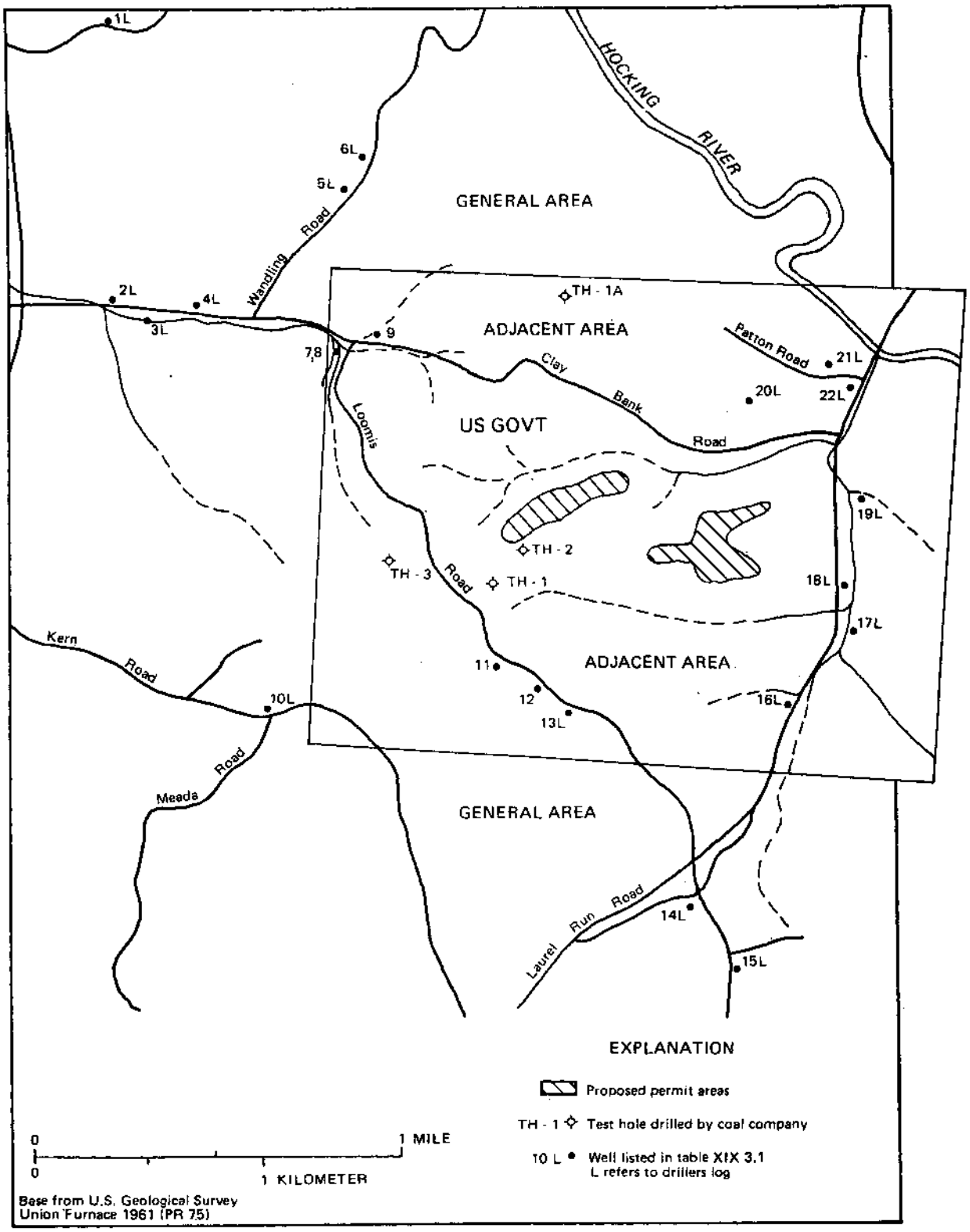


Figure XIX-3.1.— Example of planimetric map showing locations of inventoried wells, test toles, streams, roads, and proposed permit area. (Modified from Norris, 1981, p. 25)

Table XIX 3.1 – Example of records of representative wells in and near the permit area. (Modified from Norris, 1981, table 1)

[ft, feet; gal/min, gallons per minute; Qal, Quaternary alluvium; *, water-quality sample analyzed; —, no data.]
[Well locations are shown on figure XIX 3.1. Suffix 'L' after well number refers to the driller's log in Appendix of Morris reference.]

Well number	Owner	Altitude of land surface (ft)	Depth of well (ft)	Aquifer group (See fig. VIII-2)	Date drilled (month, day, year)	Well yield (gal/ min)	Specific capacity (gal/min per ft of drawdown)	Duration of driller's test (hours)	Depth to water (ft)	Date of measure-ment	Length of casing
1 L	United Presbyterian Church	905	497	3	5-20-72	10	0.022	3	290		297
2 L *	Owen Peck	760	253	3	2-19-76	5	.067	2	51	4-10-79	67
3 L	Paul Bentley	760	250	3	5-30-64	1.3	—	0.5	48		57
4 L	Franklin Cherry	760	200	2	11-14-59	.5	.002	—	12		30
5 L *	William Snyder	960	68	2	7- 6-60	4	—	—	52		29
6 L	W. J. Reams	1005	47	1	8-18-60	20	1.3	2	20		24
7 *	Carl Loomis	810	200	2	49	.5	—	—	83	4-10-79	21
8 *	Carl Loomis	810	205	2	76	1.5	—	—	50	4-10-79	45
9	Hazel Michel	820	240	2	—	—	—	—	—		—
10 L	Roger Campbell	1020	442	2	9-11-72	3	—	—	—		143
11 *	Willard Sowers	1010	36	1	—	—	—	—	13.5	4-30-79	—
12	unknown	1045	565	3	—	—	—	—	—		—
13 L *	Max Malone	985	535	3	—	—	—	—	—		—
14 L	Leonard Dickerson	990	61	1	6-23-65	30	.70	.5	18		35
15 L	Mary Woodyard	1040	150	2	10- 2-68	2	—	—	40		40
16 L	William Seal	780	94	2	12-23-72	70	7.0	24	31.7	4-24-79	50
17	C. J. Baumgardner	660	49	Qal	—	—	—	—	4	4-24-79	49
18 L	Mrs. Hairy Todd	750	157	2	6-26-67	3.5	.026	—	20		40
19 L	Charles Wood	745	125	2	1- 5-65	—	—	—	28		30
20 L	Robert Price	790	27	Qal	5-24-78	10	.45	1	5		27
21 L	Claude Brandon	915	46	Qal	5-31-66	25	.83	1	1		46
22 L *	Richard Ansel	695	34	Qal	5-24-78	2	.20	2	12	4-24-79	36

Determination of Hydrologic Setting (s)

In reference to the permit area shown in figures XIX 1.1, 2.1, and 2.2, ground water is under water-table conditions in the shallow (less than 10 ft) weathered bedrock zone and is artesian in the Hartshorne sandstone. Below the weathered zone, the interbedded shale and siltstone of the McAlester Formation and within the Hartshorne Formation are the confining beds that restrict recharge to the Hartshorne sandstone. The saturated thickness of the weathered zone is generally thin and locally variable and is an insignificant factor in the water resources of the area. Domestic pumpage in the area surrounding the proposed permit area is from the Hartshorne sandstone aquifer and from the alluvium of the James Fork. Recent water-levels in the Hartshorne sandstone aquifer within the area are given in table XIX 3.2. Artesian pressure causes water levels in the wells tapping this bedrock unit to rise; the water level in most of the area is less than 20 ft below land surface. A few wells in favorable topographic locations have artesian flow during part of the year; wells have to be "shut in." A potentiometric map shaving the water surface of the confined aquifer, by means of contour lines, is shown in figure XIX 3.2. The general direction of ground-water flow in the sandstone aquifer is from north to south toward James Fork.

About 60 percent of the precipitation in this area falls during spring and sunnier, but water level measurements show that little recharge takes place at that time because most of the water is lost by evapotranspiration before it can reach the saturated zone. The observation-well hydrograph in figure XIX 3.3 indicates that the ground-water level is lowest in autumn or winter and is highest in early spring.

The determination of the hydrologic-setting of the permit area depends upon the position of the coal bed(s) to be mined relative to the aquifer(s), the thickness and impermeability of the confining beds, and the ground-water flow conditions in the aquifer(s). The hydrologic-setting classification could be:

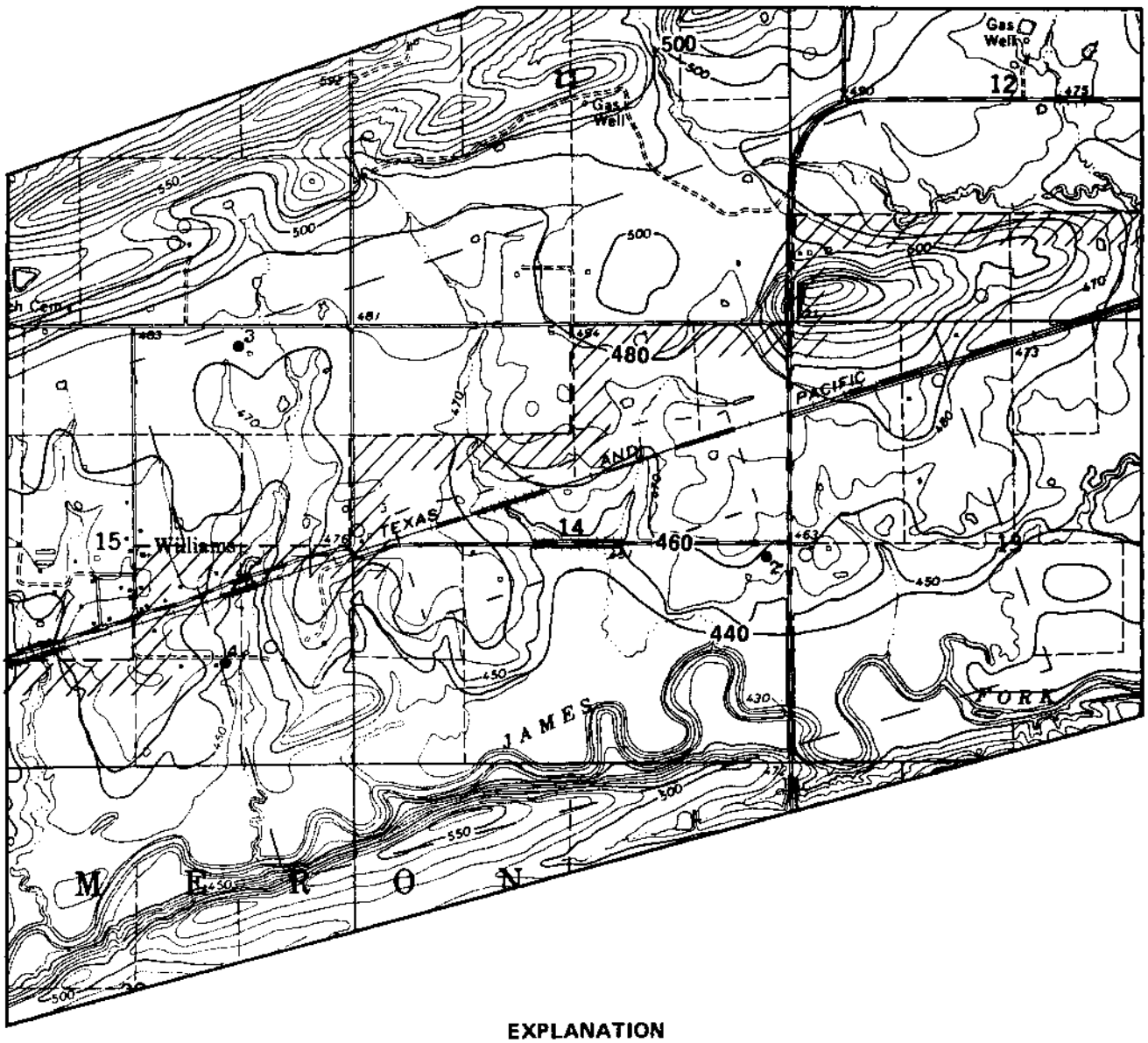
(a) HS-E, where the coal bed at the outcrop is in contact with weathered bedrock and is under water-table conditions;

(b) HS-B(2), where the coal bed(s) are separated from the confined aquifer by impermeable shale and siltstone beds, and the excavation would be dry; or

(c) HS-D, where the coal bed(s) are in hydraulic contact with the sandstone aquifer (figs. XIX 2.1, 2.2), via thin shale beds and bedrock fractures, and the excavation would be wet; or

(d) HS-F(l), where the coal bed(s) are aquifers owing to the fracture permeability and the infiltration of ground water from the coal outcrop area. Here the excavation would be wet.

The amount of ground-water infiltration into the excavation depends upon the hydraulic properties of the aquifer(s).



EXPLANATION

— 400 — Approximate potentiometric contour - Shows altitude at which water levels would have stood in tightly cased wells (1976). Contour interval 20 feet. Datum is sea level.

○ Well - See table 1 of Marcher and others, 1983.

Observation well equipped with a recorder. - D, discontinued

● 2 Well for which a chemical analysis of the water has been made. Number refers to trilinear diagram.

◉ Drill hole and number

Area of federally - owned coal

Figure XIX-3.2.— Example of potentiometric map and location of data-collection sites within the permit area, adjacent area, and general area. (Modified from Marcher and others, 1983, pl. 2)

Table XIX 3.2– Sample compilation of water-level elevations of wells within the permit and surrounding areas, February, 1978.
(Modified from Marcher and others, 1983)

[ft, feet; —, no data; Pa, Pennsylvanian Atoka Formation; Ph, Pennsylvanian Hartshorne Formation; Pm. Pennsylvanian McAlester Formation.]

Well no.	Location (township, range, section, ¼¼¼*)	Aquifer	Well depth (ft)	Land-surface elevation (LSE) (ft above sea level)	Depth to water below LSE (ft)	Water-surf ace elevation (above sea level)
**	T 1N R 2W sec. 10 SESWNW1	Pa	27	510	10.1	500
**	T 1N R 2W sec. 10 SESWNW2	Pa	102	521	1.0	520
**	T 1N R 2W sec. 11 SWNENE	Pa	56	525	14.4	511
**	T 1N R 2W sec. 12 NWSWSW	Pa	—	505	3.8	501
1	T 1N R 2W sec. 12 NWNWSE	Pa	80	502	flowing	502+
**	T 1N R 2W sec. 12 SWSESE	Pa	—	490	5.3	485
**	T 1N R 2W sec. 13 NWNESW	Ph	—	490	flowing	490+
**	T 1N R 2W sec. 13 SWNWNW	Pm	—	470	15.3	455
**	T 1N R 2W sec. 14 NENWNE	Pa	—	492	10.0	482
**	T 1N R 2W sec. 14 NESWSE	Ph	277	461	0.9	460
**	T 1N R 2W sec. 14 NWSWSW	Ph	106	476	11.1	465
**	T 1N R 2W sec. 14 SWNWNW	Ph	106	465	8.4	457
2	T 1N R 2W sec. 14 SENENE	Pm	62	465	7.2	458
3	T 1N R 2W sec. 15 NENWNE	Pa	89	473	10.9	462
**	T 1N R 2W sec. 15 SWNENE	Pa	70	455	13.3	442
**	T 1N R 2W sec. 15 SWNESW	Ph	166	450	12.2	438
4	T 1N R 2W sec. 15 SESWNE	Ph	109	449	12.1	437
**	T 1N R 2W sec. 15 SENESW	Ph	125	447	8.0	439
**	T 1N R 2W sec. 22 NWNWNW1	Pm	78	458	15.8	442
5	T 1N R 2W sec. 22 NWNWNW2	Pm	40	459	16.1	443

* read in the standard U. S. Bureau of Land Management's system of land subdivision: quarter-quarter-quarter section (located to the nearest 10 acres); for example, the well in section 13 NWNE9W is located in the northwest-quarter section, and in the northeast-quarter of this 160 acres, and in the southwest-quarter of this 40 acres.

** wells shown in figure XIX 3.2 (potentiometric map), but with no assigned number.

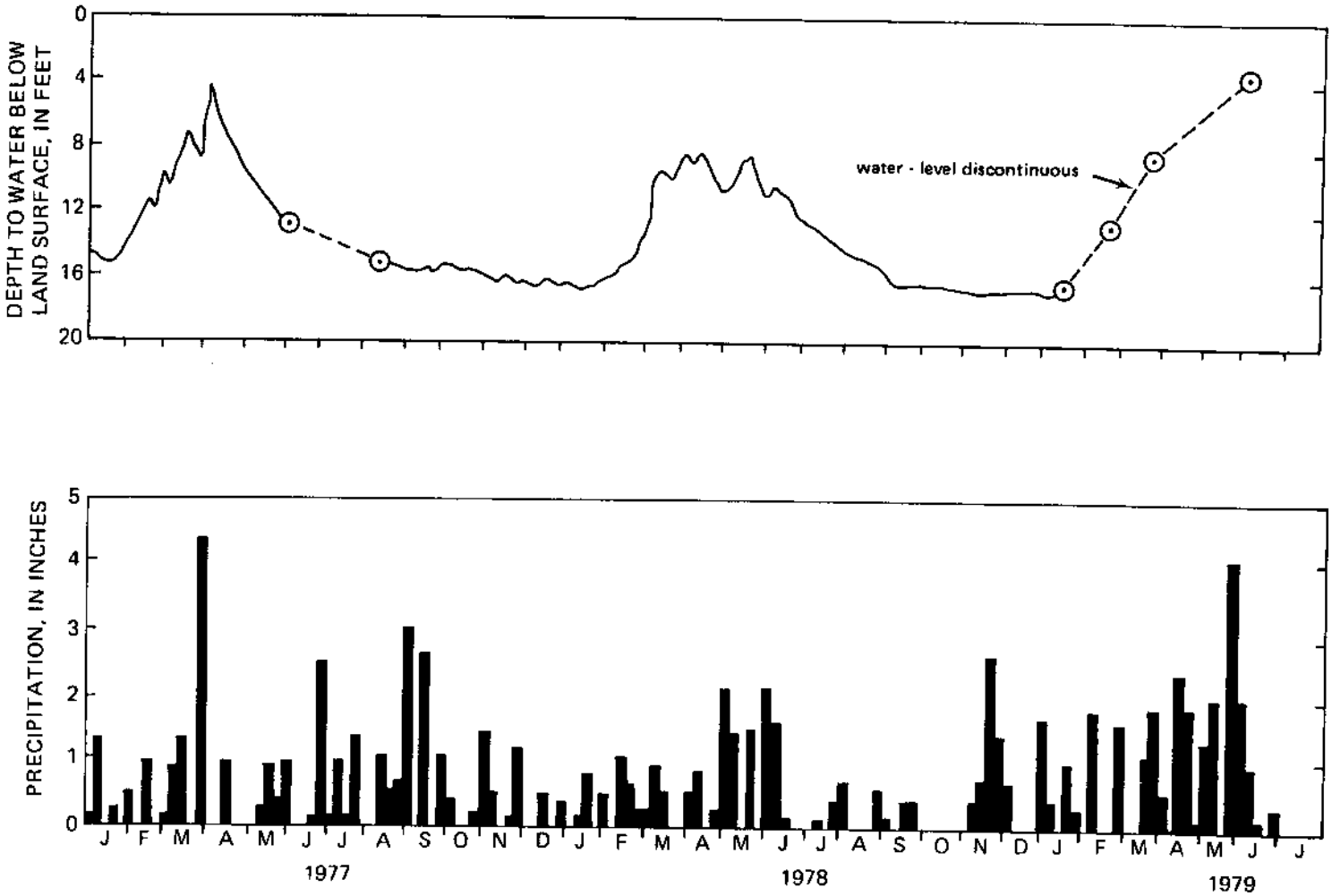


Figure XIX-3.3.— Example of water-level hydrograph of well (08N-26E-22 BBB 2) as related to precipitation.
(From Marcher and others, 1983, fig. 2)

Aquifer-Test Results

The initial hydrologic setting classification during the surface mining operation was HS-E, where the coal bed is saturated and in contact with the water-table aquifer of weathered McAlester Formation (figure XIX 3.2). After excavation of the overburden, the ground-water discharge from the weathered zone into the excavation will diminish significantly. With the unfractured bedrock formations, the hydrologic setting is possibly HS-D.

The rate of ground-water discharge into the excavation is controlled by the hydraulic properties of the aquifer units—transmissivity (T), storativity (S), and hydraulic conductivity (K). The hydrologic consequences of the dewatering are a lowering of the water table and potentiometric surface. The rate and extent of drawdown can be predicted after the aquifer properties have been calculated.

A pumping test on the Hartshorne sandstone aquifer was done at a flowing well that was converted from an exploratory core hole. Perforated casing was installed in the bottom 68 ft of the hole, which taps a sandstone aquifer, as shown on figure XIX 3.4. The constant-drawdown analysis of Jacob and Lohman (1952) was used, where discharge varies with time. This analysis can be used for testing period where the function u is less than or equal to 0.01. When the naturally flowing well has been 'shut in' for a sufficient time to represent equilibrium ground-water conditions, it is opened for a time during which flow-rate measurements are made at specified time intervals. The assumptions are that the aquifer is homogeneous, isotropic, and extensive laterally and that T and S are constant at all times and places. (Additional information on the method is available from Lohman, 1972, p. 23, and U.S. Department of Interior, 1981, p. 130.)

The pumping test data are listed in table XIX 3.3; the data plot and calculations are presented in figure XIX 3.5. Using equation X-2.3-2, table X-2.3-2, and given the T and S results, the u test, for the valid time period (t), is

$$t = \frac{r^2 S}{4 Tu} = \frac{7.48 (0.49)^2}{4 (1800)} \frac{(0.002)(1440)}{(0.01)} = 0.07 \text{ minutes} \qquad \text{XIX-1}$$

Thus, the aquifer test is valid for the testing period greater than 0.07 minutes.

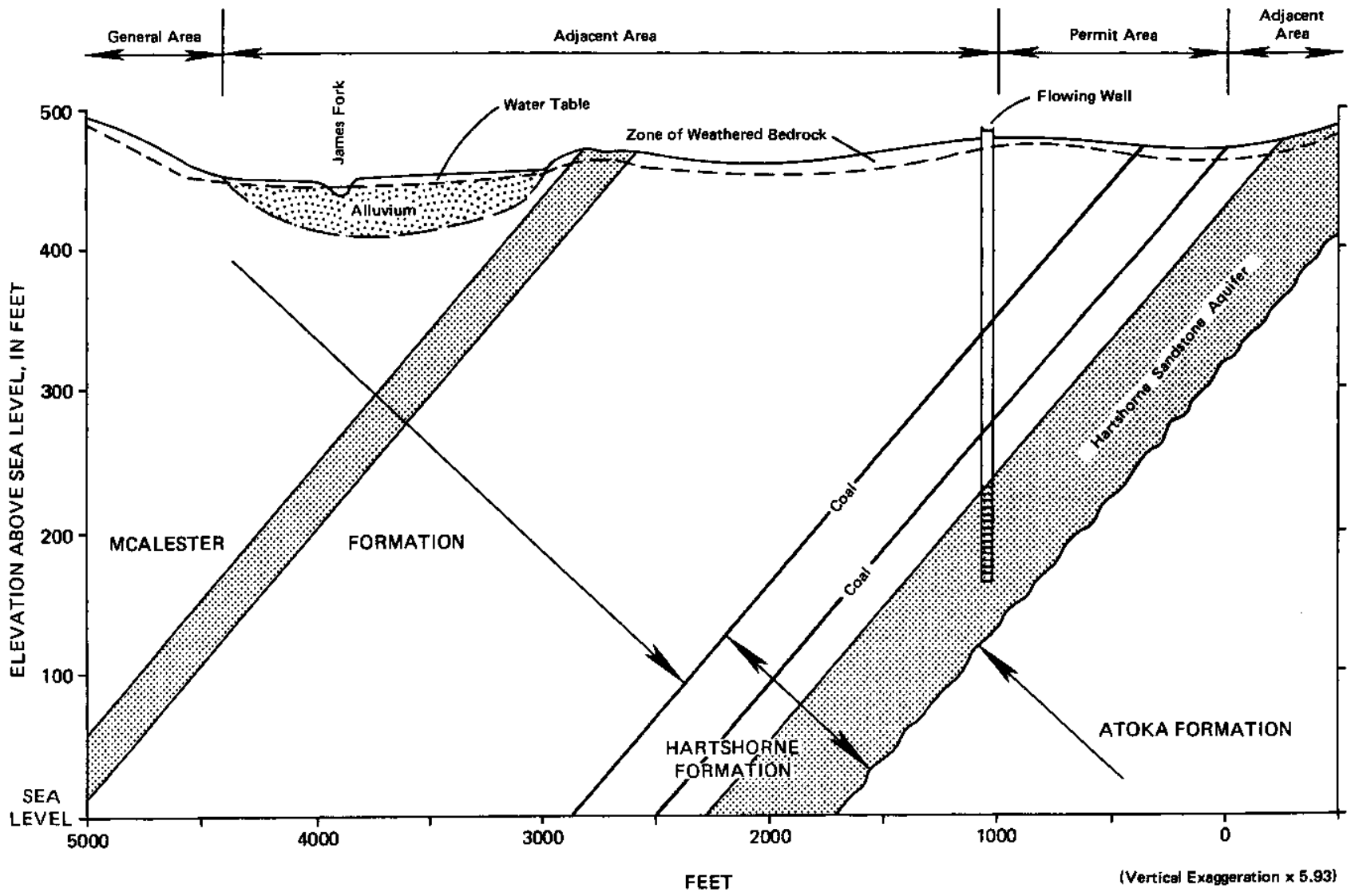


Figure XIX-3.4.— Example of geologic section through proposed permit area and vicinity showing location of flowing-well aquifer test.

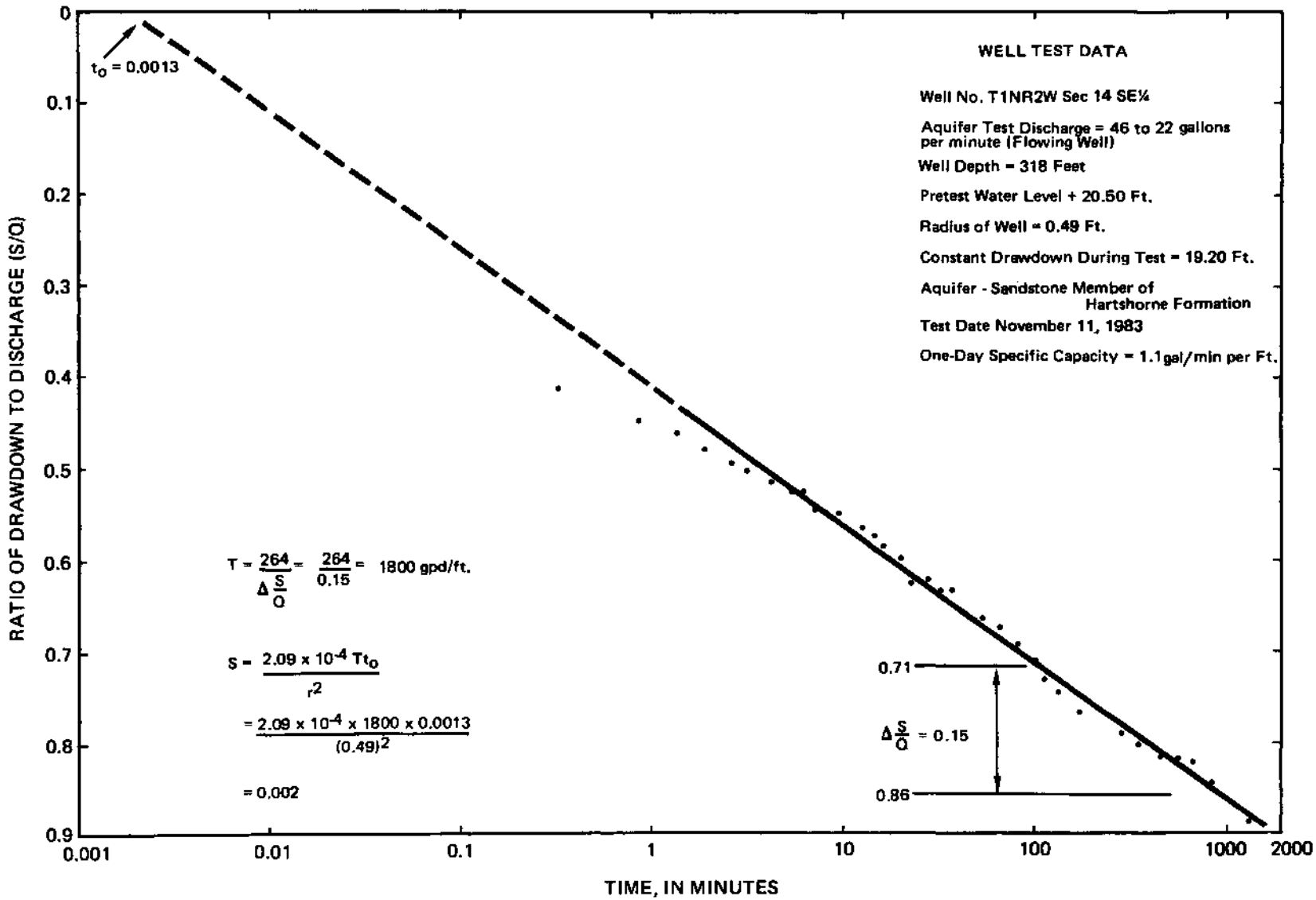


Figure X3X-3.5.— Semilogarithmic plot of s/Q versus time and analysis of constant-drawdown confined-aquifer test. (Modified from Wilson, 1965, p. 61)

The hydraulic properties determined from this testing can provide an estimate of the extent of the dewatered part of the aquifer. Drawdowns (s) at specific distances (r) from pumping wells and for specific periods of time (t) can be calculated from equations X-2.3-1 and X-2.3-2, but using "ordinary Survey units" (Ferris and others, 1962, p. 93), which are equations:

$$u = 1.87 \frac{r^2 S}{T t} \quad \text{and} \quad s = \frac{H4.6\ Q}{T} W(u)$$

where the terms are defined in table X-2.3-2 but have the following units:

s in feet; Q in gallons per minute; T in gallons per day per foot;
r in feet; S as a decimal fraction; and t in days since pumping started.

A plot showing the decrease in drawdown with distance from the well and the increase in drawdown after pumping for 1 month, 6 months, 1 year, and 10 years at a well discharge of 10 gal/min in an aquifer of T = 1,800 (gal/d)/ft and S = 0.002 is given in figure XIX 3.6. Drawdown is directly related to pumping rate. For example, the drawdown 1 mile from a well pumping 15 gal/min in an aquifer of T = 1,800 (gal/d)/ft and S = 0.002 for 1 year would be 1.5 times 1.0 ft (from the graph) and is estimated to be 1.5 ft. Graphs such as this are based on several assumptions (besides the homogeneous and isotropic characteristics); namely that pumpage is constant for the year, no recharge from rainfall reaches the aquifer, and no hydrologic boundaries are intersected by the cone of depression. Considering how poorly these are assumtptions are met in real time, use of graph interpretation requires caution.

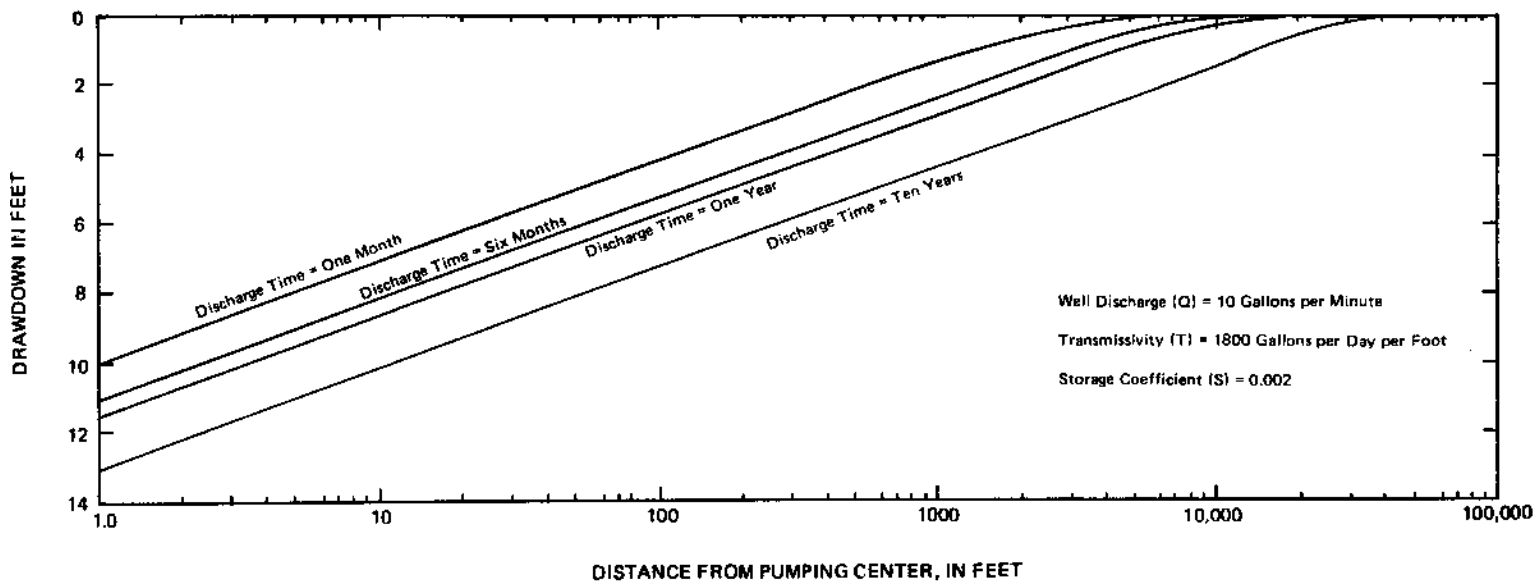


Figure XIX-3.6.—Relationship between drawdown and distance from pumping after selected time periods at constant pumping rate.

Table XIX 3.3– Example of constant-drawdown aquifer-test data.
(Data in part from Wilson, 1965, p. 61.)

[ft, feet; min, minute; gal/min, gallons per minute;
Valve opened at 6:00:00 a.m. Constant drawdown during test = 19. 20 ft]

Time of observation	Time interval (min)	Measured rate of flow (gal/min)	Time since flow started (min)	(s/Q) (ft/ (gal/min))
Day 1				
6:00:00a.m	0.00	0	0	—
6:00:20	.33	46.0	.33	0.417
6:00:52	.53	42.5	.86	.452
6:01:21	.49	41.4	1.35	.463
6:01:54	.55	39.8	1.9	.483
6:02:30	.6	38.6	2.5	.497
6:03:00	.5	38.2	3.0	.502
6:04:12	1.2	37.4	4.2	.514
6:05:12	1.0	36.6	5.2	.525
6:06	.8	36.5	6.0	.526
6:07	1	35.2	7.0	.546
6:08	1	34.9	8.0	.550
6:09	1	34.8	9.0	.552
6:10	1	34.2	10	.562
6:12	2	34.1	12	.563
6:14	2	33.6	14	.572
6:16	2	32.8	16	.585
6:19	3	32.1	19	.598
6:22	3	31.0	22	.620
6:26	4	30.9	27	.621
6:30	4	30.5	30	.630
6:35	5	30.4	35	.630
6:40	5	29.5	40	.651
6:50	10	29.1	50	.660
7:00	10	28.6	60	.670
7:15	15	28.0	75	.685
7:30	15	27.3	90	.703
7:45	15	27.0	105	.710
8:00	15	26.0	120	.738
8:30	30	25.2	150	.760
9:20	50	25.5	200	.752
10:10	50	24.6	250	.780
11:00	50	24.3	300	.791
1:40p.m.	100	23.9	400	.802

Base-Flow Discharge Determination

For the permit area presented in figure XIX 3.1, the topography of the proposed surface-mine permit site consists of deeply incised valleys separating narrow, flat-topped ridges. Drainage is by short streams tributary to the Hocking River. The upper reaches of these streams are ephemeral and have been affected by previous surface mining; the lower reaches are perennial and sustained by base flow from the second aquifer group (fig. VIII-2). This flow is somewhat modified by infiltration of ground-water from the upper (first) aquifer group through the spoils of the reclaimed-mine area. The topography, stream-drainage network, and directions of ground-water flow are shown in figure XIX 3.7; the drainage-basin boundaries and their respective drainage areas are delineated in figure XIX 3.8. No stream-gaging stations are within the general area.

The geologic-setting category of the permit area under discussion (figs. XIX 3.1, 3.7, and 3.8) is GS-1, where the Lower Freeport coal is flat lying. The hydrologic settings are HS-B(2) and HS-B(3) where the coalbed is dry and separated from the overlying first aquifer group (water-table aquifer) and the underlying second aquifer group (confined aquifer) by shale beds. Ground water from the first aquifer group will discharge into the excavation pits.

The base-flow term used in this mine permit application will be the 7 day-10 year discharge ($Q_{7,10}$) which is defined as the average minimum stream discharge for a period of 7 consecutive days that would occur, on the average, once in 10 years. Thus, the probability of this low flow occurring in a year's time is 0.1 or 10 percent.

Techniques of hydrologic analysis allow the transfer of base-flow data from distant gaging stations to ungaged stream locations if the drainage-basin characteristics of the gaged and ungaged basin are similar. These characteristics include geology, topography, vegetation, and size of drainage area.

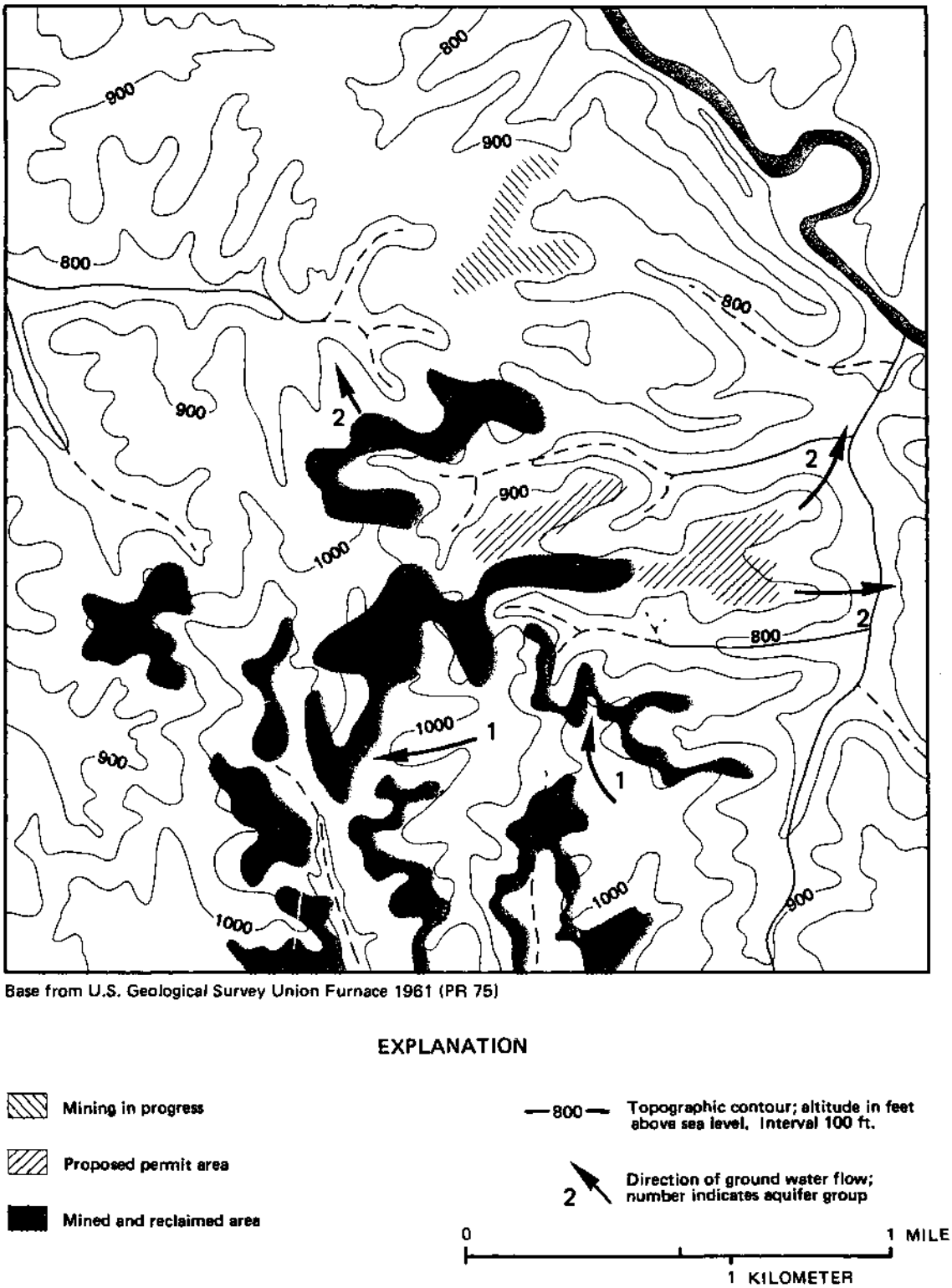


Figure XIX-3.7.— Example map showing surface drainage and directions of ground-water flow for first (upper) and second aquifer groups in permit area. (Aquifer positions are shown in fig. VIII-2.) (Modified from Norris, 1981, fig. 1)

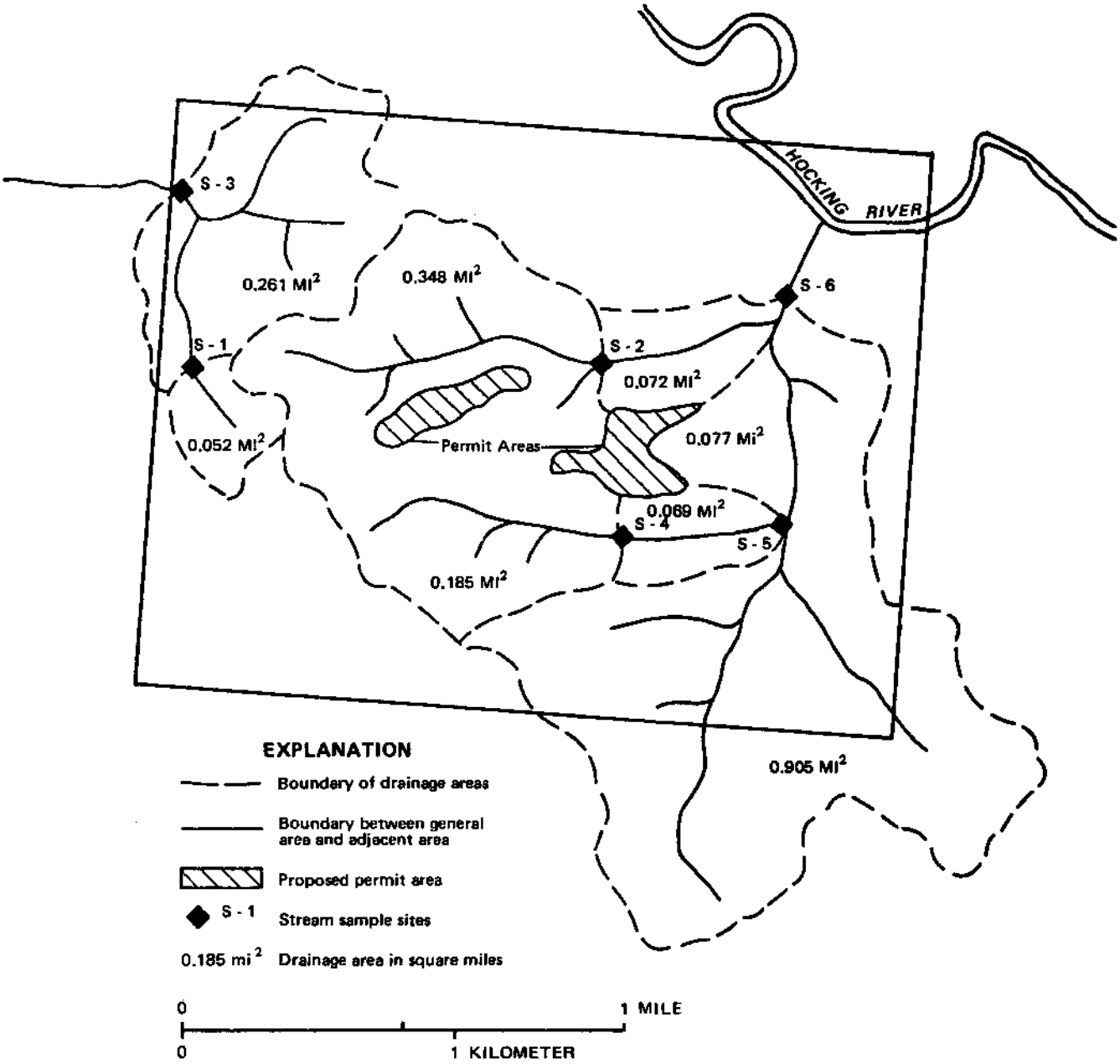


Figure XIX-3.8.— Example of map showing streams draining proposed permit area and vicinity and their drainage areas above sampling sites. (Modified from Norris, 1981, fig. 6)

7-Day, 10-Year Low-Flow Discharge

Low flow characteristics at ungaged stream sites near the permit area are estimated by comparing miscellaneous discharge measurements from these sites with the long-term records from nearby similar gaging stations. The low-flow site locations and their drainage areas within the permit area and adjacent areas are shown in figure XIX 3.8. The instantaneous discharge measured on three dates at two ungaged sites and the mean daily discharges calculated for two nearby gaged sites are tabulated in part A of table XIX 3.4. These data are then converted to unit discharge (discharge per mi^2) values by dividing the discharges by the respective drainage areas; the resulting values are given in table XIX 3.4, part B.

The low flow discharge values at the ungaged sites can be estimated by plotting on logarithmic graph paper the gaged unit discharge values against the ungaged unit discharge values, as illustrated in figure XIX 3.9. In this example, by extending the best-fit straight lines through the plotted points to the known unit discharge $Q_{7,10}$ values, the unit discharge $Q_{7,10}$ values at sites S-6 and S-4 can be estimated between 0.0015 and 0.005 $(ft^3/s)/mi^2$. Using an estimated unit discharge $Q_{7,10}$ value of 0.004 $(ft^3/s)/mi^2$ for the permit area, and the drainage areas shown on figure XIX 3.8, the unit discharge $Q_{7,10}$ values for the stream sites, S-l thru S-6 are shown in table XIX 3.5. These values are significant in determining when a stream is at base flow; and, this is important in determining the base-flow water quality. Stream discharge values significantly larger than the $Q_{7,10}$ value contain surface runoff, while values lower than $Q_{7,10}$ are ground-water base flow.

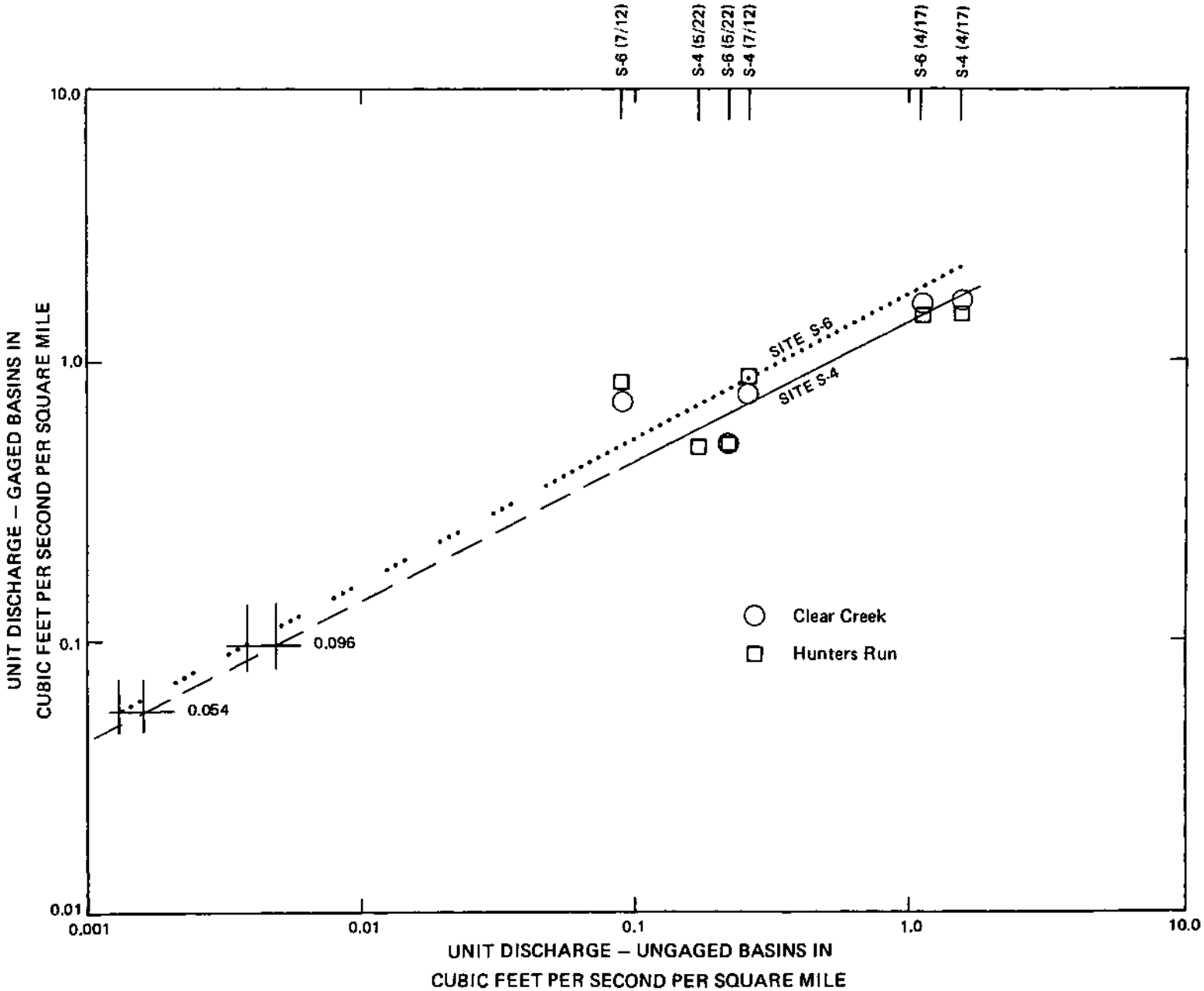


Figure XIX-3.9.— Example of plot showing relationship between unit discharge of gaged basins and that of ungaged basins. (Modified from Norris, 1981, fig. 8)

Table XIX 3.4.– Example of low-flow discharge analysis between gaged stations and ungaged stations, in vicinity of permit area.

[ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile; DA, drainage area]

A. Mean-Daily Discharges and Low-Flow Measurements

	Gaging Stations mean-daily discharges*		Sampling Sites Instantaneous low-flow measurements	
	Clear Creek near Rockbridge (DA=89.0 mi^2)	Hunters Run at Lancaster (DA=10.0 mi^2)	S-6 (DA=1.51 mi^2)	S-4 (DA=0.19 mi^2)
Date (1979)	(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)
April 17	148	15	1.66	0.29
May 22	45	5.1	.33	.033
July 12	69	8.2	.14	.05
B. Unit Discharge Values, in ($(ft^3/s)/mi^2$)				
April 17	1.66	1.5	1.10	1.53
May 22	.51	.51	.22	.17
July 12	.78	.82	.09	.26

*from U. S. Geological Survey, (1979)

Table XIX 3.5.– Example of low-flow stream sites drainage areas and estimated $Q_{7,10}$ flows, (Modified from Norris, 1981)

[mi^2 square miles; ft^3/s, cubic feet per second]

Stream site	Drainage area (mi^2)	$Q_{7,10}$ discharge (ft^3/s)
S-1	0.05	0.0002
S-2	.35	.0014
S-3	.31	.0012
S-4	.19	.0008
S-5	.25	.0010
S-6	1.51	.0060

Chemical Quality of Surface Water and Ground Water

A literature search of hydrologic data records of the U.S. Geological Survey and State Engineer's Office indicated no water-quality information (surface water or ground water) in the general area of the proposed mine was available. Several data stations listed below were established to obtain background water-quality information for premining conditions:

1) six stream sampling sites (fig. XIX-3.8).
2) spring and seep, and
3) six of the inventoried wells (indicated lay asterisk in table XIX 3.1).

Chemical analyses of samples from these sites are given in table XII-2.

Surface-Water Quality

Analyses of the surface-water samples indicate the presence of acid mine drainage from abandoned mines and reclaimed areas. The results from stream sites S-2, S-4, S-5, and S-6 (fig. XIX-3.8) indicated the surface water was affected by acid mine drainage based upon the criteria—low pH (less than 4.5), high specific conductance (greater than 800 umho/cm (micromhos per centimeter)), high concentrations of iron (greater than 5 mg/L) and of sulfate (greater than 250 mg/L). These concentrations are related to the oxidation of the iron sulfide minerals (pyrite and marcasite) associated with the coal (Norris, 1981, p. 50).

Ground-Water Quality

Ground-water quality is highly variable, from both natural causes and the effects of man's activities. Ground water from wells that tap the local flow system is more likely to be potable than water from wells in the same aquifer but distant from the outcrop, that is, in the regional flow system.

As indicated in table XII-2, ground-water analyses show large differences from well to well. Water samples from the third (deepest) aquifer group (See fig. VIII-2) are unaffected by coal mining, as evidenced by the high pH (near 8.0) and low concentrations of dissolved iron, manganese, and sulfate. Locally, water from this aquifer group is used for drinking and cooking. For this general area, the total dissolved solids (TDS) can be estimated from 0.6 times the specific conductance. The high specific conductance (1650 umho/cm) reflects natural water quality and an estimated TDS = 990 mg/L. (High conductance in some deep wells is related to local brine contamination associated with oil- and gas-well exploration and production. Inclusion of sodium and chloride in the chemical analyses verify the presence of brine.)

Ground water from alluvial deposits and the second aquifer group (See fig. VIII-2) indicates a possible effect from past mining or from exposure of coal beds to the atmosphere. The high concentrations of dissolved iron and suspended iron (6.2 mg/L and 3.8 mg/L, respectively) in well G-4 (table XII-2) might indicate some effect of acid-mine drainage from the mining already in progress. Ground-water flow through fractures in the coal beds could also discharge acid-mine drainage to the underlying aquifer.

The seep at this site (G-6) drains directly from a site that was surface mined in the early 1960's and shows severe effects of mining in terms of low pH (near 3.0), high specific conductance (2100 umho/cm), and high sulfate concentrations (1300 mg/L) (table XII-2).

Ground-Water Use

Two significant well-inventory tasks in the general area adjacent to the proposed permit area (See fig. VII-1) are to determine and document ground-water use and ground-water pumpage. For example, a domestic well needs to supply 20 to 80 gal/d per person, and the average per-capita supply figure for municipal water-supply systems is about 150 gal/d. Irrigation pumpage can be one or more acre-feet (325,850 gal/acre-ft) each day depending upon the temperature, rainfall, and crop. A planimetric map showing the ground-water use locations near the proposed surface-mine operations is shown in figure VII-1; a summary of ground-water pumpage in the area is given in table XIX-3.6. Prolonged ground-water pumpage could be one of several reasons for water-level declines being monitored in an observation-well network.

Ground-water pumpage at the individual wells could be determined from "in-line" water meters, which are commonly used by municipal, industrial, or commercial water users. The ground-water pumpage listed in.table XK-3.6 is estimated from the size of household, number of head of stock, or from the power consumed in pumping the water (kilowatt-hours of electricity, thousands of cubic feet of natural gas, or gallons of diesel fuel). The power technique involves the field determination of a conversion factor to convert the units of energy consumed into gallons of water pumped. This factor differs from well to well because of variable head lift, hydraulic properties, water-use needs, and pump efficiency.

Table XIX 3.6. – Example of pumpage tabulation in general area.
(well locations shown on fig. VII-1)
[D-l Cl = D-l Clinker ; Sub D-2, unspecified aquifers below mineable coal beds.]

Well Location		Water Use	Aquifer (s)	Estimated Daily Pumpage (gallons)
T 8S R39E section	25DBDD	Stock	D-l & D-2 Coal	2,000
	26BDBA	Stock	D-l Overburden	2,000
T 8S R40E section	28ABD	Stock	D-2 a*	2,000
	31ABD	Stock	D-2 Goal	2,000
	33ACDB	Stock	D-2 Goal	700
	33BCDB	Stock	D-l Cl & Goal	2,000
	$34EDAA_1$	Stock	D-l Cl	1,000
	$34BDAA_2$	Domestic	D-l Cl	1,000
	34BDEA	Domestic	D-2 Coal, Sub D-2	1,000
T 9S R39E section	25DDC	Stock	D-l Overburden	2,000
T 9S R40E section	3ACAB	Stock	Sub D-2	2,000
	4CDAB	Stock	D-2 Coal	2,000
	5BACC	Stock	Sub D-2	1,000
	70CAB	Stock	D-l Goal & Overburden	2,000
	10CDDD	Industrial	Sub D-2	85,000
	10DDBA	Industrial	D-2 Goal, Sub D-2	28,000
	21CACD	Domestic	D-l Overburden	1,000
	21CDBB	Domestic	Unknown	1,000
	21CDBD	Commercial	D-l Coal	9,000
	21DDBA	Stock	Sandstone	2,000
	22DMD	Stock	D-l Coal	2,000
	22DADA	Domestic	D-l Coal	1,000
	30BBA	Stock	D-l Coal	2,000

Ground-Water-Monitoring Plan

The ground-water monitoring plan includes a schedule for periodic measurement of water levels in observation wells and chemical analyses of water samples from aquifers that could be potentially impacted by proposed mining operations.

The major aquifers in the Decker surface-mine area are the D-l and D-2 coals of the Tongue River-Wasatch aquifer (figs. VII-1 and X-l.2-2). The location of observation wells selected for the monitoring plan are shown in figure XIV-1. Most of these wells are at the mine-permit boundary or within the adjacent area. An example well-inventory data for this well network are given in table XIX-3.7, which includes well location, land-surface elevation, well depth, and aquifer(s) tapped. Some water-level data for this network are given in table DC-1, which gives the initial (premining) water-level measurements and their dates, and water levels on a given postmining date (June 4, 1975), and the difference between the two. The water-level declines of some of these wells, during the mining period are plotted on the hydrograph in figure XIII-2-4. These data indicate that the greatest water-level declines were in the shallow D-l aquifer.

An example of chemical analyses from the monitoring plan is presented in table XIV-5. The wells selected for water quality analyses represent all three areas: permit area, adjacent area, and general area.

Table XIX 3.7– Example of hydrologic data for observation-well network. (From VanVoast and Hedges, 1975, plate 3.)

Well location*	Well number	Land-surface altitude (ft above sea level)	Well depth (ft below land surface)	Water-level altitude, April, 1975 (ft above sea level)	Aquifer
9S 40E 03 $DABA_1$	WRN 10	3,433	79	3,421	D-2 Coal
9S 40E 04 $CABC_2$	WRN 14	3,514	78	3,448	D-l Coal
9S 40E 09 MDD_1	WRN 15	3,500	140	3,426	D-2 Coal
9S 40E 09 $AADD_2$	WRN 16	3,500	89	3,418	D-l Clinker
9S 40E 16 ABCA	WR 1	3,498	104	3,404	D-l Coal
98 40E 08 DCAA	WR 3	3,612	215	3,431	D-l Coal
9S 40E 17 DACB	WR 4	3,585	220	3,428	D-l Coal
9S 40E 16 $ABCD_1$	WR 6	3,499	135	3,406	D-l Coal
9S 40E 16 $ABCD_2$	WR 7	3,498	207	3,445	D-2 Coal
9S 40E 21 $ACCA_1$	WR 8	3,537	165	3,426	D-l Coal
9S 40E 21 CADA	WR 10	3,537	169	3,426	D-l Coal
9S 40E 21 BCAC	WR 11	3,575	210	3,429	D-l Coal
9S 40E 17 DACC	WR 12	3,486	230	3,427	D-l Coal
9S 40E 09 $BDDA_1$	WR 14	3,598	192	3,419	D-l Coal
9S 40E 19 BAC	WR 15	3,685	390	3,445	D-l & D-2 Coal Combined
9S 40E 18 ABAD	WR 16	3,640	237	3,451	D-l & D-2 Coal Combined
9S 40E 29 BBAC	WR 17	3,570	300	3,455	D-l & D-2 Coal Combined

* Subscripted number indicates the number of the well inventoried within the acre area.

4.0 POTENTIAL IMPACTS OF MINING ON HYDROLOGIC SYSTEM

Predicted Water-Level Declines Due To Surface Mining

One of the impacts of surface mining is the dewatering of coal aquifers and (or) of aquifers overlying the coal seam. The decline of water levels in the D-l and D-2 coal seams near Decker, Mont., was illustrated on a hydrograph in figure XIII-2-4.

Examples of model-generated water-level declines due to the surface mining of a 10-ft thick coal aquifer are shown in figure XIX-4.1. The geologic setting is GS-l, which is flat lying coal seam; the hydrologic setting is HS-F(l), where the coal bed is a confined aquifer. The potentiometric surface at this site is 10 ft above the top of the aquifer and 5 ft below the land surface. The aquifer-test results gave a transmissivity value of 5 ft^2/d, hydraulic conductivity of 0.5 ft/d, and a storage coefficient (storativity) of 0.0001. The modeled excavation size was ¼xl mi.

The areal distribution of drawdown after 1 year and 20 years are plotted in fig. XIX-4.1, parts A, B, and C. The drawdown after 1 year of mining (part A) ranges from 20 ft at the mine pit to about 1.5 ft at a distance of 2 miles from the high wall. The drawdown after 20 years of mining (part B) at the 2-mi point has increased to 10 ft. These drawdowns are plotted in part C.

The water-level declines at a proposed permit are 1 mile from a reservoir (such as shown in figure XIV-1), or a perennial stream are shown in figure XIX-4.1, part D. This setting represents a hydraulic connection between the aquifer and the reservoir or stream.

Examples of model-generated extent and depth of water-levels declines resulting from 10 years of surface mining are shown in figure XIX-4.2. The geologic setting is GS-1; the hydrologic setting is HS-F(2), where the coal bed is a water-table aquifer. Aquifer test results yielded hydraulic conductivity of 2.3 ft/d and a specific yield of 0.05. An assumed recharge of 0.1 inches per year was included in the model. The maximum water-level decline is greater than 25 ft.

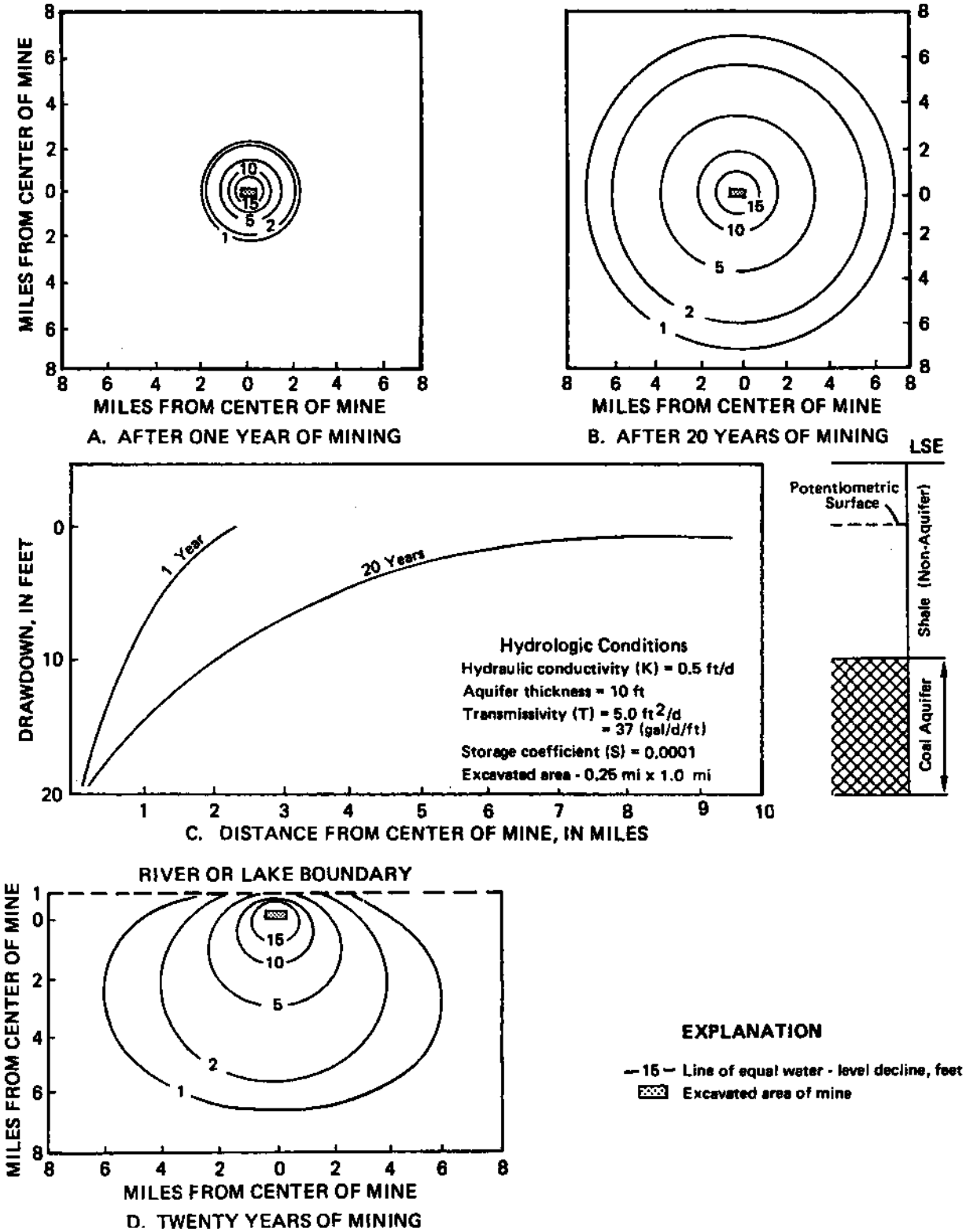


Figure XIX-4.1.— Examples of model-generated drawdown graph and maps for a dewatered surface-mine excavation in a homogeneous, isotropic aquifer after 1 year (A), 20 years(B) of continuous pumping, and as influenced by surface water after 20 years (D).
(From Slagle and others, 1985, figs, 8, 9, 11)

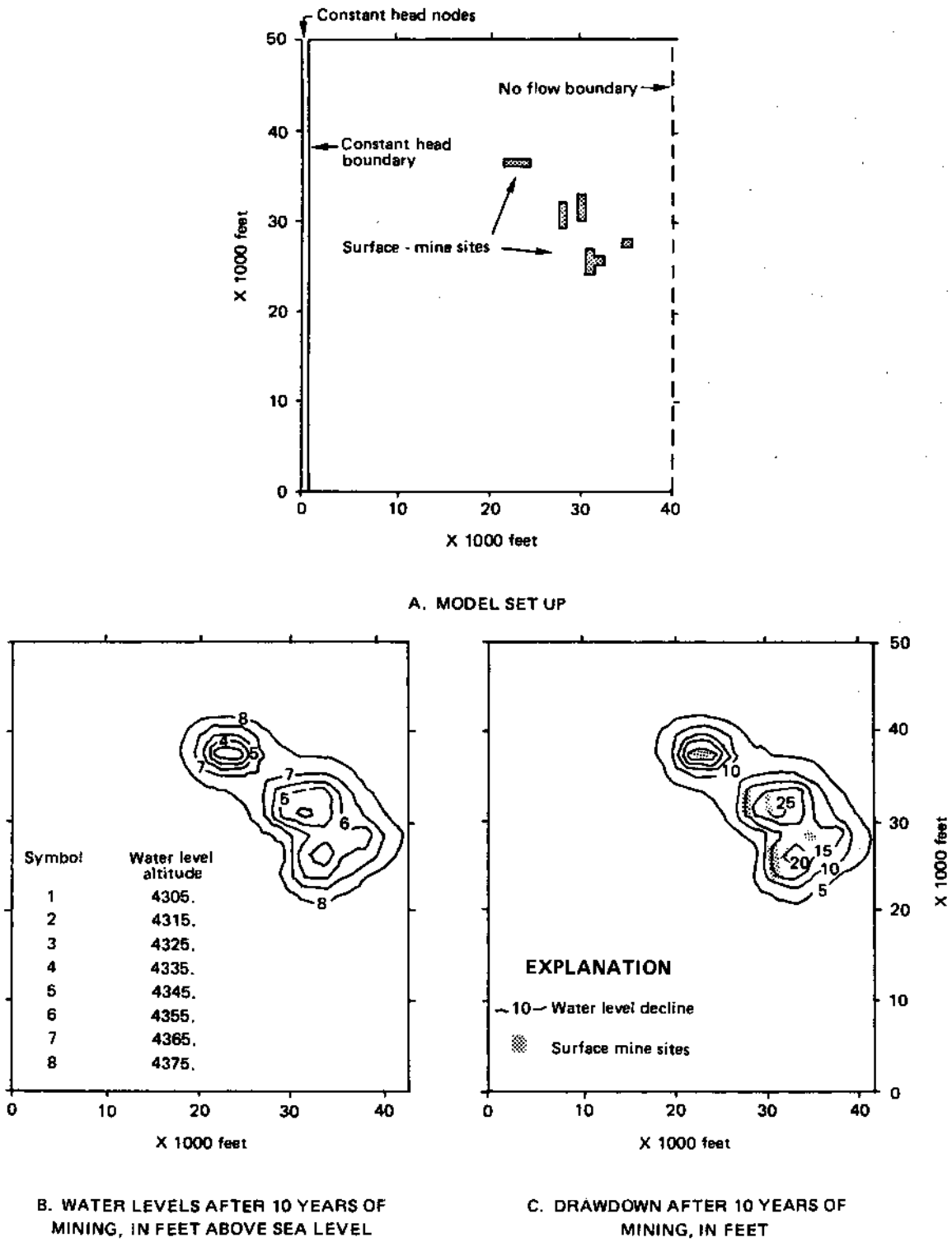


Figure XIX-4.2.— Examples of model-generated maps shaving (A) surface-mines locations, (B) water levels after 10 years of mining, and (C) corresponding water-level declines since start of mining. (Modified from U.S. Department of the Interior, Office of Surface Mining, 1981b, figs. IV-G-1, and V-G-3.)

Potential Water-Level Declines Due to Underground Mining

The hydrologic impacts due to underground mining can be predicted with the assistance of a ground-water flow model. An example of the layout of a proposed underground mine and the 5-year schedule for mining is presented in figure XIX-4.3. The geologic settings are GS-1 (flat lying coal bed in sedimentary rock sequence) and GS-6 (coal bed underlying alluvial valley floor); the hydrologic settings are HS-D (coal bed saturated and in contact with sandstone aquifer) and HS-F(l) (the coal bed is a confined aquifer). An example of a generalized geologic cross section through the permit area is given in figure XIX 4.4 which shows (1) overlying glacial sand and gravel deposits underlain by clay; (2) a thick sequence of interbedded shales, sandstones, coals, and limestones (confining layer); (3) the coal to be mined, and (4) the underburden which consists of a sandstone aquifer underlain by shale. These settings are illustrated in detail in figure VI-8, HS–D&F. The hydraulic properties given in figure XIX-4.4 were determined from routine aquifer tests. (Additional information on the test results can be obtained in Davis and Walton, 1982.)

During the first year, ground-freezing techniques are planned for the construction of the 20-foot diameter shaft through the sand and gravel deposits. During year 2, the shaft is to be excavated through the confining layer. The drainage rate during this construction period is estimated to be 50 gal/min. The estimated mine drainage rate due to shaft and drift completion during years 3, 4, and 5 are presented in figure XIX-4.5. The rate increases from 50 gal/min in years 2 and 3 to 233 gal/min in year 4 and to 446 gal/min in year 5. The estimated drawdown distribution in the coal and sandstone aquifer at the end of the 5-year period is shown in figure XIX-4.6. Drawdowns may range from 400 ft in the immediate vicinity of the mine drifts to less than 1 ft at distances of ½ mi from the mine drifts. Water levels in the unconsolidated deposits may decline as much as ½ ft near the center of the mine drifts (Davis and Walton, 1982, p. 847).

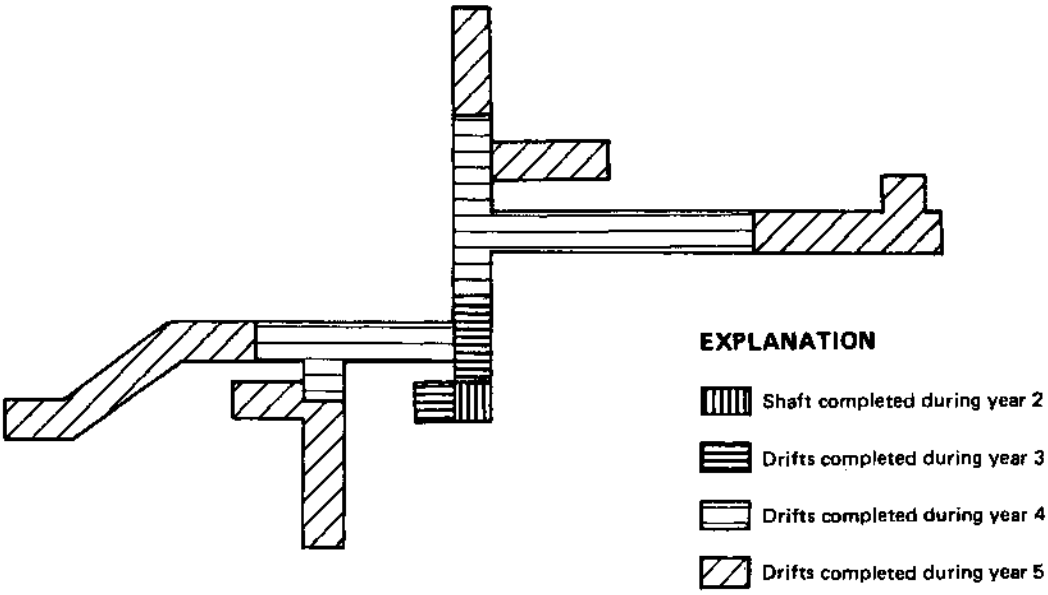


Figure XIX-4.4.— Generalized stratigraphic column with average hydraulic properties used in ground-water model.
(Modified from Davis and Walton, 1982)

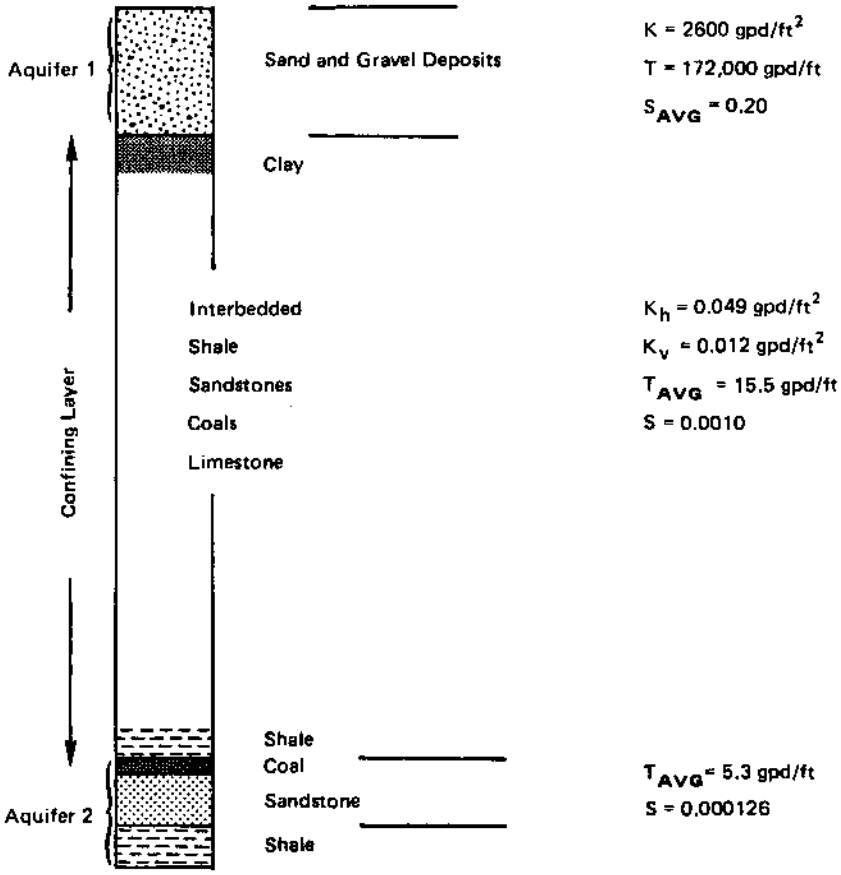


Figure XIX-4.3.— Example of underground mine layout and development schedule. (From Davis and Walton, 1982, fig. 8)

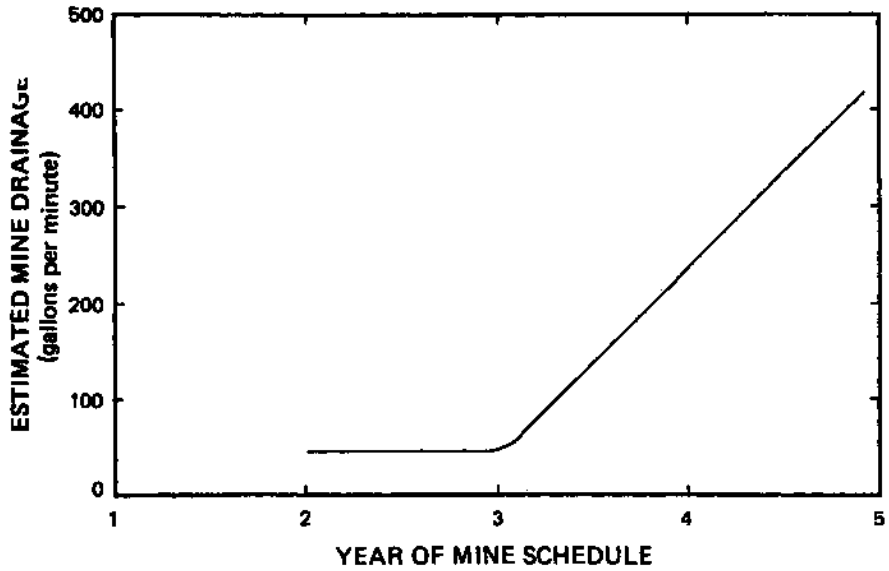


Figure XIX-4.5.— Example of curve showing projected mine drainage during 5-year development of deep underground coal mine. (From Davis and Walton, 1982, fig. 9)

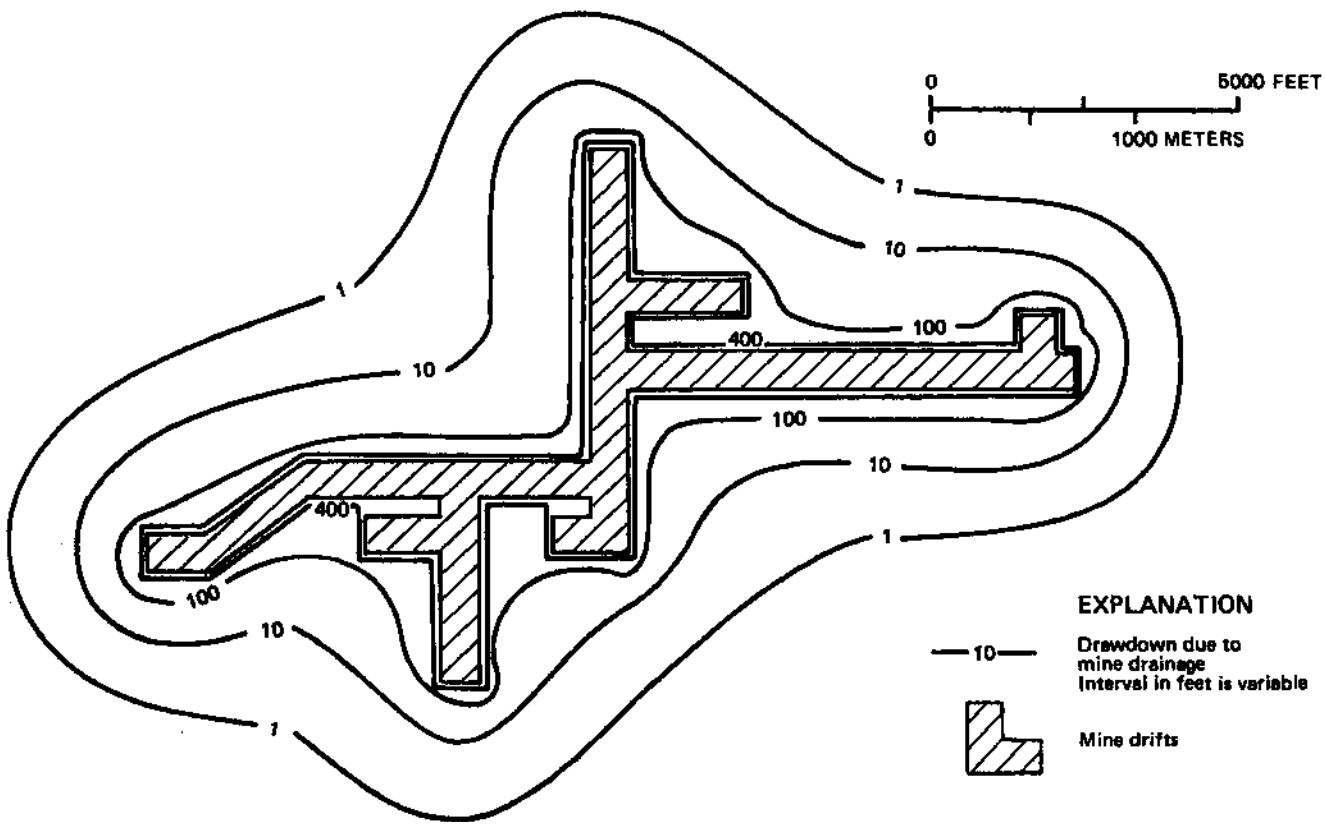


Figure XIX-4.6.— Example of water-level change map for the underburden sandstone aquifer after 5 years of deep underground coal-mine drainage. (From Davis and Walton, 1983, fig. 10)

Change in Ground-Water Storage and Ground-Water/Surface-Water Relationship

The proposed surface-mine shown in figure XIX-3.7 will be a mountaintop-removal operation. The postmining impact will be about a 10 percent increase in the size of the reclaimed spoil area, within the 0.751 mi^2 drainage area. This will provide additional ground-water storage, which will, in turn, cause an increase in ground-water (base-flow) discharge to tributary streams.

About 20 percent of the drainage areas above stream sites 2 and 4 (figure XIX 3.8) have been affected by past surface mining operations. The increase in areas of spoils within these two drainage areas, resulting from mining, will be 10 percent and 5 percent, respectively.

Overburden Analysis (Acid-Base Account)

Ground water in waste spoil banks generally contains high concentrations of total dissolved solids, is low in pH, and is a calcium magnesium-sulfate type water. Ground water discharging from spoil banks is called "acid-mine drainage," and is the product of oxidation of iron disulfide minerals (such as pyrite).

In the Appalachian and Midwestern coal basins, the coal-bearing overburden bedrock commonly consists of a complex series of shale and sandstones inter-bedded with generally thinner, more regular beds of limestone, siltstone, coal, and underclay. A method of chemical overburden analysis is the "acid-base account" (Sobeck and others, 1978). This method is concerned with the measurements of total or pyritic sulfur and neutralization potential (by calcium carbonate).

In the proposed permit area, 30 "soil extract" (rock) samples, were obtained from the drill-hole cuttings. These samples were pulverized into a rock slurry with distilled water and tested for (1) percent sulfur, (2) pH, and (3) alkaline carbonates such as $CaCO_3$. The sulfuric acid yielded by 1000 tons of overburden material containing 0.1 percent sulfur requires 3.125 tons of calcium carbonate to neutralize it (Sobeck, and others, 1978, p. 3). An example of a drill-hole log of the proposed surface-mine site and a corresponding plot of expected sulfur concentration (as percent of total overburden material) with depth is given in figure XIX-4.7, which also indicates zones of toxic and nontoxic materials. The depth zones of nontoxic materials are from 0 to 44 ft, 56 to 69 ft, and 80 to 83 ft. The nontoxicity of these zones results from excess $CaCO_3$. The toxic zones, as defined by pH values less than 4.0, are from 53 to 56 ft and from 69 to 71 ft. A zone of potentially toxic material is from 44 to 53 ft.

The toxic material will be selectively handled, or separated, to ensure favorable minesoils and economical reclamation for the intended land use.

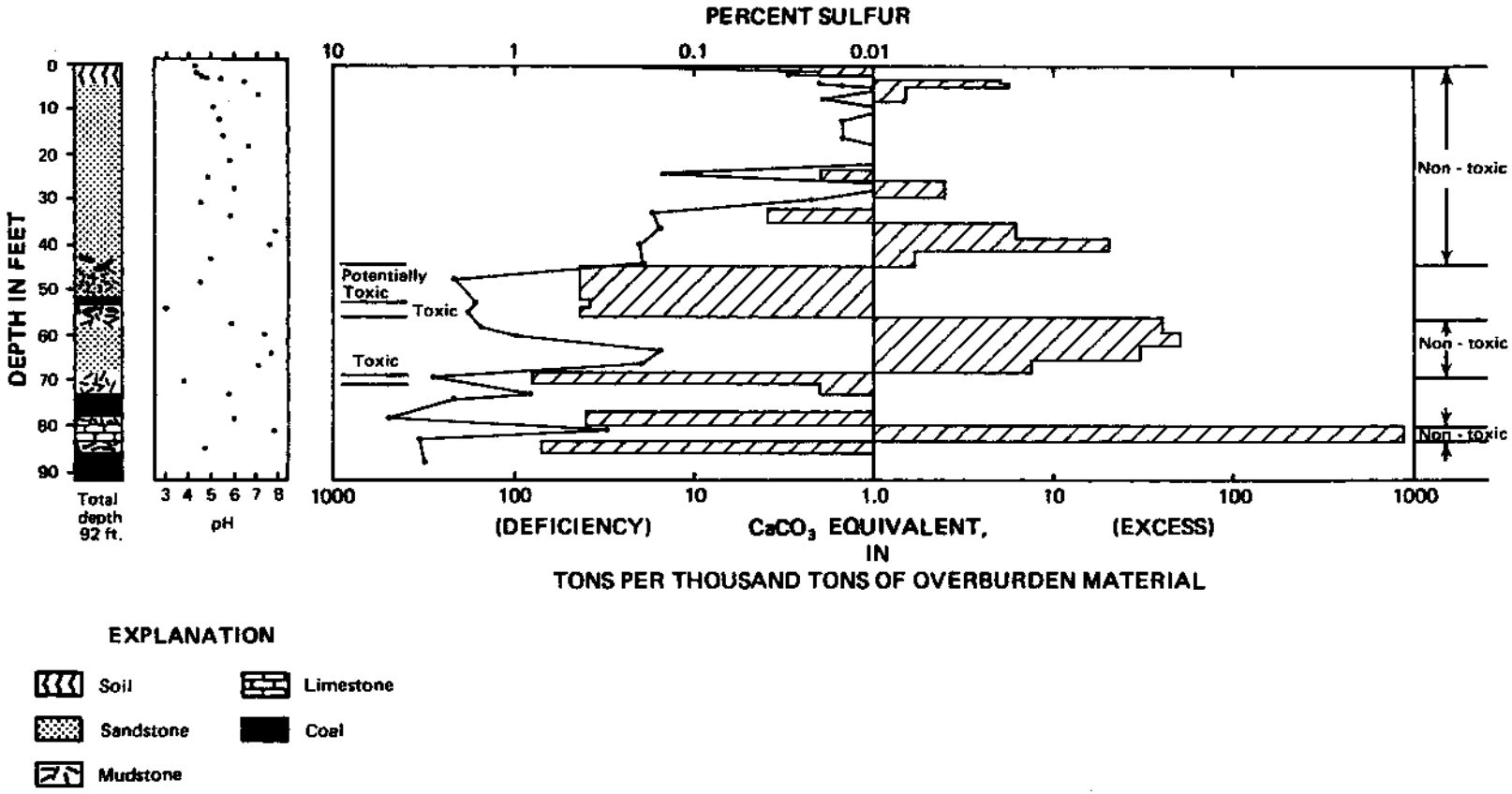


Figure XIX-4.7.— Example of overburden analysis, by acid-base account method, for proposed surface-mine permit area.
(From Sobek and others, 1978, fig. 1)

Potential Water-Quality Degradation Due to Surface Mining

Ground water and base flow of streams in the proposed permit area (figs. XIX-3.1, and XIX-3.8) are currently impacted by seepage from mined and reclaimed areas, as evidenced by the low pH, the corresponding high sulfate concentrations (370 to 990 mg/L), and specific conductance values (830 to 1500 umho/cm) at stream sites (See table XII-2). The seep water (G-6 in table XII-2) from the base of the spoils (pH = 3.2, zero bicarbonate, high dissolved iron, manganese, and sulfate) is indicative of typical acid-mine drainage-type water that causes degradation of surface water.

The chemical analysis of well G-4 (table XII-2) indicates infiltration of acid-mine drainage water into the alluvium from past and present mining operations; this will probably continue to degrade ground water in the alluvial deposits within the adjacent area. The sandstones of the Allegheny Formation (fig. VIII-2) also may be impacted by infiltration from mined and reclaimed area. The upper aquifer group will not be impacted, however, by mining operations by virtue of its higher topographic position. The Lower aquifer group also will not be impacted because it is overlain by confining beds of the Logan Formation (See fig. VIII-2).

5.0 POSTMINING HYDROLOGIC MONITORING

Ground-Water Monitoring Plan for Surface-Mine Operations

The postmining ground-water-monitoring plan for proposed surface-mine operations will monitor the reclaimed mined areas as well as the proposed surface-mine areas. An example of a location map of the plan is given in figure XIX 5.1. The plan, subject to approval by the regulatory authority, includes selected inventoried wells, a sampled spoil pile seep, inventoried base-flow sites, new observation wells, new seeps, and observation wells converted from company exploratory test holes.

The plan includes measurements of water levels and water quality analyses of both ground water and low-flow surface water. The previously inventoried and sampled wells and seep include sites 8, 13L, 19L, 20L, 22L, and G-6 (fig. X3X-3.1). The aquifers monitored will be the hydrogeologic groups 2 and 3 (fig. VIII-2) and the alluvial deposits. The previously established stream-sampling sites (S-2, S-4, and S-6) (fig. XII-4) will be included. Test hole 3 will be converted to an observation well for the Lower aquifer group.

The additional monitoring sites include the following; (site locations are shown in fig. XIX-5.1)

(1) observation wells 23, 24, 25, 26, and 27, which will be installed in the sandstones of the Allegheny and Pottsville Formations, primarily for the purpose of systematic water quality sampling.
(2) stream-flow sampling sites 5, 7, and 8, which will be necessary to define base-flow water quality and to plot water-quality degradation changes with respect to specific drainage areas.
(3) spoil-pile seeps G-9 and G-10, which will be necessary to separately define the background water quality and water quality related to the proposed mine site.

Cross sections through the permit area and adjacent areas are shown in figures XIX 5.2 and XIX 5.3. These sections illustrate the topographic setting of the permit area, the water levels in the aquifer groups 1 and 2, and the ground-water relationship between the aquifers and the streams.

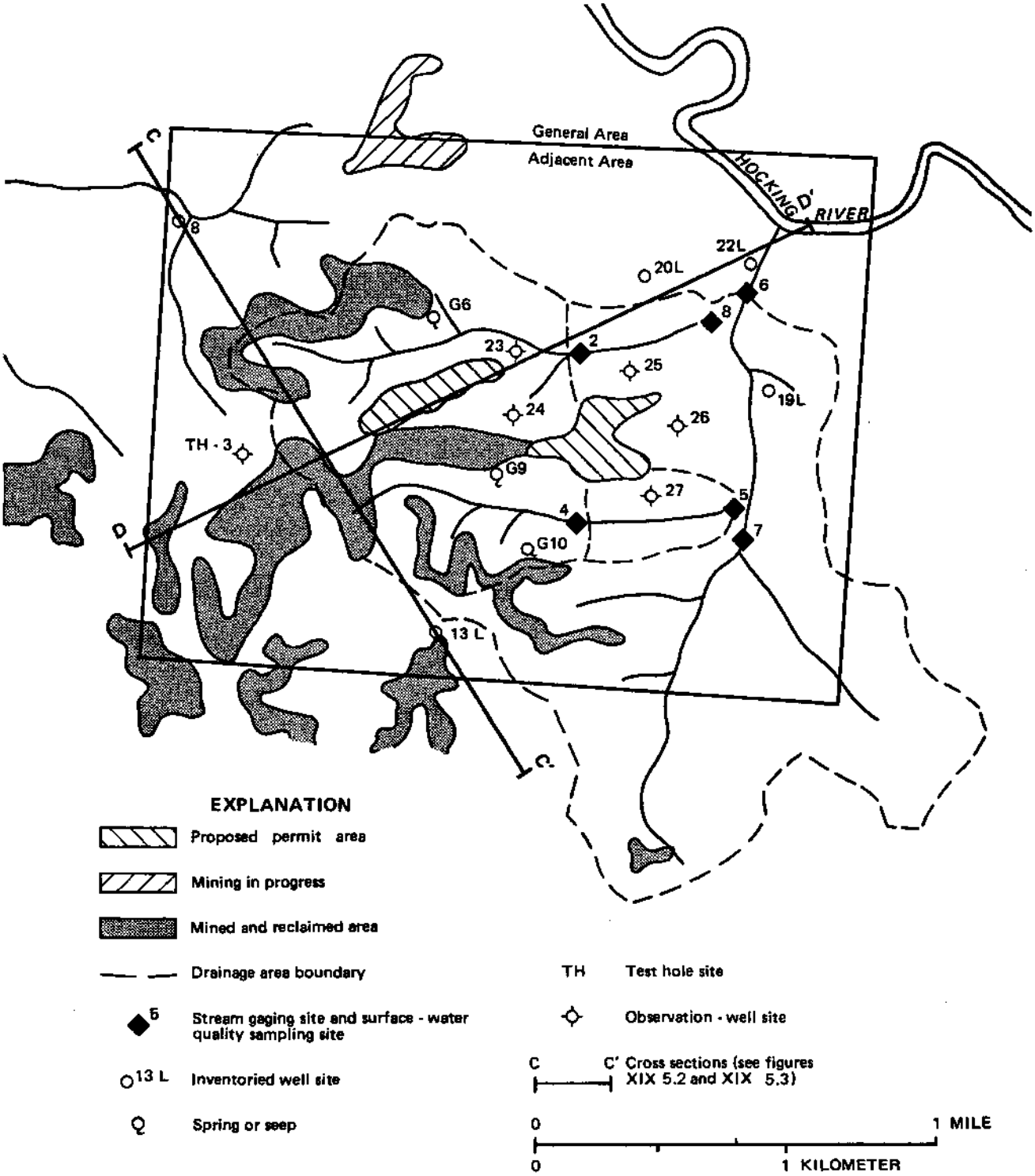


Figure XIX-5.1.— Example of postmining ground-water monitoring plan for surface mine operations.
(Modified from Norris, 1981, fig. 2)

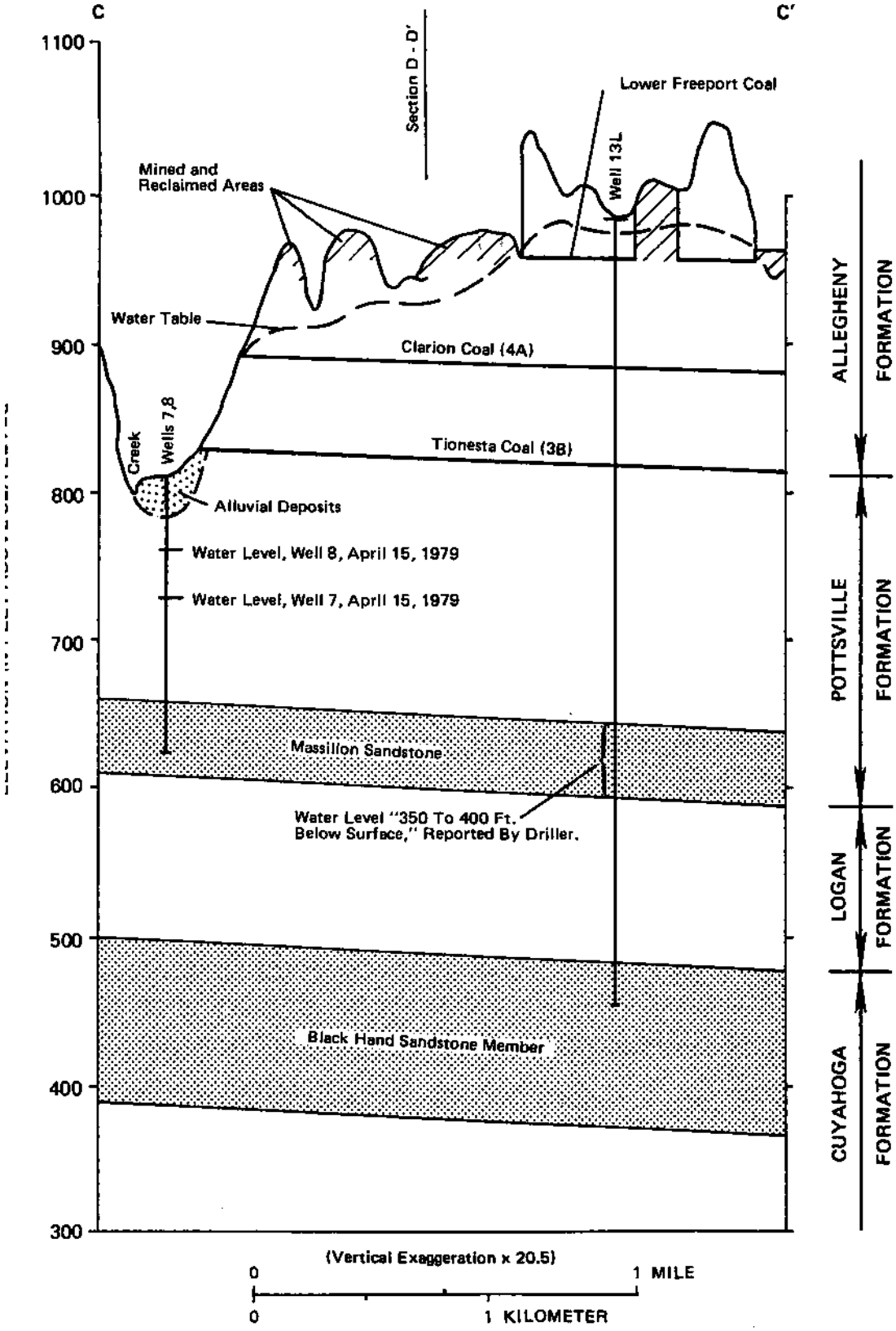


Figure XIX-5.2.— Example of geologic section(C-C') showing premining water levels in the upper two aquifers.
(Modified from Morris, 1981, fig. 5)

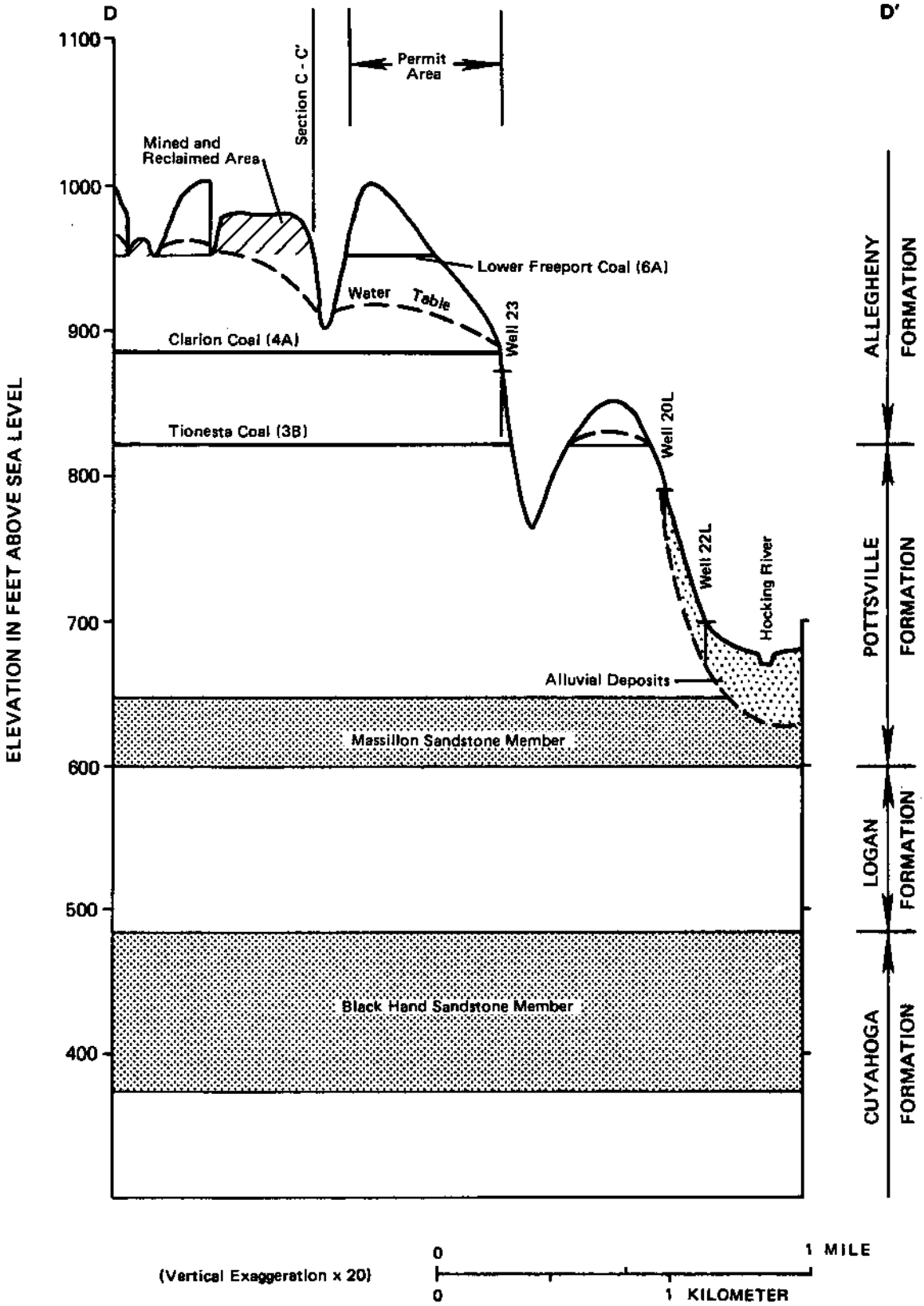


Figure XIX-5.3.— Example of geologic section (D-D') showing permit area and premining water levels in the upper two aquifers and the alluvial deposits.

Ground-Water Monitoring Plan for Underground-Mine Operations

The proposed postmining ground-water-monitoring plan for the terminated underground mining operation (fig. XIX 4.3) is shown in figure XIX 5.4. This plan, subject to approval by the regulatory authority, includes springs, observation wells, and water-quality sampling sites.

The water-table aquifer will be monitored at springs and shallow wells along the hills and valleys. The confined sandstone aquifer of the mined area will be monitored at the deep observation wells. Most pumping for local ground-water use is from wells shallower than 200 ft. Conversion of coal-exploratory holes to cased observation wells is planned. Unused and abandoned landowner wells will serve as observation wells for the shallow aquifer zones, Well-construction information will be needed to define the contributing water-bearing zones.

Initially, water levels will be measured monthly in all but two wells. Recorders will be installed on the two observation wells of the M-l well cluster (fig. XIX 5.4). Measurements will be reduced to quarterly when the trend of the analyses approaches the character of the natural background conditions (as in a nearby long-term observation well in the U. S. Geological Survey or State Geological Survey ground-water monitoring network). Additional wells will be added, or additional measurements will be scheduled, should water-level changes resulting from mining operations, extend beyond the mine boundary. The observation wells will be pumped annually to ensure adequate communication between the borehole and the aquifers. Water samples will be collected during the pumping tests for chemical analyses.

Well sites, Rl, R2, and R3 which penetrate the water-table aquifer downgradient from the storage pile, where any water-quality changes are likely to occur (fig. XIX-5.4) will be sampled monthly to document the changes in ground-water chemistry that result from infiltration of water from the waste-rock refuse facility. Additional wells will be added around the perimeter and at a greater distance from the refuse pile if leachate infiltration into the ground-water system is extensive. Springs downgradient from the refuse pile (SI and 52 in figure XIX 5.4) will also be sampled.

Water-quality samples will also be collected quarterly to document the ground-water quality during seasonal changes in recharge to the aquifer. More frequent sampling may be needed if significant changes in concentrations of sulfate, iron, manganese, acidity, and dissolved solids are noted in the quarterly samples.

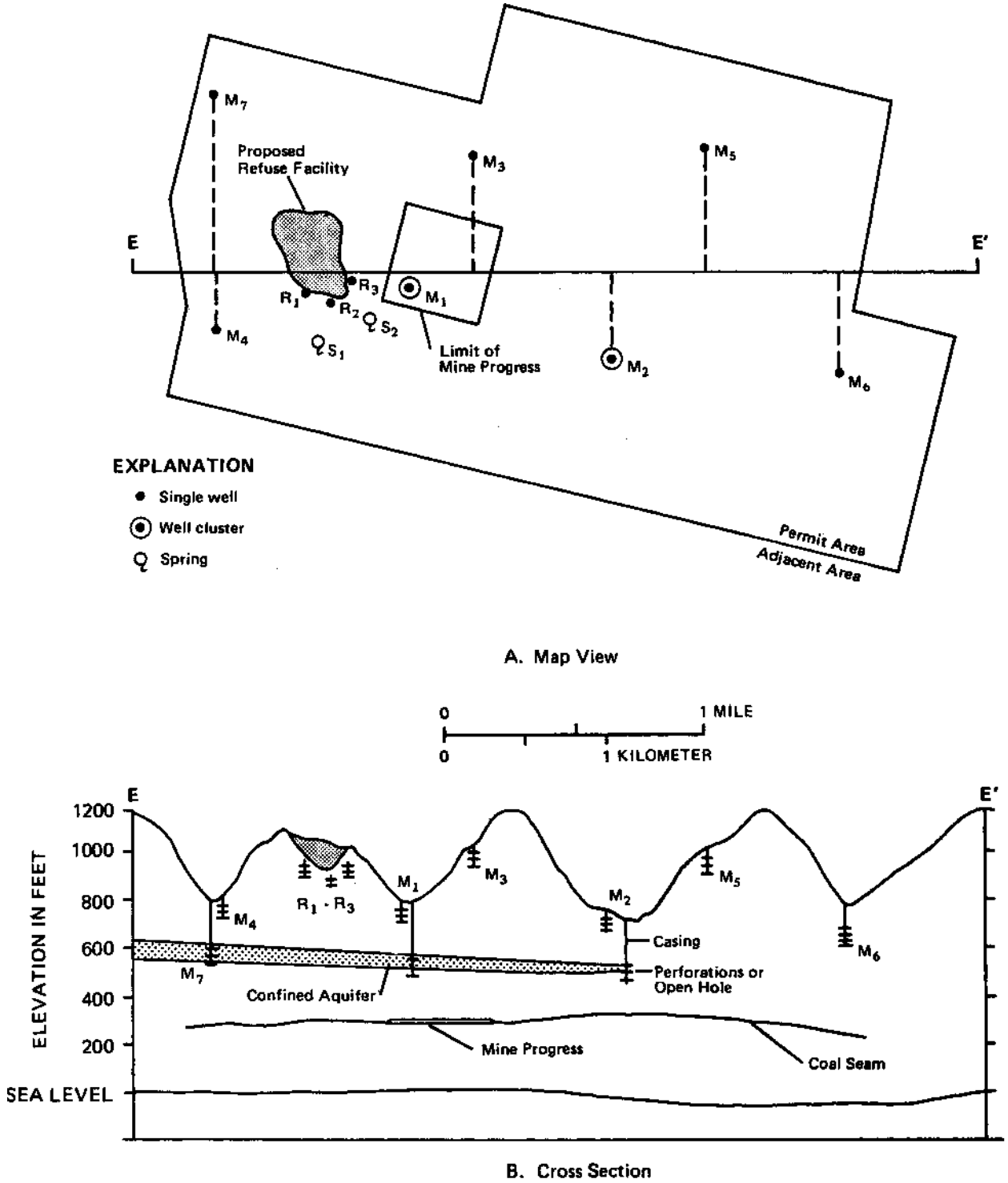


Figure X3X-5.4.— Example of map and vertical section showing locations of sampling sites and depths in observation well network for proposed underground mine.
(From Stoner, U.S. Geological Survey, 1981, written communication)

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☆ U.S. GOVERNMENT PRINTING OFFICE: 1986-642-043