A Feasibility Study to Estimate Minimum Surface-Casing Depths of Oil and Gas Wells to Prevent Ground-Water Contamination in Four Areas of Western Pennsylvania

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 87-4136

Prepared in cooperation with the

PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL RESOURCES,
BUREAU OF OIL AND GAS MANAGEMENT

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Lemoyne, Pennsylvania
1995

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
	0.003785	cubic meter
million gallons (Mgal)	3,785	cubic meter
gallon per minute (gal/min)	0.06309	liter per second
	0.00006309	cubic meter per second

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) -- a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level of 1929".

A FEASIBILITY STUDY TO ESTIMATE MINIMUM SURFACE-CASING DEPTHS OF OIL AND GAS WELLS TO PREVENT GROUND-WATER CONTAMINATION IN FOUR AREAS OF WESTERN PENNSYLVANIA

By Theodore F. Buckwalter and Paul J. Squillace

ABSTRACT

Hydrologic data were evaluated from four areas of western Pennsylvania to estimate the minimum depth of well surface casing needed to prevent contamination of most of the fresh ground-water resources by oil and gas wells. The areas are representative of the different types of oil and gas activities and of the ground-water hydrology of most sections of the Appalachian Plateaus Physiographic Province in western Pennsylvania. Approximate delineation of the base of the fresh ground-water system was attempted by interpreting the following hydrologic data: (1) reports of freshwater and saltwater in oil and gas well-completion reports; (2) water well-completion reports, (3) geophysical logs; and (4) chemical analyses of well water.

Because of the poor quality and scarcity of ground-water data, the altitude of the base of the fresh ground-water system in the four study areas cannot be accurately delineated. Consequently, minimum surface-casing depths for oil and gas wells cannot be estimated with confidence. Conscientious and reliable reporting of freshwater and saltwater during drilling of oil and gas wells would expand the existing data base. Reporting of field specific conductance of ground water would greatly enhance the value of the reports of ground water in oil and gas well-completion records.

Water-bearing zones in bedrock are controlled mostly by the presence of secondary openings. The vertical and horizontal discontinuity of secondary openings may be responsible, in part, for large differences in altitudes of freshwater zones noted on completion records of adjacent oil and gas wells. In upland and hilltop topographies, maximum depths of fresh ground water are reported from several hundred feet below land surface to slightly more than 1,000 feet, but the few deep reports are not substantiated by results of laboratory analyses of dissolved-solids concentrations.

Past and present drillers for shallow oil and gas wells commonly install surface casing to below the base of readily observed fresh ground water. Casing depths are selected generally to maximize drilling efficiency and to stop freshwater from entering the well and subsequently interfering with hydrocarbon recovery. The depths of surface casing generally are not selected with ground-water protection in mind. However, on the basis of existing hydrologic data, most freshwater aquifers generally are protected with current casing depths. Minimum surface-casing depths for deep gas wells are prescribed by Pennsylvania Department of Environmental Resources regulations and appear to be adequate to prevent ground-water contamination, in most respects, for the only study area with deep gas fields examined in Crawford County.

INTRODUCTION

Activities of the oil and gas industry in western Pennsylvania have, at times, contaminated fresh ground water. One of the causes of this contamination has been inadequate well construction. If an oil or gas well is not cased to a sufficient depth, undesirable fluids such as salty water, oil, or gas may rise in the uncased borehole and enter freshwater aquifers. If the space (annulus) between the casing and the borehole is not cemented sufficiently, contamination of freshwater aquifers may occur below and along the outside of the casing. Improved well construction standards and, in particular, surface-casing depth requirements for new wells, may prevent contamination of freshwater aquifers.

This report by the U.S. Geological Survey was performed in cooperation with the Bureau of Oil and Gas Management of the Pennsylvania Department of Environmental Resources (PaDER).

Purpose and Scope

This report presents the methods and results of a study to estimate the minimum surface-casing depths necessary to prevent contamination of fresh ground-water resources by oil and gas wells in four study areas in western Pennsylvania: Crawford County (Geneva quadrangle[1]), Jefferson County (Hazen and Reynoldsville quadrangles), Warren County (Warren quadrangle), and Allegheny County (Pittsburgh East quadrangle). Estimates in the report are based largely on knowledge of the relations between surface-casing depths and the base of the fresh ground-water system in the study areas.

The scope of the work included a literature review of geology and ground-water reports of study areas. In addition, the oil and gas literature of western Pennsylvania was consulted to determine oil and gas well construction techniques and to find statistics on surface-casing depths of the common types of oil and gas wells. Locations of oil and gas wells in study areas were plotted and altitudes of total depths of surface casing were determined from oil and gas well-completion records. Geophysical logs were evaluated with emphasis on locating ground water and delineating changes in ground-water quality with depth. Locations of water wells in study areas were plotted and total depths tabulated. Ground-water quality data were compiled from water wells, core holes, and oil and gas wells. Hydrogeologic sections were prepared for study areas showing relations of surface-casing depths of oil and gas wells, water-well bottoms, and altitudes of freshwater and saltwater reports of oil and gas wells. All of the preceding information and data were comprehensively evaluated for the study areas to attempt to estimate the location of the base of the fresh ground-water system. With this knowledge, minimum surface-casing depths for oil and gas wells could then be estimated to prevent ground-water contamination of freshwater aquifers by oil, gas, and brines of oil and gas wells.

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[1] Quadrangle refers to U.S. Geological Survey 7-1/2-minute topographic quadrangles. A 7-1/2-minute quadrangle covers about 50 square miles.

Previous Investigations

Regulations describing minimum surface-casing depths of oil and gas wells have been promulgated by PaDER for conservation wells. Conservation wells are defined by the Oil and Gas Conservation Law 1961, July 25, P.L. 825, Act No. 359 to include all wells drilled to penetrate the Devonian Onondaga Formation and deeper horizons or a depth of 3,800 ft, whichever is deeper. The minimum casing required for conservation wells is defined by the following table from the Pennsylvania Bulletin (1983):

Proposed Total Depth (in feet)	Minimum Casing Required (in feet)
3,800 - 5,000	400
5,001 - 5,500	500
5,501 - 6,000	600
6,001 - 6,500	700
6,501 - 7,000	800
7,001 - 8,000	1,000
8,001 - 9,000	1,200
9,001 - 10,000	1,400
Deeper than 10,000	1,800

In Chautauqua County, southwestern New York, surface casing and cementing requirements for oil and gas wells were especially designed to protect aquifers (see Glossary). The Chautauqua County requirements prescribed a minimum of 450 ft of surface casing or 100 ft of surface casing installed in bedrock, whichever is greater, and circulation of cement to the surface; the amount of cement should be 50 percent greater than the amount calculated to fill the annular space outside the casing (New York State Department of Environmental Conservation, 1982).

Fettke (1938) made a comprehensive study of the 130-mi^2 Bradford Oil Field located in northcentral McKean County, Pa., and in southcentral Cattaraugus County, N.Y. Information about the ground-water system is contained in the report with some conclusions derived from surface-casing depths of oil wells drilled by cable-tool rigs. Fettke (1938, p. 417) noted that surface casing was installed to seal off ground water. Beneath major valleys, Fettke (1938, p. 284) concluded that the average lower limit of ground water was a depth of 450 ft and rarely exceeded 600 ft. Conductor-casing or drive-pipe lengths (Fettke, 1938, p. 41-78) indicate the depth of valley fill. This information and the surface-casing data permitted a test of the Bradford Oil Field casing data of Fettke (1938, p. 41-78) using the modern, minimum surface-casing criteria established for nearby Chautauqua County, N.Y. Analysis of this data shows that the Chautauqua County criteria would not protect the deeper freshwater in the Bradford Oil Field. About one-third of the 74 oil wells for which conductor-casing information is available had surface casing deeper than 450 ft or more than 100 ft of surface casing installed in bedrock.

Lytle (1965) discussed drilling and surface-casing practices in the Warren 15-minute quadrangle located in Warren County, northwestern Pennsylvania. The casing procedures, described by Lytle, probably would protect most freshwater aquifers. Lytle (p. 22-23) noted: "The portable spudding machine with wire line is generally used in the quadrangle. A 10-in. hole is spudded to bedrock and a wooden conductor or, if the walls of the hole will not stand, 8-in. drive pipe is used. About 20 to 150 ft of drive pipes are used, depending on the location of the well. As much as 250 ft of drive pipe might be needed in few areas where the glacial cover is that thick. An 8-in. hole is drilled to the casing point, a point below which fresh water is no longer encountered (varying from 180 to 600 ft below the surface), and 6-1/4-in. casing is installed. A 6-1/4-in. hole is then drilled to total depth which generally includes a 10- to 20-ft pocket below the bottom of the sand." (The cable tool or portable spudding machines used extensively in the past, and still in limited use today, are being phased out for shallow oil and gas well drilling by modern air-rotary-drilling rigs.)

Waite and Blauvelt (1983) discussed in detail the drilling, well construction, and management of fluids (freshwater, saltwater, stimulation fluids) for oil and gas fields of western Pennsylvania. Several of their illustrations of oil- and gas-well construction are used in a later section of this report. Casing requirements for oil and gas wells were not prescribed in the report. However, Waite and Blauvelt (1983, Part D, p. 52) noted that the existing casing-depth standards for conservation wells were sufficient to protect ground water in most cases.

In West Virginia, oil and gas wells are required by law to be cased and cemented to 30 ft below the base of freshwater (Foster, 1980). The base of fresh ground water is determined during drilling by the oil or gas operator. A map of West Virginia that indicates the altitude of the base of fresh ground water was prepared as a guide for oil, gas, and water well drilling by Foster (1980, map 1). Data density differed greatly across the State, and data were not available for numerous 5-minute map areas. Reports of freshwater noted on oil and gas well logs, and water-well data, were used by Foster in the preparation of this map.

A second map indicating the altitude of the top of saline water and a third map showing the thickness of the zone between fresh and saline water in West Virginia at 1:1,000,000 scale also was prepared by Foster (1980, map 2). The thicknesses of rock separating fresh and saline ground water in areas of West Virginia adjacent to Pennsylvania ranged from 0 to 750 ft, and the average thickness between fresh and saline ground water was about 250 ft. Foster (1980, map 1) noted that casing of oil and gas wells should extend into the interface that separates the base of freshwater from the top of saltwater.

The references listed in table 1 were valuable for obtaining water-well and water-quality data and for geologic information for preparation of hydrogeologic sections. Some of the geologic nomenclature of western Pennsylvania was revised in 1980 and 1983 by the Pennsylvania Geological Survey (Berg and others, 1980; 1983). The revised nomenclature is used in this report and, therefore, may not agree with the geologic nomenclature of some of the reports cited in table 1.

Table 1.--Summary of major geologic and ground-water references of study areas

Reference classification	Study areas			
	Crawford County: Geneva 7-1/2-minute quadrangle	Warren County: Warren 7-1/2-minute quadrangle	Jefferson County: Hazen 7-1/2-minute and Reynoldsville 7-1/2-minute quadrangles	Allegheny County: Pittsburgh East 7-1/2-minute quadrangle
Geology	Geology and ground-water resources of western Crawford County (Schiner and Gallaher, 1979)	Oil and gas geology of the Warren quadrangle (Lytle, 1965) Atlas of preliminary geologic quadrangle maps of Pennsylvania (Berg and Dodge, 1981)	Geology and mineral resoures of the Hazen, Falls Creek, Reynoldsville, and DuBois quadrangles, Clearfield and Jefferson Counties, Pennsylvania (Glover and Bragonier, 1978)	Geology and mineral resources of the Pittsburgh quadrangle, Pennsylvania (Johnson, 1928) Greater Pittsburgh region geologic map and cross sections (Wagner and others, 1975)
Ground water	Geology and ground-water resources of western Crawford County (Schiner and Gallaher, 1979)	Ground water in northwestern Pennsylvania (Leggette, 1936)	Water resources of the Clarion River and Redbank Creek Basins, northwestern Pennsylvania (Buckwalter and others, 1983) Ground-water resources of the DuBois area, Clearfield and Jefferson Counties (Shuster, 1979) Selected water resources data, Clarion River and Redbank Creek Basins, northwestern Pennsylvania--part 2 (Buckwalter and others, 1979)	Summary ground-water resources of Allegheny County (Gallaher, 1973) Geology and mineral resources of the Pittsburgh quadrangle, (Johnson, 1928) Ground-water quality and data on wells and springs in Pennsylvania, volume I--Ohio and St. Lawrence River basins (Koester and Miller, 1980)

Description of Study Areas

Locations of the four study areas are shown in figure 1, and the topography and drainage characteristics of these areas are shown in figures 2-6. [The hydrogeologic sections noted on the figures are discussed in succeeding sections concerning the geology of the respective quadrangles.] The study areas were confined to boundaries of U.S. Geological Survey 7-1/2-minute topographic quadrangles. The quadrangles provided accurate bases for plotting well locations and for determining topographic settings. One minute of latitude is roughly 1 mi. One minute of longitude decreases approaching the poles, but can be considered for this study as about 1 mi in length also. Therefore, a 7-1/2-minute quadrangle covers about 50 mi^2. Criteria used in the selection of study areas include (1) availability of water, oil, and gas well-completion records, (2) representation of selected sections of the Appalachian Plateaus Physiographic Province, (3) representation of areas with major rivers (ground-water discharge areas) and major river basin divides (ground-water recharge areas), and (4) representation of major types of oil and gas fields.

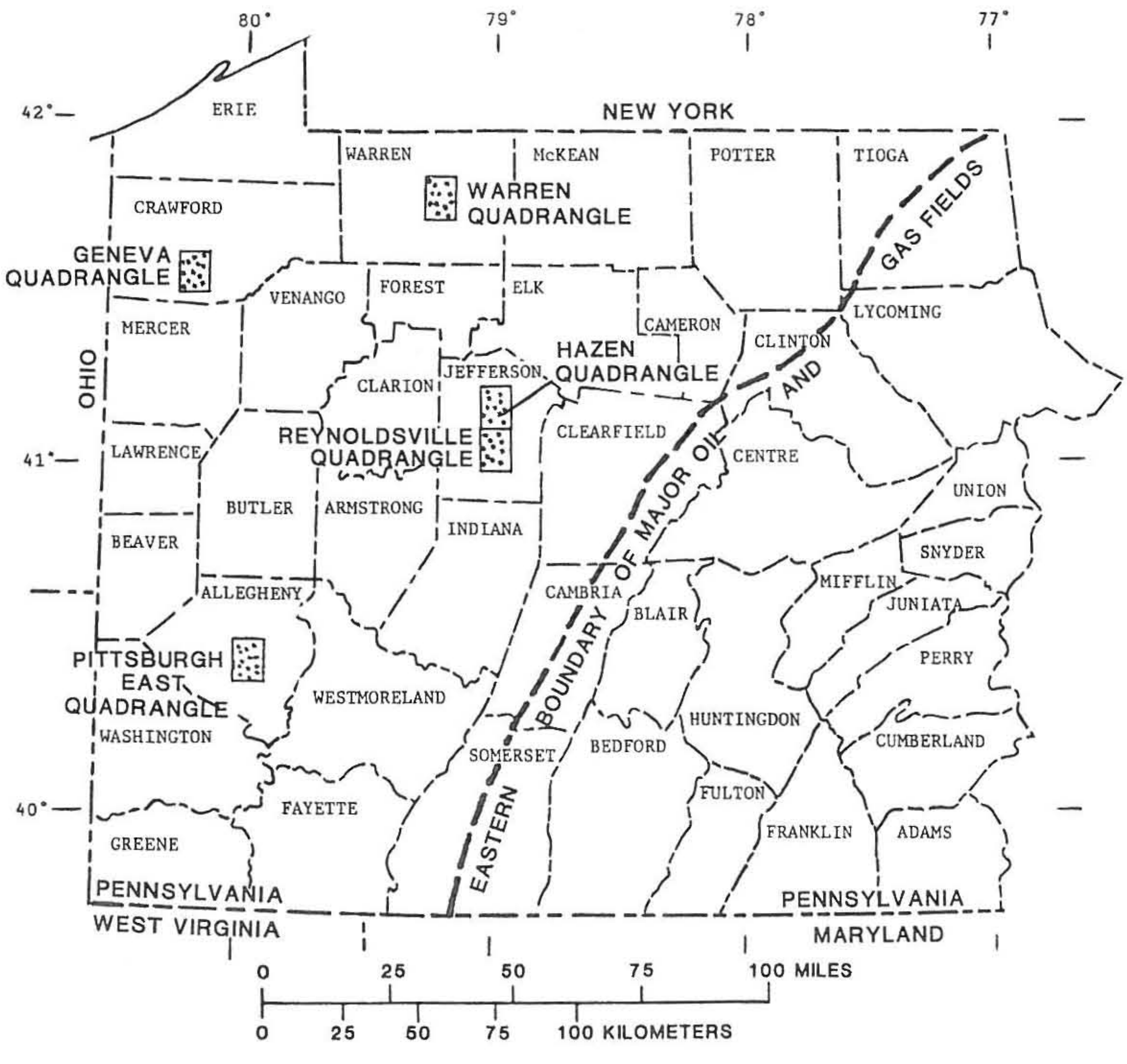


Figure 1. Locations of study areas.

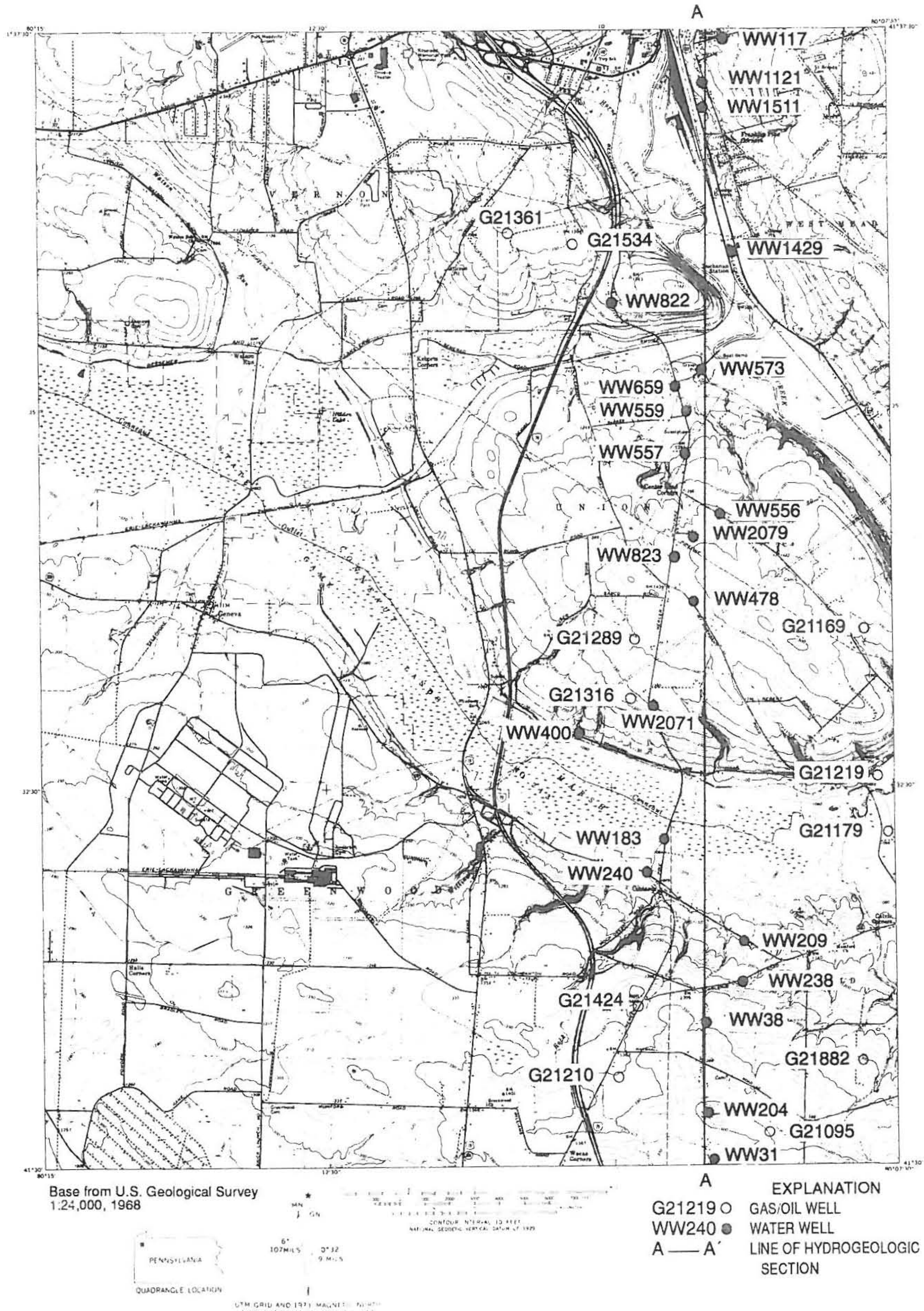


Figure 2. Geneva, Pa. 7-1/2-minute topographic quadrangle showing locations of water and oil and gas wells for hydrogeologic section A-A′ on plate 1.

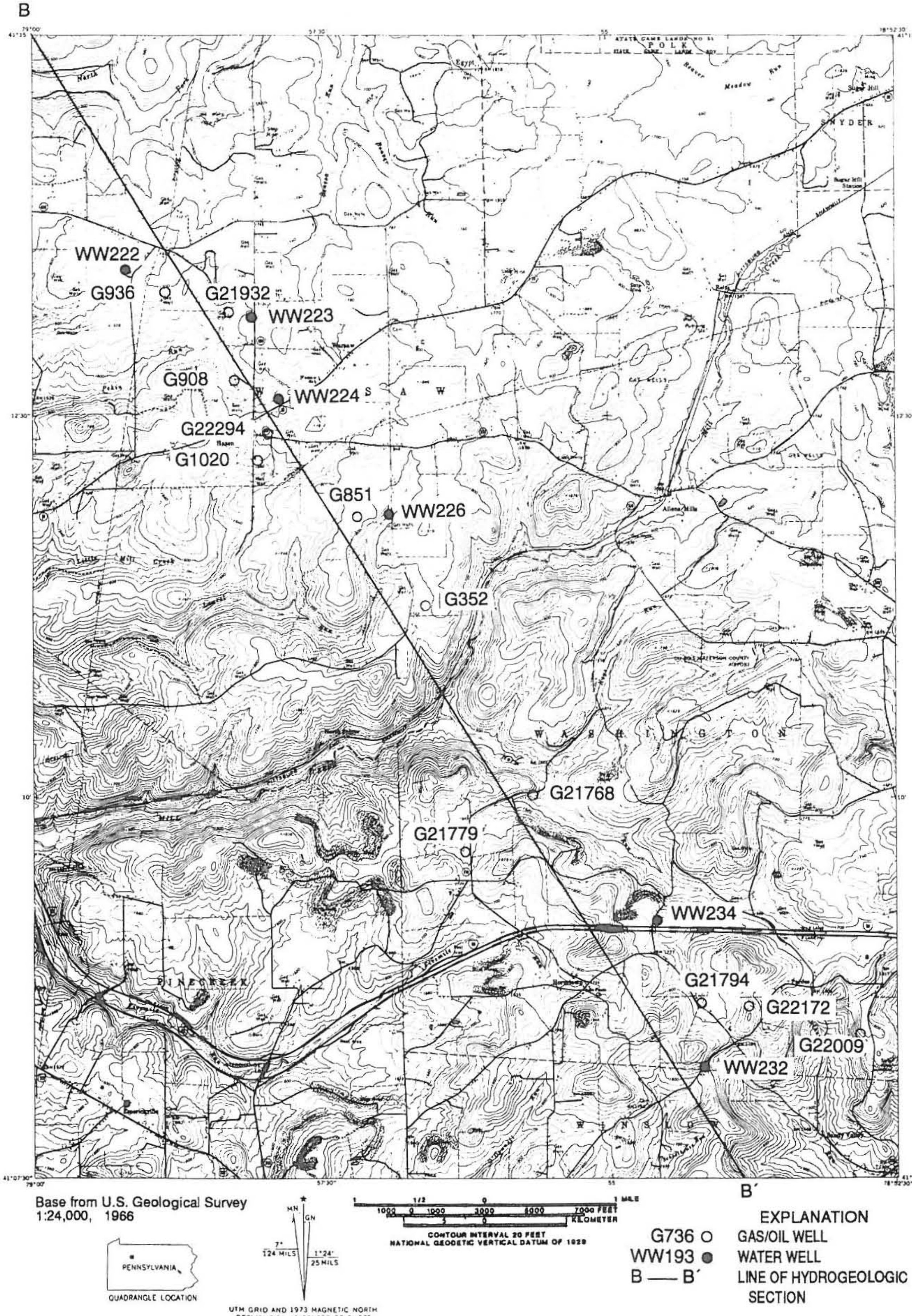


Figure 3. Hazen, Pa. 7-1/2-minute topographic quadrangle showing locations of water and oil and gas wells for hydrogeologic section B-B' on plate 1.

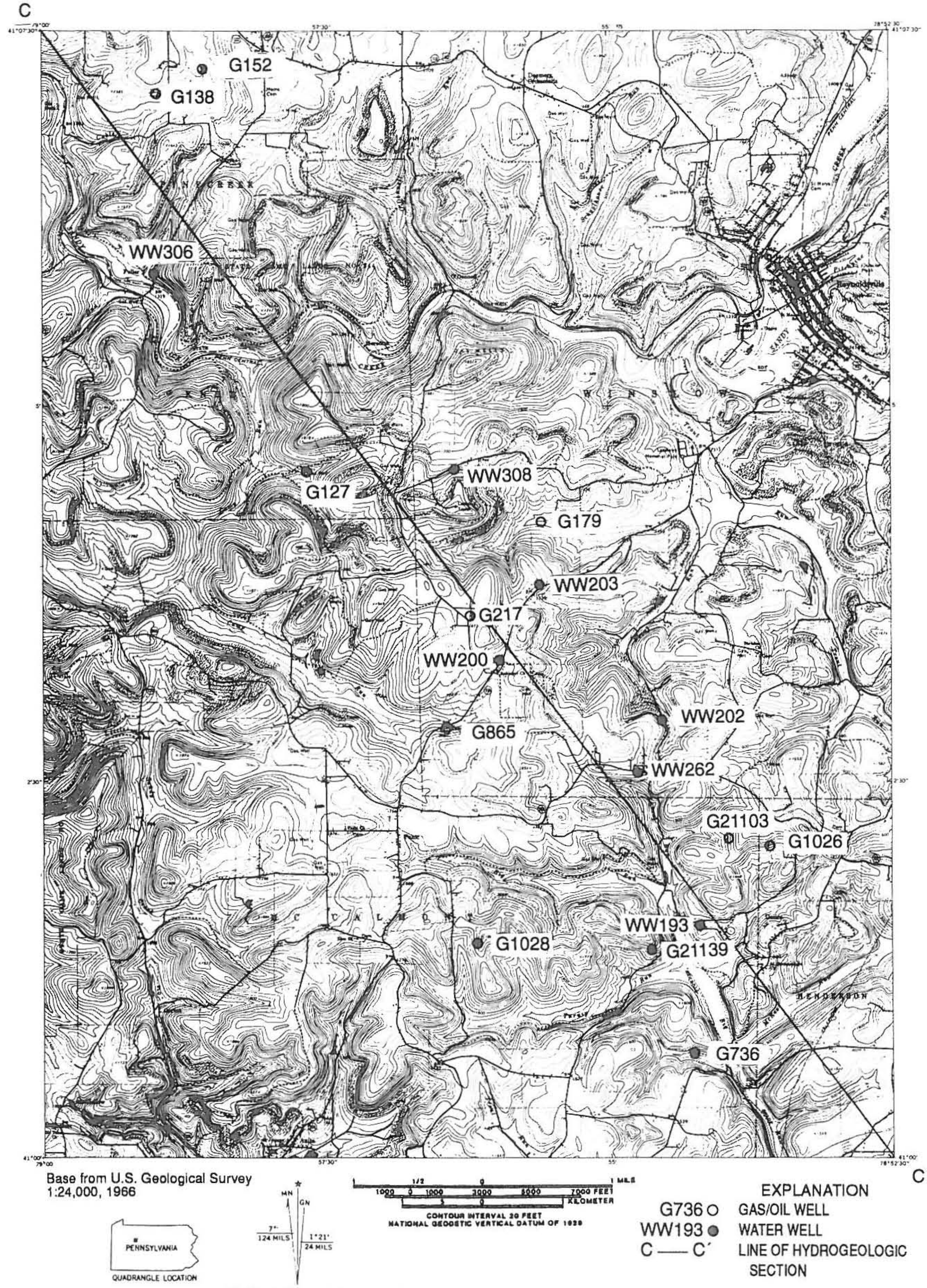


Figure 4. Reynoldsville, Pa. 7-1/2-minute topographic quadrangle showing locations of water and oil and gas wells for hydrogeologic section C-C′ on plate 1.

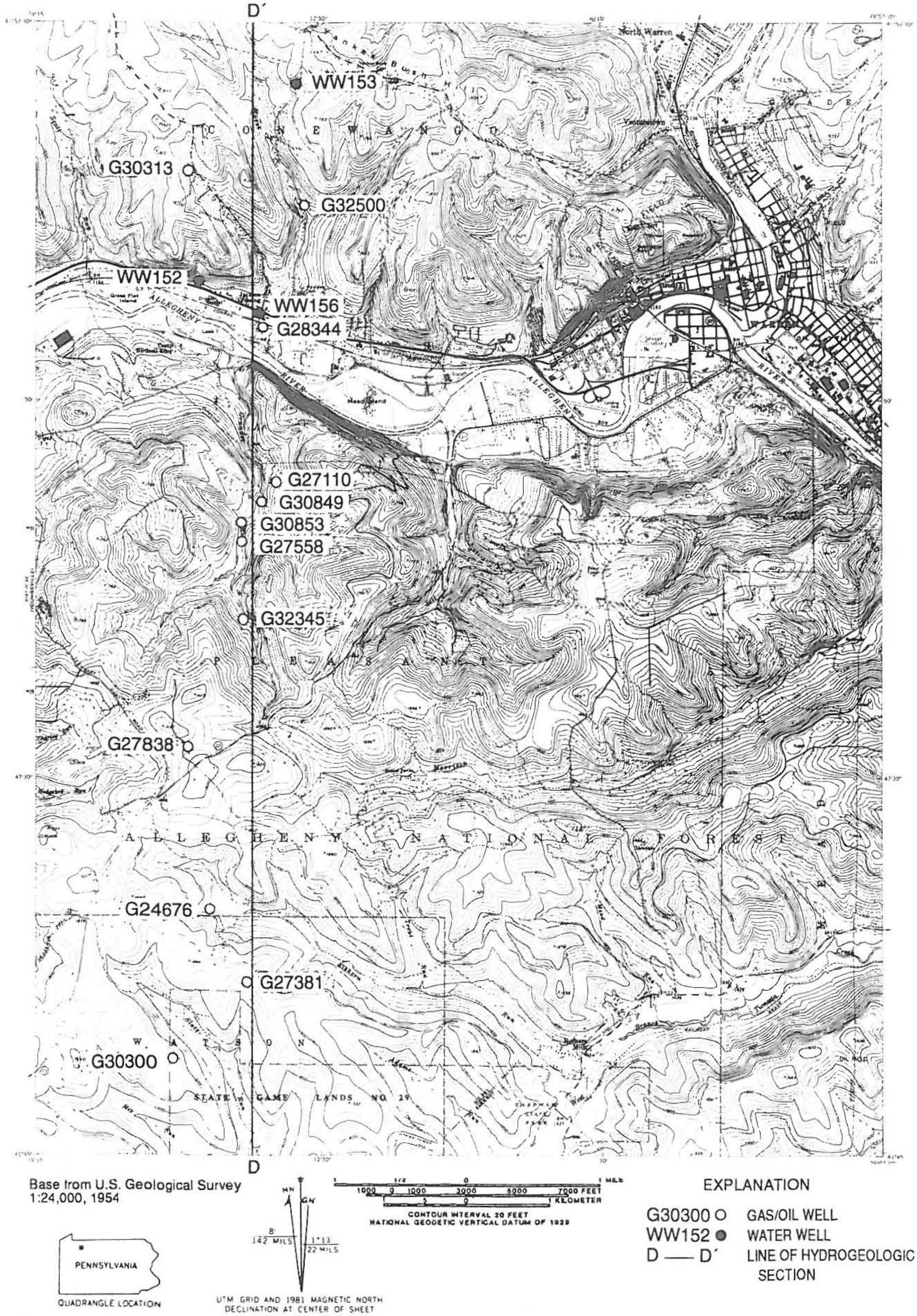


Figure 5. Warren, Pa. 7-1/2-minute topographic quadrangle showing locations of water and oil and gas wells for hydrogeologic section D-D' on plate 1.

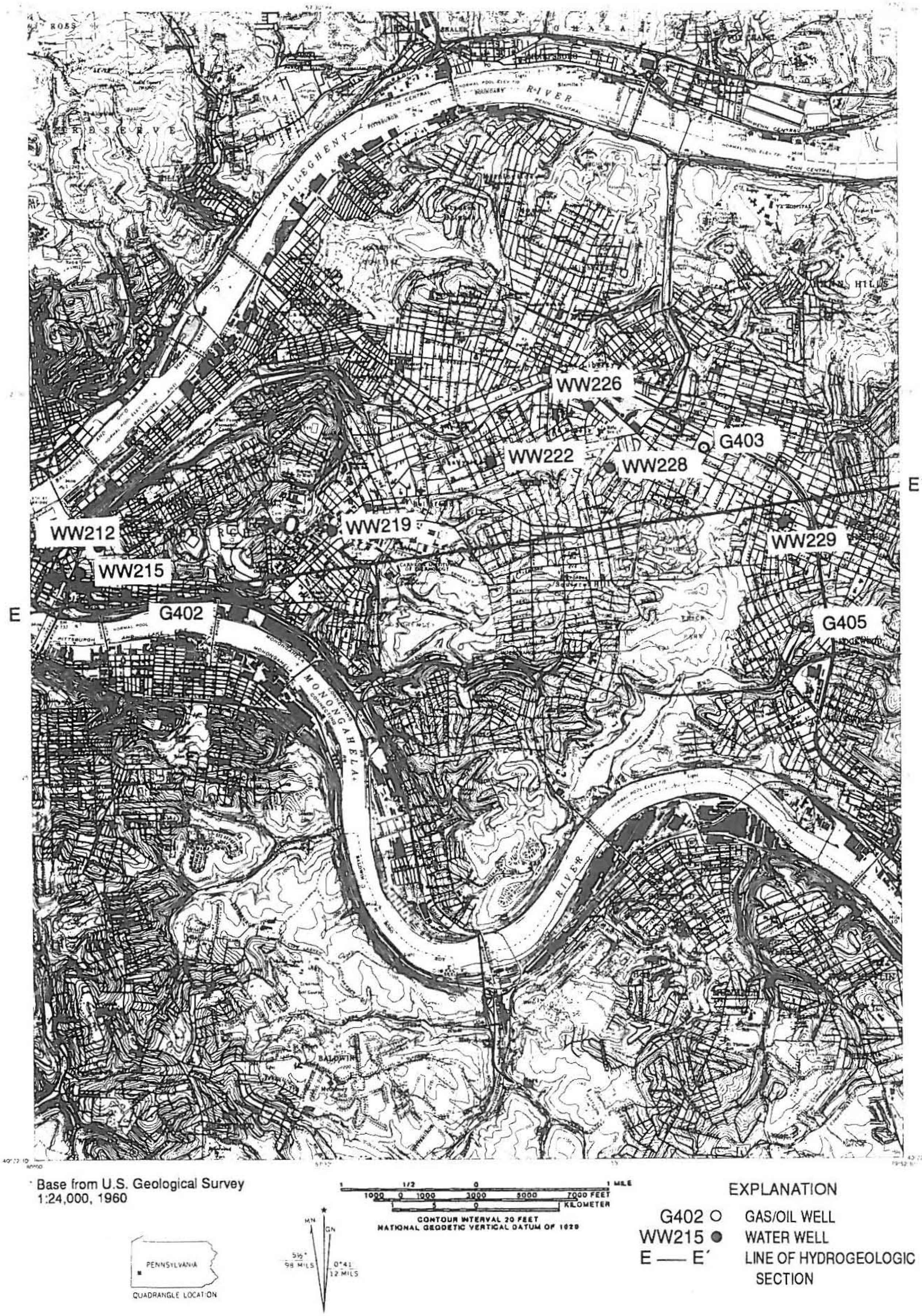


Figure 6. Pittsburgh East, Pa. 7-1/2-minute topographic quadrangle showing locations of water and oil and gas wells for hydrogeologic section E-E′ on plate 1.

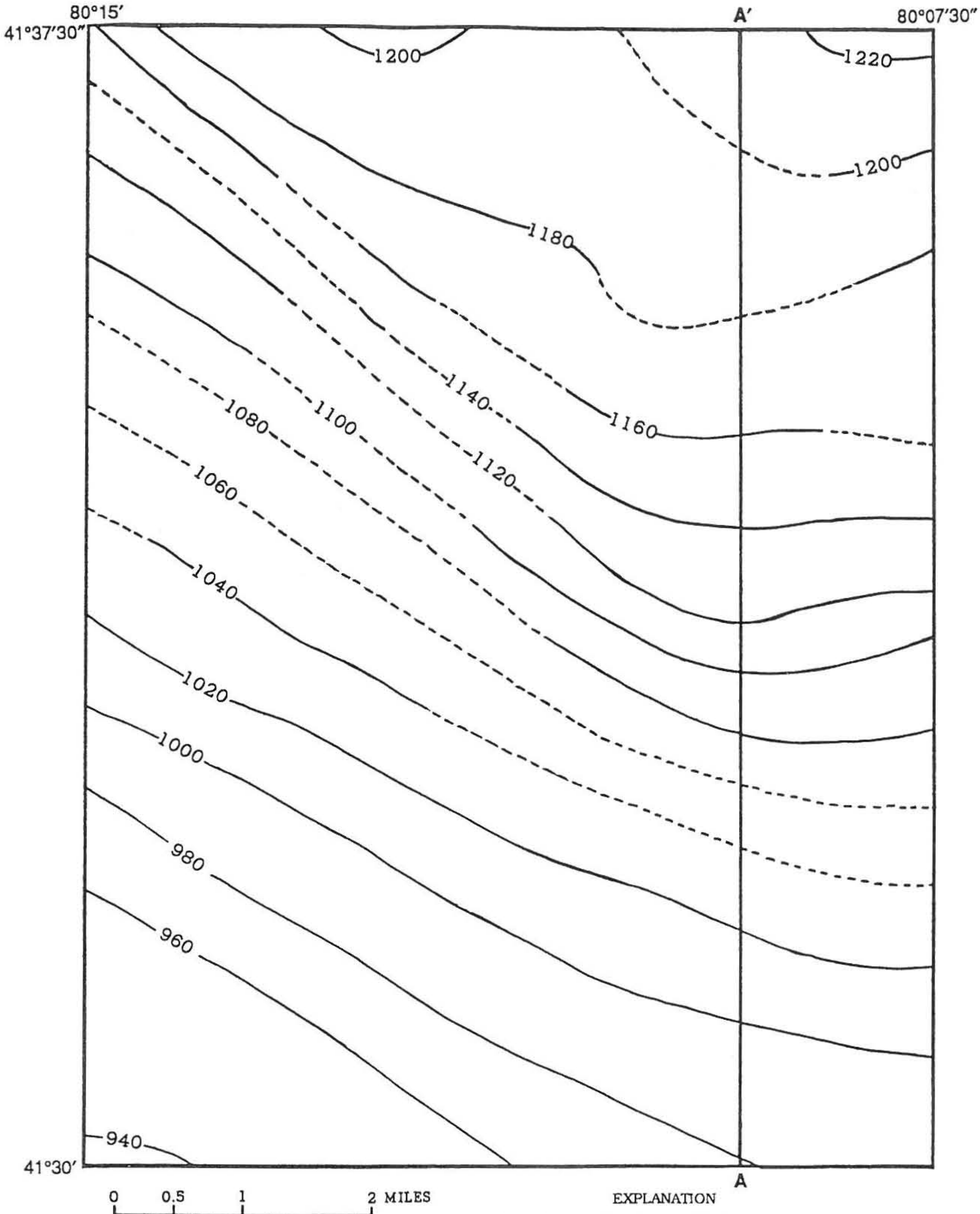
General Geology

All four study areas lie within the Appalachian Plateaus Physiographic Province. Sedimentary rocks of the Appalachian Plateau consist mainly of alternating beds of sandstone, shale, siltstone, and carbonate rocks, which dip gently to the southwest. Before the deposition of the Pennsylvanian rocks, the Mississippian rocks were uplifted and eroded, causing a break in the geologic record. This break, called an unconformity, is commonly recognized as an irregular contact between Mississippian and Pennsylvanian rocks. The attitude of the rocks on either side of the unconformity is essentially the same. Therefore, for the purposes of this report, general comparisons among study areas can be made of reference surfaces in the Pennsylvanian, Mississippian, and Upper Devonian. The few folds in the bedrock represent the long range effects of the building of the Appalachian Mountains. Many of these folds trend northeast-southwest.

The topography of the Appalachian Plateau is controlled predominantly by streams, which cut deep valleys through the sedimentary rocks. Alluvium (stream-deposited sediment) commonly fills many valley bottoms. Glaciers also deposited sediment in the northwestern corner of Pennsylvania, which is the southernmost end of continental glacial migration in the area. The stratigraphic nomenclature in this report generally follows the revised usage of the Pennsylvania Geological Survey (Berg and others, 1983) and may not conform to the usage of the U.S. Geological Survey.

Geneva Quadrangle

The shallow bedrock of the Geneva quadrangle structurally dips to the southwest (fig. 7) and consists predominantly of alternating strata of siltstone, shale, and sandstone (Schiner and Gallaher, 1979). In plate 1, the Riceville Formation and Chagrin Shale are combined and are of Late Devonian age. Rocks of Mississippian age are divided into three units: Berea Sandstone through Cussewago Sandstone undivided, Cuyahoga Group, and Shenango Formation. The Pottsville Group, which caps only the highest hilltops, is of Pennsylvanian age. The study area lies in the glaciated section of the Appalachian Plateaus Physiographic Province. Unconsolidated glacial overburden of the Quaternary System covers most of the bedrock and consists of varying mixtures of clay, silt, sand, gravel, and boulders. Repeated advances and retreats of glaciers have left glacial drift (undifferentiated glacial deposits) that reaches a maximum thickness of up to 500 ft in the valleys but usually is less than 25 ft thick in the upland areas. Glacial drift is not shown in the hydrogeologic section (plate 1) except in the valleys.



EXPLANATION

—1040- - - STRUCTURE CONTOUR--Showing altitude of the top of the Cussewago Sandstone. Dashed lines indicate more widely spaced control. Datum is sea level.
Contour interval 20 feet.
National Geodetic Vertical Datum of 1929

A——A′ LINE OF HYDROGEOLOGIC SECTION

Figure 7. Structure contours of the top of the Cussewago Sandstone, Geneva quadrangle. (From Schiner and Gallaher, 1979).

Hazen and Reynoldsville Quadrangles

The Hazen and Reynoldsville quadrangles lie in the Pittsburgh Plateaus Section of the Appalachian Plateaus Physiographic Province. The shallow bedrock consists predominantly of alternating beds of sandstone, shale, and siltstone, and rocks of Pennsylvanian age also contain coal and carbonate beds. The numerous bedrock folds in the study area control the shallow bedrock structure and are generally symmetrical and plunging (figs. 8 and 9). Folding is most pronounced in the Hazen and especially Reynoldsville quadrangles. Dips along flanks of folds commonly range from 60 to 250 ft/mi and plunge from 0 to 60 ft/mi. The hydrogeologic sections (plate 1) were constructed along a southeast-northwest direction perpendicular to the fold axis. Rocks of Devonian age are found in the Riceville Formation and Venango Group. Rocks of Mississippian age range stratigraphically from the lower Cussewago Sandstone through the Burgoon Sandstone, which are undivided in the hydrogeologic section. Rocks of Pennsylvanian age are divided into three groups: Pottsville Group, Allegheny Group, and Conemaugh Group.

Warren Quadrangle

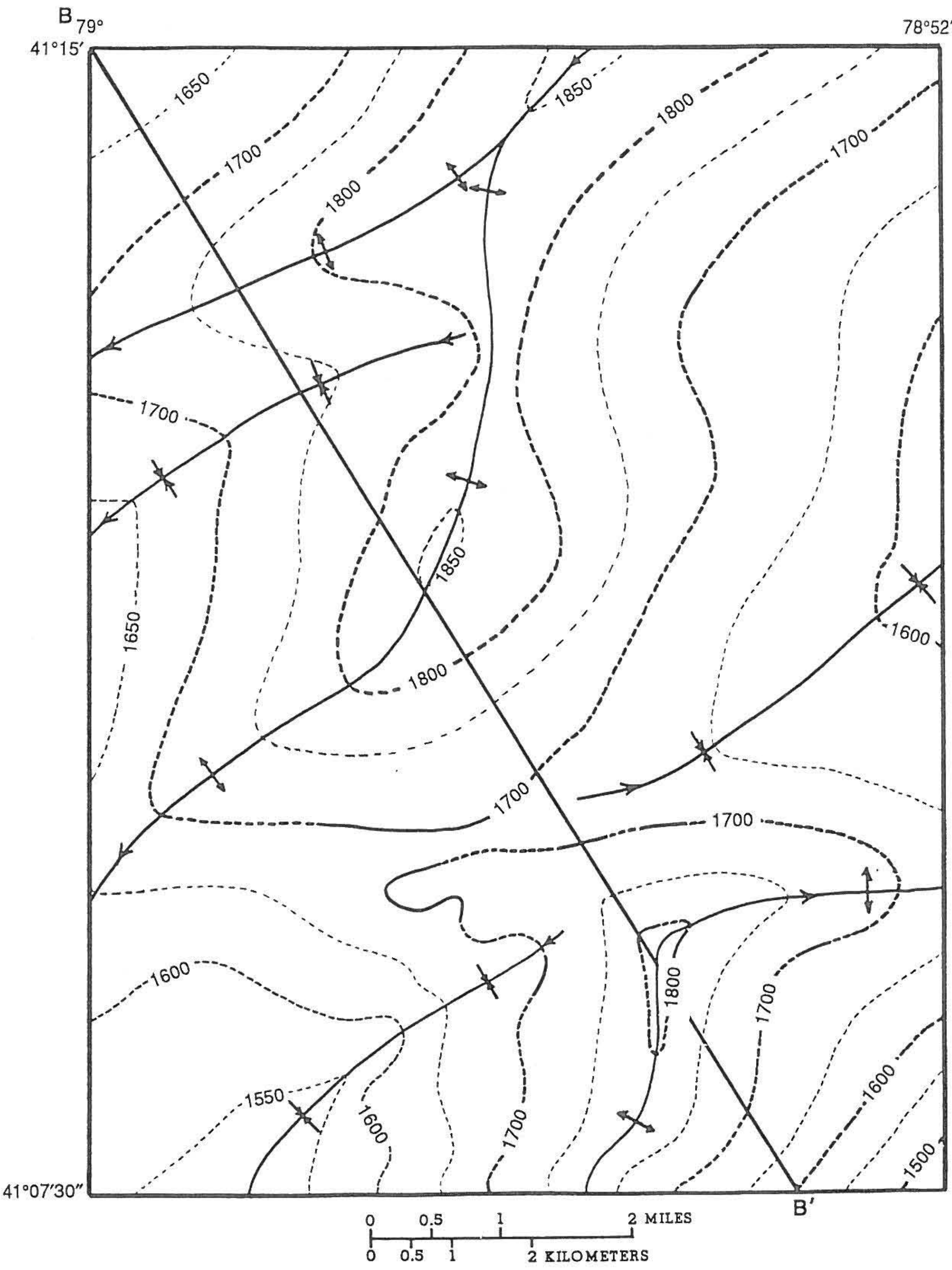
The Warren quadrangle lies in the Glaciated Section and Allegheny High Plateaus Section of the Appalachian Plateaus Physiographic Province. The shallow bedrock dips gently to the southwest (fig. 10) and consists predominantly of alternating beds of shale, siltstone, and sandstone and some conglomerate sandstone beds (Lytle, 1965). The structure contour map is drawn on the base of the "Pink Rock", which comprises about the lower 350 ft of the Chadakoin Formation. Rocks of Devonian age are divided into three stratigraphic units: Bradford Group, Chadakoin Formation, and Venango Group. The Mississippian-Devonian contact is contained in the unit that ranges from the Corry Sandstone through Riceville Formation. The Mississippian Cuyahoga Group has variable thickness over the study area because of an unconformity at the top of the Cuyahoga Group. The rocks of the Pottsville Group of Pennsylvanian age cap only the highest hills in the Warren quadrangle because much of the Pottsville Group has been eroded.

The unconsolidated Quaternary sediments of the area consist of alluvium in the valleys and a thin glacial till (unstratified ice-deposited sediment) that extends to a southern limit at the city of Warren (Lytle, 1965). Alluvium deposits (up to 70 ft thick) and the thin discontinuous glacial till are not shown in the hydrogeologic section (plate 1).

Pittsburgh East Quadrangle

The shallow bedrock of the Pittsburgh East quadrangle consists mainly of alternating beds of sandstone, shale, limestone and coal (Johnson, 1928). Rocks of the Mauch Chunk Formation are Mississippian in age. Rocks of Pennsylvanian age are divided into four units: Pottsville Group, Allegheny Group, Conemaugh Group, and Monongahela Group.

Structurally, the shallow bedrock forms an anticline and a syncline (fig. 11). The gentle folding has caused the bedrock along the geologic section to dip westward. However, the beds generally dip to the south in the remaining part of the quadrangle.



EXPLANATION

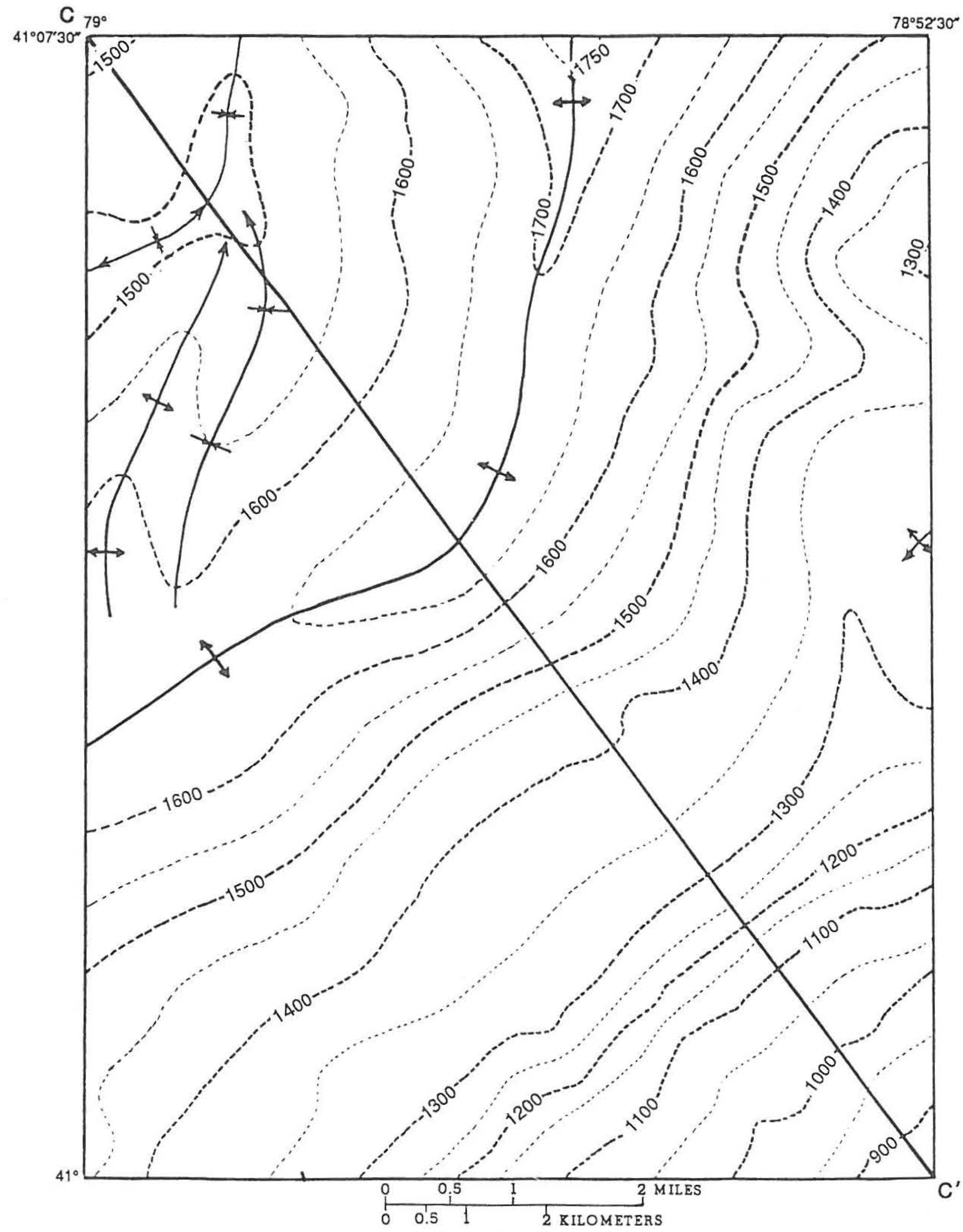
— 1500 --- STRUCTURE CONTOUR--Showing altitude of the base of the Lower Kittanning No. 3 coal bed. Dashed lines indicate more widely spaced control.
Contour interval 50 feet.
National Geodetic Vertical Datum of 1929

ANTICLINE--Showing direction of plunge and axial plane trace.

SYNCLINE--Showing direction of plunge and axial plane trace.

B —— B' LINE OF HYDROGEOLOGIC SECTION

Figure 8. Structure contours of the base of the Lower Kittanning No. 3 coal bed of the Allegheny Group, Hazen quadrangle. (Modified from Glover and Bragonier, 1978).



EXPLANATION

---900--- STRUCTURE CONTOUR--Showing approximate altitude of the base of the Lower Kittanning No. 3 coal bed. Dashed lines indicate more widely spaced control.
Contour interval 50 feet.
National Geodetic Vertical Datum of 1929

ANTICLINE--Showing direction of plunge and axial plane trace.

SYNCLINE--Showing direction of plunge and axial plane trace.

C——C' LINE OF HYDROGEOLOGIC SECTION

Figure 9. Structure contours of the base of the Lower Kittanning No. 3 coal bed of the Allegheny Group, Reynoldsville quadrangle. (Modified from Glover and Bragonier, 1978).

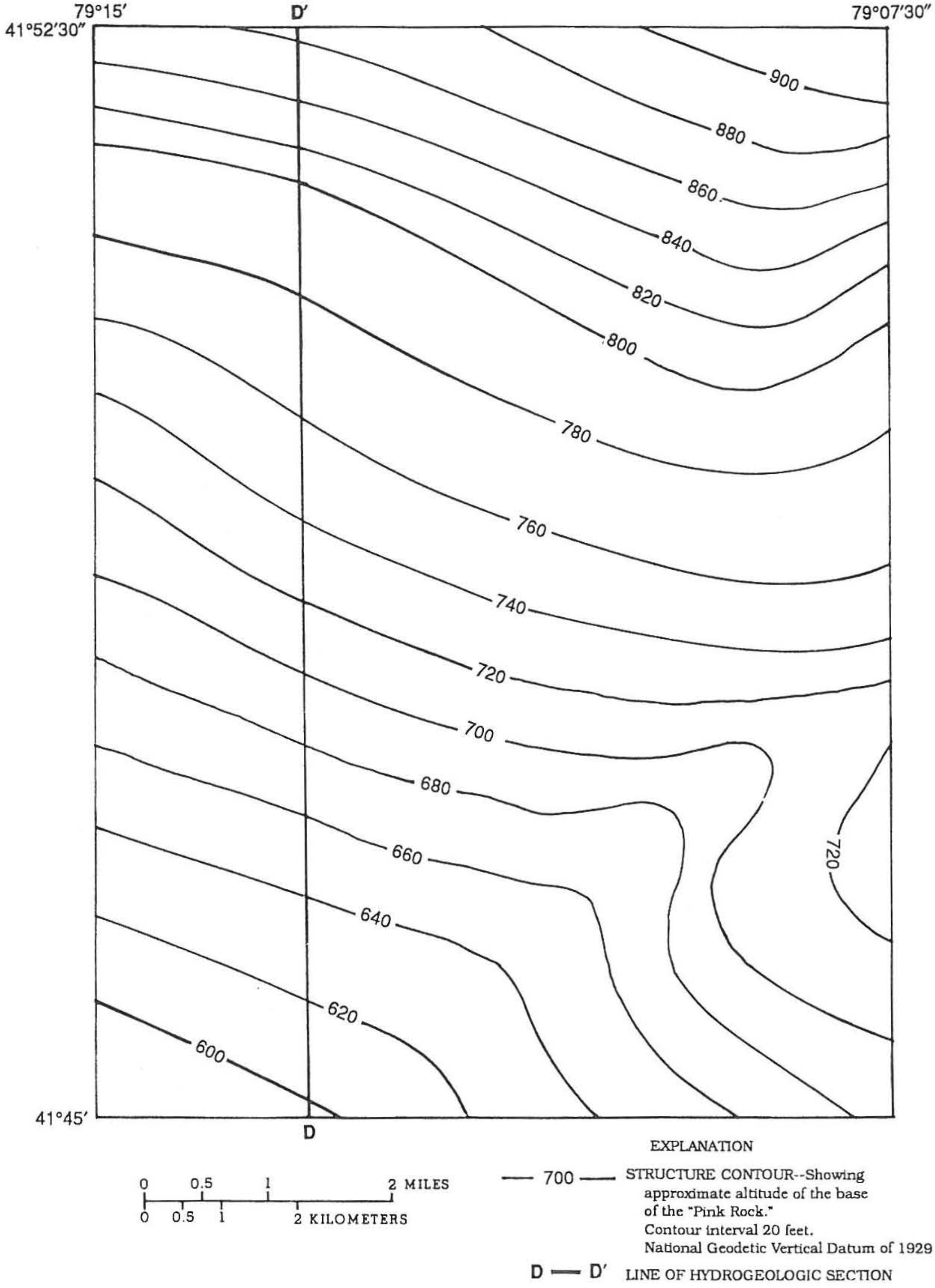
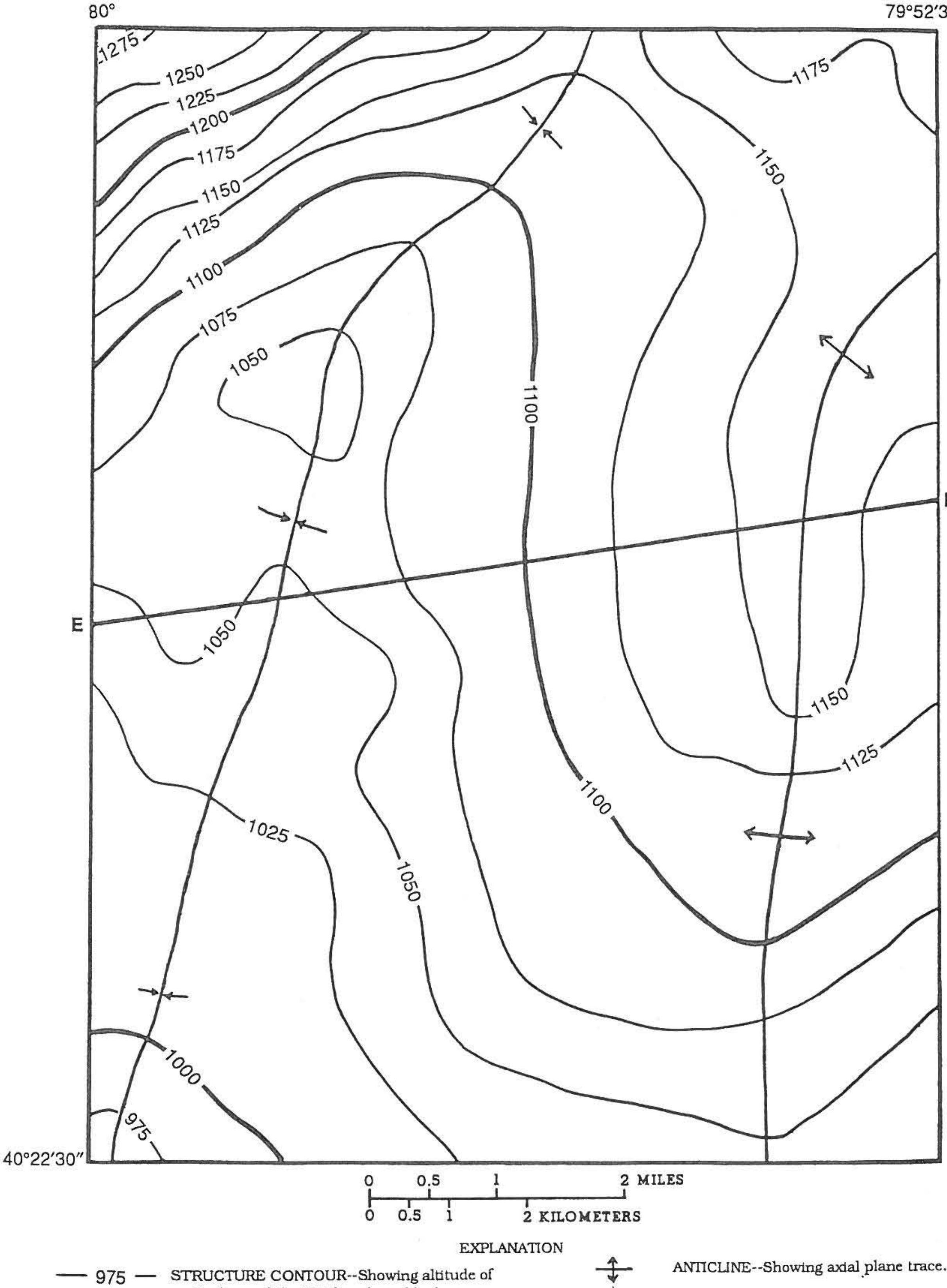


Figure 10. Structure contours of the base of the "Pink Rock" in the Chadakoin Formation, Warren quadrangle. (From Lytle, 1965).



EXPLANATION

— 975 — STRUCTURE CONTOUR--Showing altitude of the base of the Pittsburgh coal bed. Contour interval 25 feet. National Geodetic Vertical Datum of 1929

ANTICLINE--Showing axial plane trace.

SYNCLINE--Showing axial plane trace.

E —— E' LINE OF HYDROGEOLOGIC SECTION

Figure 11. Structure contours of the base of the Pittsburgh coal bed of the Monongahela Group, Pittsburgh East quadrangle. (From Johnson, 1928).

Oil and Gas Development

Oil and gas fields of Pennsylvania can be separated into three groups: shallow sand oil fields, shallow sand gas fields, and deep sand gas fields. Definitions of shallow and deep are given in the glossary. Well constructions and surface-casing practices vary within and between types of oil and gas fields. The study areas of this report were selected to provide a representation of the three major groups of oil and gas fields (table 2).

Table 2.--Oil and gas development of study areas

Study area	Major type of oil or gas field	Major producing formation	Average depth of producing formation (feet)	Average number of wells per square mile	Remarks
Geneva quadrangle	Deep sand gas field	Lower Silurian Medina Group	5,000	0.2	Most wells drilled recently with air or mud rotary drilling methods.
Warren quadrangle	Shallow sand oil field	Upper Devonian Bradford Group	1,200	25	High drilling activity in 1980's in old and new fields; drilling in selected areas on 200 and 400 foot centers. Initial production in some fields about 1875.
Hazen and Reynoldsville quadrangles	Shallow sand gas field	Upper Devonian Elk Group	3,000	3	Wells distributed throughout most of the area. Older wells drilled with cable tool; newer wells drilled with air rotary.
Pittsburgh East quadrangle	Shallow sand gas field	Mississippian sandstones and Upper Devonian Venango Group	2,000	2	Most wells drilled prior to 1930 by cable tool methods.

Surface-Casing Constructions of Typical Oil and Gas Wells

This section of the report briefly describes the surface casing and cementing methods of typical oil and gas well constructions in western Pennsylvania and notes potential deficiencies of the surface casing constructions that may result in contamination or dewatering of fresh ground-water aquifers. Detailed discussion of the step by step procedures of drilling, casing installation, and cementing of various well types is beyond the scope of this report. These procedures are presented in a study prepared for PaDER by Waite and Blauvelt (1983).

Typical oil and gas well constructions common to western Pennsylvania are shown in figures 12-14 (modified from Waite and Blauvelt, 1983). The range of surface-casing depths and cementing practices noted on the figures agree generally with the findings in the study areas of this report.

Deficiencies in ground-water protection in oil wells may include insufficient depth of surface casing and lack of cement between the surface casing and borehole. The uncemented annular space from the bottom of the surface-casing seal (fig. 12) to the bottom of the hole may enable undesirable fluids, such as salty water, oil, or gas to rise in the borehole. Movement of these fluids into freshwater in the fractured bedrock is possible if surface casing is not deep enough. Freshwater aquifers also may be dewatered if surface casing is too short or poorly installed. Fresh ground water under these circumstances may move down the annular space of the well to deeper permeable strata. Water wells in the dewatered aquifer may go temporarily or permanently dry.

In gas wells that tap the Tuscarora Formation of Silurian age (gas production averaging 11,000 ft in depth) and in some other deep gas wells, surface casing is typically 1,400 to 1,600 ft long and is cemented to land

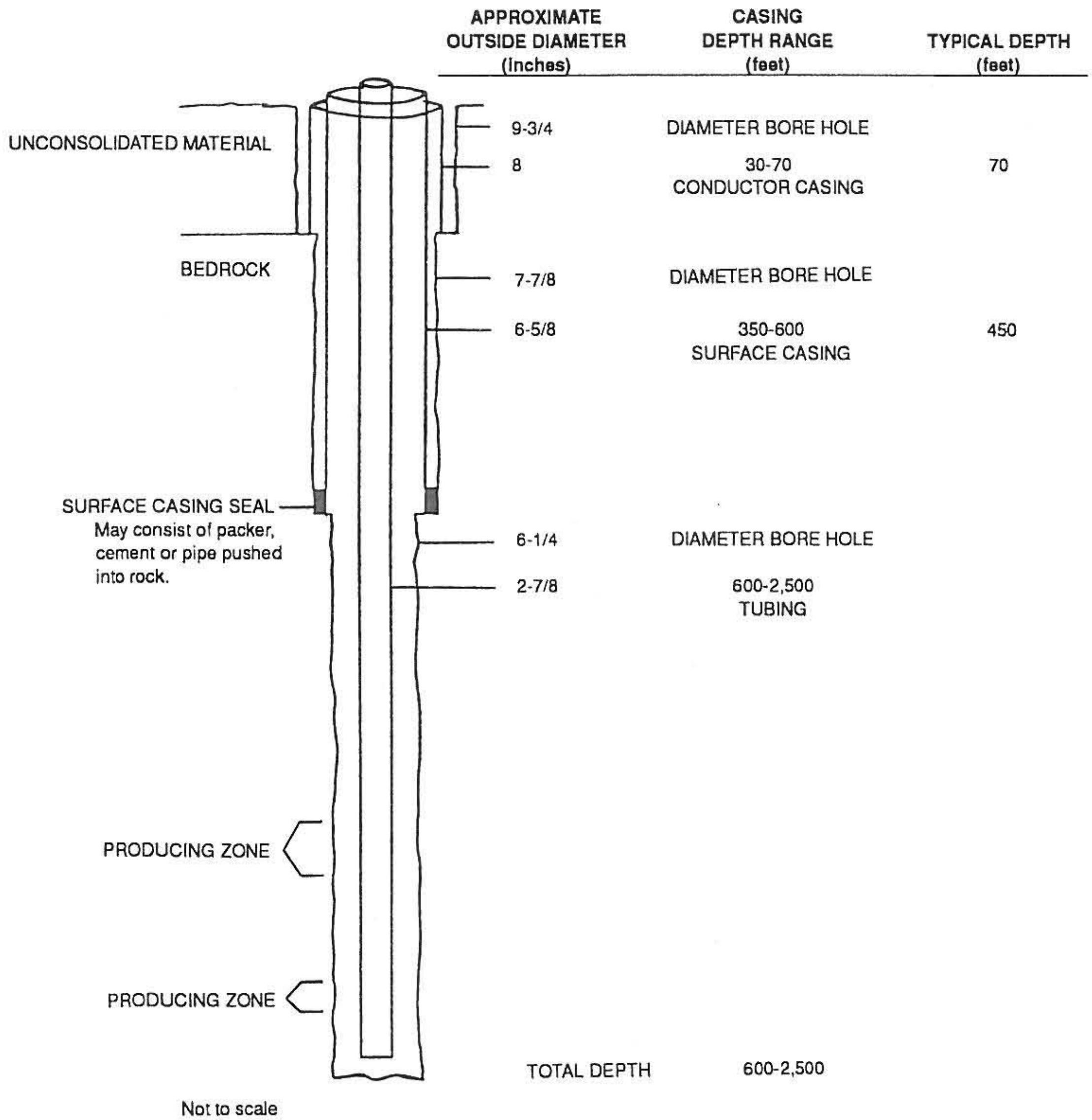
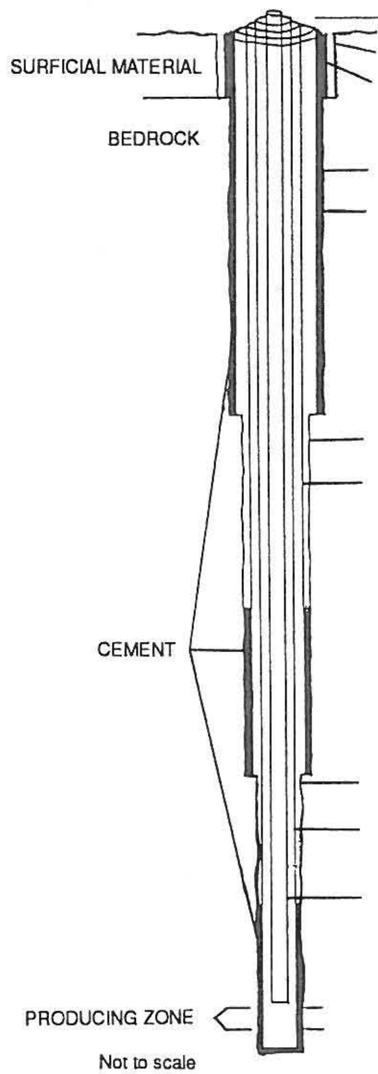


Figure 12. Typical construction of a shallow oil well in Warren, McKean, or Elk County. (Modified from Waite and Blauvelt, 1983).

surface. Additionally, intermediate casing strings as long as 9,000 ft and production casing commonly are cemented. High pressures and strength requirements for supporting the heavy weight of casing and tubing in some of these deep wells requires the filling of annular spaces with cement. Fresh ground water is protected by these well-construction techniques needed to produce the gas.

Intermediate casing strings (water strings) are set in selected oil and gas wells after surface-casing installation. The purposes of the intermediate strings include protection of the hole from caving, providing attachment for blowout preventers, and prevention of entry of unwanted fluids. The annular space of intermediate strings of casing often is cemented for strength requirements. Intermediate strings of casing when cemented may act to protect freshwater located below the surface casing and prevent upward migration of gas, brine, or stimulation fluids.



APPROXIMATE OUTSIDE DIAMETER (inches)	CASING DEPTH RANGE (feet)	TYPICAL DEPTH (feet)
18	DIAMETER BORE HOLE	
16	15 - 50 CONDUCTOR CASING	30
15	DIAMETER BORE HOLE	
11-3/4	100 - 500 SURFACE CASING	250
11	DIAMETER BORE HOLE	
8-5/8	600 - 1,400 WATER STRING (INTERMEDIATE CASING STRING)	1,000
7-7/8	DIAMETER BORE HOLE	
4-1/2	3,000 - 4,000 PRODUCTION CASING	3,600
2	3,000 - 4,000 TUBING	3,500
TOTAL DEPTH	2,100 - 3,900	3,600

Figure 13. Typical construction of a shallow gas well in coal region in Clearfield, Cambria, or Jefferson Counties. (Modified from Waite and Blauvelt, 1983).

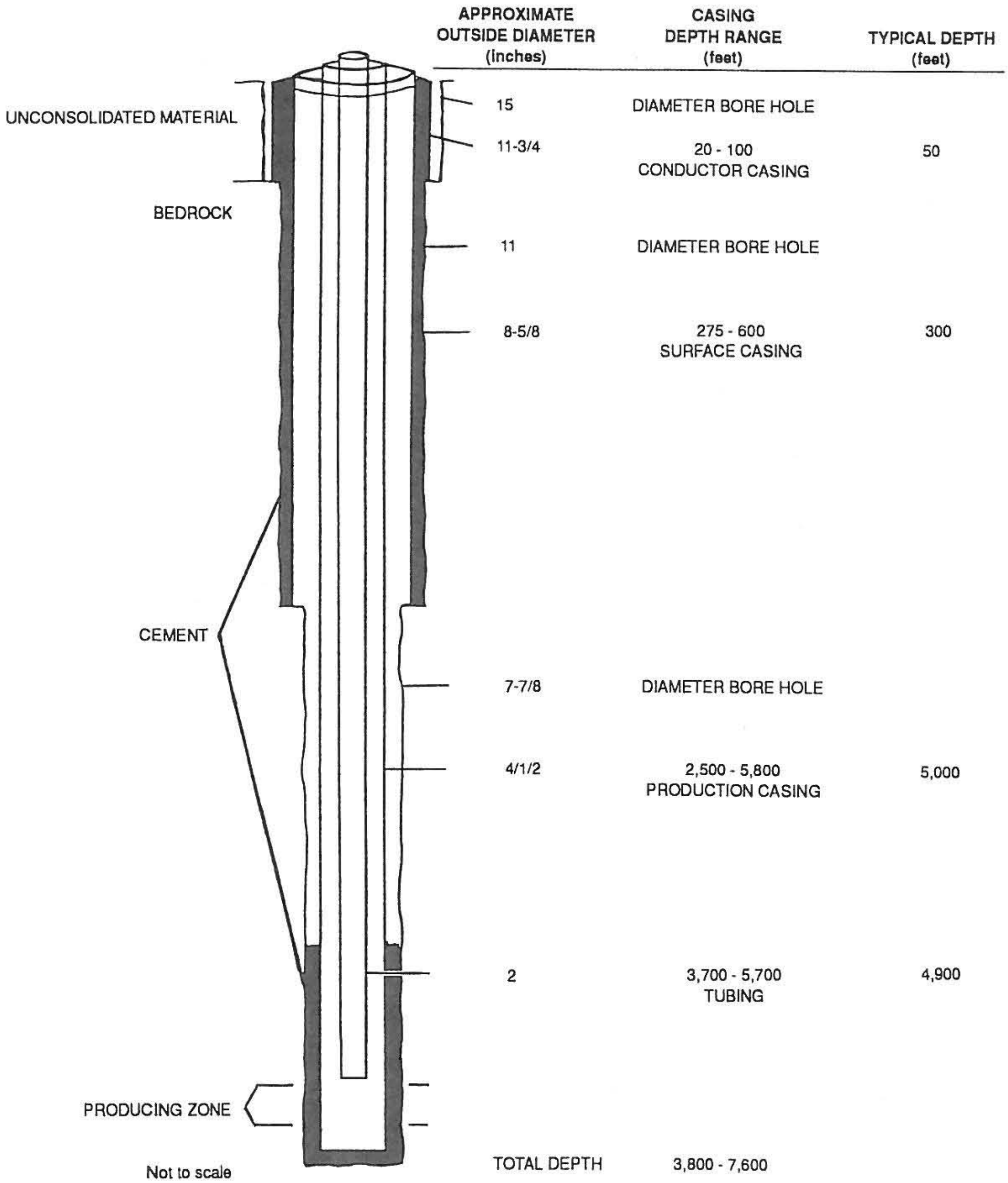


Figure 14. Typical construction of a deep gas well outside the coal region in Crawford or Erie County. (Modified from Waite and Blauvelt, 1983).

TYPES AND ACCURACY OF DATA

Oil and Gas Well-Completion Reports

The presence of ground water is not recorded in oil and gas well-completion reports for many wells and, when reported, generally represents major water-bearing zones; freshwater and saltwater are discriminated mostly by subjective taste tests. The depths of minor freshwater-bearing zones (see Glossary) generally are not observed during drilling with modern air-rotary methods because of the high air pressures. Drilling by cable-tool methods facilitates detection of water-bearing zones due in part to the slow drilling rates. Unfortunately, the reports on many old oil and gas wells drilled by cable-tool methods do not mention depths of freshwater and saltwater, and many old oil and gas wells do not even have reports.

Quantification of aquifer characteristics from water reports in oil and gas well-completion reports is difficult. Recordings of yields of water-bearing zones are sparse in oil and gas well-completion reports and, when present, often use nonquantitative terms such as "10 bailers per hour," "big flow," "small flow," "4 bailers," and "hole full." Yields from water-bearing zones of oil or gas wells by using air-rotary methods are only occasionally reported and commonly are referred to in the unquantifiable terms of a 1-, 2-, or 5-in. "stream."

In oil and gas well-completion reports, the accuracy of land-surface elevations and water depths is difficult to determine and probably varies from area to area and from operator to operator. Land-surface elevations of old wells were sometimes determined from 15-minute topographic quadrangles and may reflect errors of perhaps 50 to 100 ft, especially in rugged terrain. Old well records sometimes must be used because they are the only ones available. The elevations of most recently-drilled wells are more accurate because of the use of 7-1/2-minute topographic quadrangles and frequent surveying of many wells. Altimeter measurements by U.S. Geological Survey personnel of land-surface elevations of gas wells in Forest, Elk, and Jefferson Counties in the mid 1970's rarely differed by more than plus or minus one contour interval (20 ft) from well elevations reported by gas operators using 7-1/2-minute topographic maps.

Interpretations of altitudes of freshwater and saltwater zones in old oil and gas records of, for example, the 1930's through the 1950's may be misleading because geohydrologic conditions of today may be different from those of the past. Various factors responsible for changes in geohydrologic conditions through time include movement of fresh and saline water through unplugged and abandoned wells, changes in fresh ground-water withdrawals, and brine-disposal techniques.

Water Well-Completion Reports

Total depths of water wells were evaluated as one indicator of the presence and depth of freshwater. Water-well depths were obtained from published reports and from Pennsylvania Geological Survey files of water well-completion reports. The water in wells used for water supply can usually be assumed to be fresh. Water-well records were searched for reports of salty water.

Total depths of water wells in the four study areas are commonly not representative of the base of the fresh ground water because water wells often are completed at shallow depths as soon as adequate yields are obtained. Other water wells may be drilled as much as several hundred feet below the deepest reported water-bearing zone. Thus, the bottom of the water well may be below the altitude of the base of the naturally occurring freshwater system. Although information often is lacking, unusually deep water wells may exist, not because of deep water-bearing zones, but for additional borehole storage, or unsuccessful deep exploration for additional water.

Not all water wells within a study area were evaluated because well-record files are incomplete. The well data summarized for this report were based mostly on well inventories from prior ground-water assessments and probably represent a cross section of the depths and types of water wells in the study areas. Some water-well data have well-location errors and errors in land-surface elevations of perhaps 50 to 100 ft because locations were not field checked during all of the ground-water studies.

Geophysical Logs

Most commercial geophysical logs of oil and gas wells on file with PaDER are not suitable for determination of freshwater-bearing zones; most logs are run after surface casing has been installed and cemented negating most electric log interpretation. Many logs are only run at deep oil and gas producing horizons. Where suitable electric logs are run in uncased holes, water samples critical for documenting any electric log interpretations commonly are not collected. The thin beds and changing bedrock lithology common to western Pennsylvania also cause difficulties in defining formation boundaries and accurate quantification of essential elements of geophysical log interpretation.

Geophysical logs made with a U.S. Geological Survey logger designed for water wells showed changes in lithology and water quality with depth at several wells. Fluid-conductivity logs were especially helpful in selecting depths to sample for field and laboratory analyses. Brine-trace logs were valuable in evaluating vertical flow at various depths in wells. Temperature logs assisted in delineating water-bearing zones, water-thieving zones, and depth intervals with no vertical flow. Lithology in wells was described mostly from well cuttings and natural-gamma logs.

Water Quality

Field and laboratory analyses of ground-water samples are an excellent means of documenting salinity. Common field analyses include measurements of specific conductance and chloride concentration. Useful laboratory determinations are analyses of concentrations of major anions and cations. Water-quality analyses in the ground-water literature of western Pennsylvania and of the study areas of this investigation are mostly from water wells. Unfortunately, few water wells penetrate many of the deeper freshwater aquifers, resulting in a lack of water-quality analyses near the base of the freshwater system. The report by Koester and Miller (1980) summarizes most of the published U.S. Geological Survey laboratory analyses of ground water for western Pennsylvania including several analyses of samples of ground water from wells in most of the study areas of this investigation. The report also includes some ground-water quality data from files of various agencies of PaDER.

GEOHYDROLOGIC SETTING

Ground-Water Occurrence and Movement

Recharge to the freshwater aquifers comes from precipitation. Only part of the total precipitation reaches the aquifers; the remainder is divided between transpiration, evaporation, and runoff. Water recharging the aquifers percolates through the unsaturated soil or bedrock into the aquifers.

Studies done in the Appalachian Plateaus Physiographic Province by Stoner and others (1987), Wyrick and Borchers (1981), and Pennington and others (1983) report that fractures are the predominant cause of permeability (hydraulic conductivity) in bedrock aquifers. In Greene County, Pa., Stoner determined that the average hydraulic conductivity decreased with depth below land surface at a rate of one order of magnitude per 100 ft of depth because of closure of fractures with depth. This determination was based on aquifer tests performed on three well pairs. Median yields from wells and springs in the county were relatively independent of geologic formation, but higher yielding wells were found in coal beds and sandstones that were less than 200 ft below land surface. A digital ground-water flow model done by Stoner, based on data collected in Greene County, indicated that only 0.5 percent of total ground-water circulation occurs in aquifers located deeper than 175 ft. In Wyoming County, W. Va., Wyrick and Borchers (1981, p. 30) determined, through pump tests, that horizontal bedding-plane fractures pinch out under valley walls, which effectively formed impermeable barriers. In a study area located in northern Appalachian Plateaus, Pennington and others (1984, p. 28) reported that during drilling of monitoring wells, discrete water-bearing fractures were intersected, and he suggested there was little or no correlation between lithology and well yield in their study area.

Ground water moves in the direction of decreasing head (water altitude) from areas of recharge to areas of discharge. Fractured sandstone, coal, and carbonate beds generally are more permeable (transmit water more easily) than thick shale beds, and therefore, probably provide the main conduits by which water may move. Ground water tends to flow vertically through less permeable beds and laterally, to areas of discharge, through more permeable beds. In the study areas, springs and most lakes and streams represent areas of ground-water discharge.

The base of the fresh ground-water system in the Appalachian Plateaus Physiographic Province is dependent on local conditions. The base would probably be shallower in flat-lying, upland areas, with relatively impermeable bedrock aquifers, possibly composed of shales. The base would probably be deepest in a major drainage valley with relatively permeable aquifers, possibly composed of sandstone or carbonate rocks.

Published data for most of western Pennsylvania generally are lacking concerning the base of the fresh ground-water system and freshwater-saltwater contacts. However, a report by Carswell and Bennett (1963) about the Neshannock quadrangle (15-minute), Mercer and Lawrence Counties, Pa., states that the ground water occurs in a complex system in which precipitation percolates to the water table and then moves laterally along the shallow and deep sandstone units to discharge into streams that drain the area. The sandstone units are of Mississippian and Pennsylvanian age and are interbedded with units of shale, limestone, and coal. The base of this ground-water system is represented by the fluid contact of the freshwater with the highly mineralized connate brine. Carswell and Bennett theorize that, if diffusion is assumed to be negligible and brine is assumed to be static, the freshwater-saltwater contact will rise in the direction of the flow. Thus, depth to the base of the freshwater system will be least under channels of major ground-water discharge and greatest under major recharge areas (ground-water divides).

Harrison (1983) examined the geohydrology in the Glaciated Section of the Appalachian Plateaus Physiographic Province in northwestern Pennsylvania. His evaluation included the study area in Crawford County (Geneva quadrangle) of this report. Harrison (1983) stated that the ground-water flow system is essentially controlled by topography in the undeformed, flat-lying bedrock. Recharge occurs in upland areas, and discharge in the lakes and valleys, but local ground-water movement may be independent of the regional flow system. The base of the regional flow system was admittedly not well understood, but according to Harrison (1983) seemed to extend to a maximum depth of about 500 ft below land surface. However, Harrison noted that in upland areas, underlain by low permeable shales and where local relief was low, the base of the freshwater can be less than 100 ft from land surface. He based his conclusions on data collected by Schiner and Gallaher (1979).

Westlund (1976) studied ground-water occurrence and ground-water flow in a major oil field in northcentral McKean County, northwestern Pennsylvania. This area has topography, geology, and oil fields closely resembling the study area in Warren County (Warren quadrangle) of this report. Westlund (1976) concluded that the flow system roughly parallels the contour of the land surface. He stated that the infiltrating precipitation moves downward through the soil and underlying fractured shales until the more permeable sandstone layers are reached. Ground-water movement in the sandstone layer is essentially horizontal and towards a drainage area. The average depth of ground-water circulation of freshwater is 360 ft in upland areas and 450 ft in valleys, where all fractures are considered to be essentially closed. Westlund based his conclusions of the depth of the fresh ground-water system on reports of casing lengths used by drillers to exclude ground water from the oil sand.

The effects of any lineaments or major faults on depth of freshwater are unknown, but if increased vertical permeability results, the depth of the freshwater would doubtlessly increase. The resultant increased circulation of freshwater would also aid in flushing of connate waters in the vicinity of these fracture zones. No major faults were noted in the published geologic maps of the study areas. Mapping and documentation of lineaments were beyond the scope of this study.

Ground-Water Quality

The classification of waters described by Schiner and Gallaher (1979) is used in this report:

Term	Chloride concentration (mg/L)	Dissolved solids (mg/L)	Specific conductance (µS/cm)
Freshwater	<100	<500	<900
Slightly saline	<100 - 1,500	500 - 3,000	900 - 5,000
Moderately saline	1,500 - 7,000	3,000 - 10,000	5,000 - 20,000
Very saline	7,000 - 26,000	10,000 - 35,000	20,000 - 60,000
Brine	>26,000	>35,000	>60,000

The 35,000 mg/L of dissolved solids in the classification of saline water was set to be the same as ocean water. Brines represent concentrated ocean water containing mostly sodium chloride. The occurrence, geochemistry, and hydraulics of brine in western Pennsylvania are discussed by Poth (1962). Brines typically are present with oil- or gas-bearing strata.

Upward movement of brines from oil and gas sands through abandoned wells (or the annular space of wells) to freshwater aquifers is controlled not only by lithostatic pressures but also by pressures from gas and oil in the reservoir rock. When oil and gas formation pressures have been depleted from production, for example, then heads on brines in the oil and gas sands probably will not be sufficient to move the brine the hundreds of feet vertically to the freshwater aquifers.

The relation between chloride concentration and specific conductance and the relation between specific conductance and dissolved solids (Schiner and Gallaher, 1979) are shown in figures 15 and 16, respectively. The data were compiled from wells in northwestern Pennsylvania.

Recommended drinking-water limits of particular interest in this report include the 500 mg/L limit for dissolved solids and the 250 mg/L limit for chloride concentrations (U.S. Environmental Protection Agency, 1977). Chloride usually is not harmful to humans, but chloride concentrations above 250 mg/L often impart a salty taste to the water that is objectionable to many people (U.S. Environmental Protection Agency, 1977).

The ability to detect a salty taste varies among individuals. Reports of saline water in well-completion reports often are derived from subjective taste tests by drillers; thus, reports of saline water would have greater validity if subsequently documented by laboratory analysis for chlorides or dissolved solids. In this report, the term "salty" will be used when neither the amount of dissolved solids nor the chloride concentrations are known. Whenever possible, the terms in Schiner and Gallaher (1979) will be used.

Samples of saline ground water are lacking for large areas of western Pennsylvania. Saline ground waters have been sampled in a few localities in western Pennsylvania directly below fresh ground water, but data about the

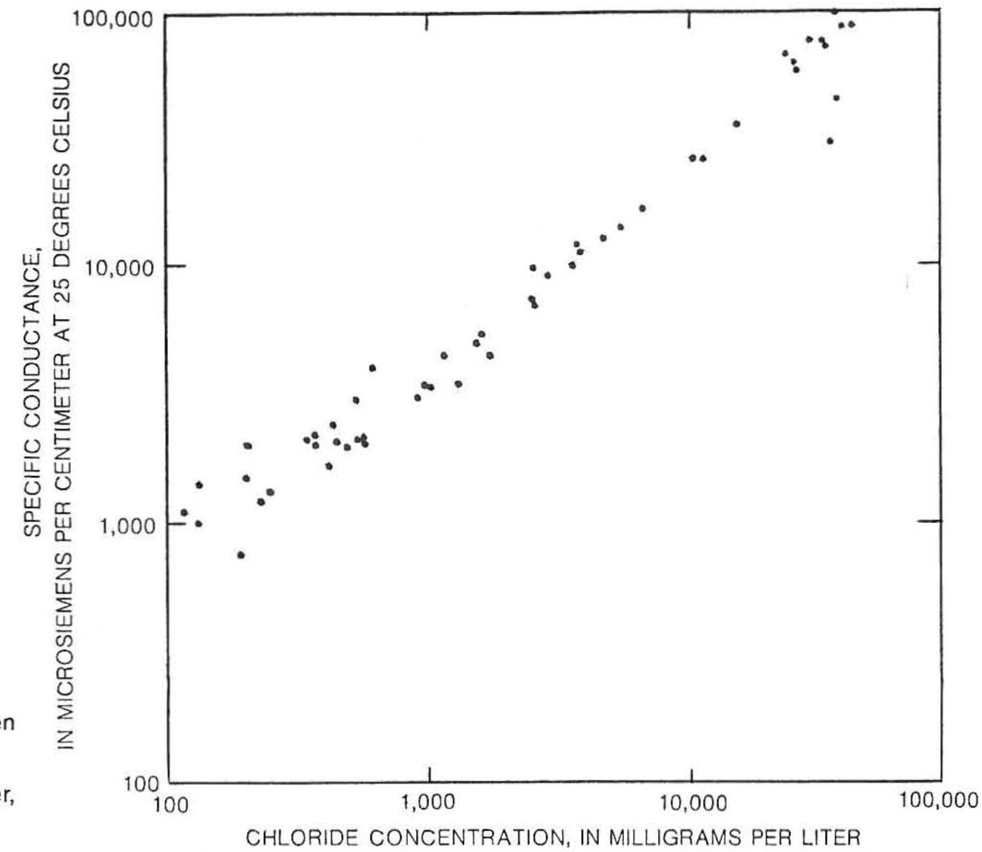


Figure 15. Relation between chloride concentration and specific conductance. (From Schiner and Gallaher, 1979).

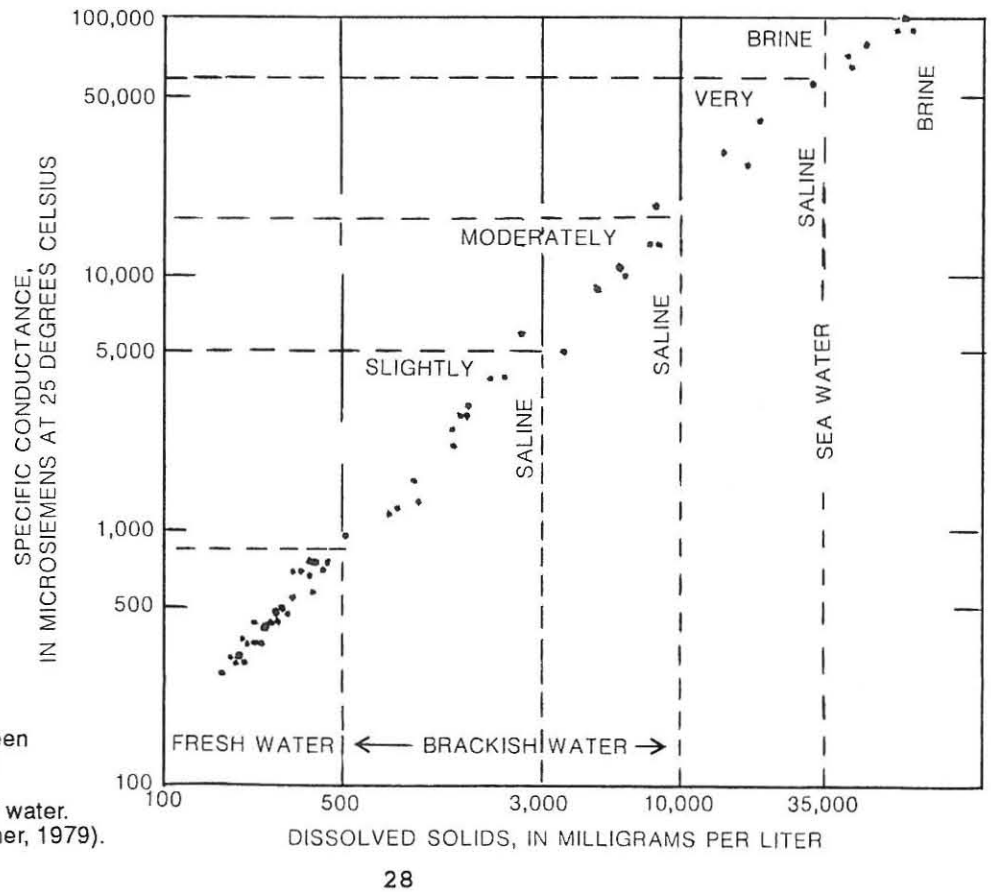


Figure 16. Relation between specific conductance and dissolved solids, and the classification of salinity of water. (From Schiner and Gallaher, 1979).

freshwater/saline-water interface do not exist for most areas. A compilation of laboratory analyses of ground water for the Ohio River and St. Lawrence River Basins from the existing files of the U.S. Geological Survey and the PaDER shows only about 75 wells with chloride concentrations greater than 250 mg/L (Koester and Miller, 1980). About half of these 75 wells were located in Erie County, which does not include a study area. Thus, the data base for saline ground waters of western Pennsylvania is too small to make interpretations about the fresh-saline ground-water interface.

The following four sections provide a brief description of the ground-water quality of the study areas. The ground-water references in table 1 provide more information about the characteristics of the freshwater quality of the study areas. Information about the depth and characteristics of saline waters generally is missing in these reports because of large intervals of "dry rock" below the fresh ground water, few deep wells available for sampling, and lack of deep test-well drilling. Additionally, data are scarce about wells with saline water because these wells often are either destroyed or have the lower section plugged because the water is not potable. Water-well drillers familiar with the situation avoid drilling into saline waters.

Geneva Quadrangle

About 290 water wells in the Geneva quadrangle (Crawford County) have well inventory information including aquifer identification, well depth, location, static water level, and depth(s) to water-bearing zone(s) (Schiner and Gallaher, 1979). Wells tap glacial deposits and bedrock mostly of Mississippian and Devonian age. The best bedrock aquifer for water quality and quantity is the Cussewago Sandstone. The well depths range from about 20 to 500 ft; the median depth of 290 water wells is about 70 ft. Only 15 water wells have water-quality information (table 3). Salty water was noted in only a few water well-completion reports. The limited water-quality data (table 3) also confirm that most water-supply wells tap freshwater. Using the relation between specific conductance and dissolved solids (fig. 16), the specific conductance data (table 3) indicate that the dissolved-solids concentration of the ground water tapped by most water-supply wells is lower than the 500 mg/L recommended limit. Chloride concentrations of most water wells are probably also less than the 250 mg/L recommended limit.

In test well Cw-2356, saline water was sampled at a depth of 240 ft from probably Devonian bedrock; sampling at 560 ft yielded a chloride concentration of 4,050 mg/L. Gamma ray and fluid conductivity geophysical logs of Cw-2356 helped confirm the bedrock lithology and changes in ground-water quality with depth. Other selected wells in western Crawford County tapping Devonian rock also had saline water. Schiner and Gallaher (1979) noted that salinity increases with depth because of the flushing out of connate water by freshwater. Water movement is generally very slow in the almost impermeable Devonian rock, and except for upland areas near the major valleys, little flushing has taken place below the Mississippian. However, rocks of the Lower Mississippian Shenango Formation in some areas also are relatively impermeable and poorly flushed. For example, the water in well Cw-313, about 3 mi southwest of Geneva, is saline water (table 3).

Table 3.--Ground-water quality of wells on Geneva 7-1/2-minute quadrangle (modified from Schiner and Gallaher, 1979)

[ft, feet; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

Aquifer age	Aquifer	Well number	Well depth (ft)	Altitude of total depth of well (ft)	Chloride (mg/L)	Specific conductance (µS/cm)	Remarks
			Water-supply wells				
Quaternary	Pleistocene outwash	992	56	1,211	65	500	
	Do	2047	57	1,018	61	568	
Mississippian	Shenango Formation	10	51	1,311	30	525	
	Do	42	72	1,240	10	450	
	Do	313	70	1,215	270	1,200	
	Meadville Shale[1]	265	53	1,209	30	240	
	Sharpsville Sandstone[1]	2288	76	1,322	10	420	
	Orangeville Shale[1]	399	72	1,063	5	360	
	Cussewago Sandstone	695	36	1,124	45	500	
	Do	895	494	906	9	587	
	Do	902	204	1,056	8	389	
Devonian	Conewango Group[2]	659	70	1,057	5	350	
	Do	2097	60	1,060	10	295	
			Test wells				
Quaternary	Pleistocene outwash	361	425	707	4	357	
Mississippian	Sharpsville Sandstone[1]	2356	574	822	5	600	Sample depth 152 feet
Devonian	Conewango Group[2]	Do	Do	Do	1,250	2,800	Sample depth 240 feet
	Do	Do	Do	Do	4,050	14,000	Sample depth 560 feet

[1] On hydrogeologic section mapped as Cuyahoga Group (Mc) following the terminology of Berg and others (1983).

[2] On hydrogeologic section mapped as Riceville Formation and Chagrin Shale undivided (Drc) following the terminology of Berg and others (1983).

The only two reports of freshwater in gas well-completion records for the Geneva quadrangle were at depths of less than 180 ft. Gas well-completion records noted that, in six deep gas wells saltwater was encountered in the Lower Devonian Oriskany Sandstone at depths of from 3,367 to 3,742 ft. Waite and Blauvelt (1983) reported that a brine sample from the Oriskany Sandstone in Crawford County had concentrations of dissolved solids and chloride of 70,650 mg/L and 37,200 mg/L, respectively. The lack of reports of ground water in the Mississippian and Upper Devonian bedrock in the gas well-completion reports may be related to the use of mud during rotary drilling of some wells, the high air pressures used in drilling other wells, low permeability because of fracture closure at depth, and/or failure to record the presence of ground water on the gas well-completion forms.

Hazen and Reynoldsville Quadrangles

About 100 water wells on the Hazen and Reynoldsville quadrangles (Jefferson County) have well-completion information including aquifer identification, well depth, location, static water level, and depth(s) to water-bearing zone(s). Most wells tap bedrock of the Allegheny and Pottsville Groups, these units are the major aquifers of the study area. Water-supply wells range in depth from 18 to 385 ft and have a median depth of 85 ft; more than 90 percent have depths less than 200 ft. Less than 10 percent of water wells have depths greater than 200 ft and less than 385 ft. The specific conductances of seven water-supply wells (table 4) range from 76 to 840 μS/cm; the median is 180 μS/cm. Salty water was not reported in well-completion records provided by water well drillers. Most water-supply wells in the quadrangles can probably be assumed to tap freshwater. Salty ground water was rarely observed and was not considered a problem for water-supply wells in Jefferson County (Buckwalter and others, 1981). In an assessment of ground-water resources of parts of Jefferson and Clearfield Counties, Shuster (1979) noted the shallowest occurrence of salt water is at 600 ft below land surface.

Ground-water data were collected by U.S. Geological Survey personnel during the drilling of two core holes in the Hazen quadrangle (Je-67 and Je-68) by the Pennsylvania Geological Survey. Water-bearing zones were observed at depths of 105 and 510 ft in Je-67. A sample collected at 200 ft and composed primarily of water from the water-bearing zone at 105 ft indicated a chloride concentration of 2.5 mg/L and specific conductance of 125 μS/cm. A sample collected from 640 ft and composed mostly of water from the water-bearing zone at 510 ft had a chloride concentration of 144 mg/L and a specific conductance of 700 μS/cm. At Je-68, a composite sample collected at 600 ft composed of water from four water-bearing zones at 88, 140, 190, and 290 ft had a specific conductance of 265 μS/cm. The water in a sample collected at Je-68 from a depth of 800 ft, probably from a water-bearing zone at about 800 ft, had a specific conductance of 5,500 μS/cm and a chloride concentration of 1,670 mg/L, an indication that the water was just into the moderately saline classification. A fluid-conductivity geophysical log also confirmed the presence of saline water at 800 ft. The altitude of 1,015 ft above sea level for the saline water-bearing zone of Je-68 falls within the altitude range of saltwater reports noted on gas well-completion records for the Hazen quadrangle. Altitudes and frequency of freshwater and saltwater

Table 4.--Ground-water quality of wells on Hazen and Reynoldsville 7-1/2-minute quadrangles (from Buckwalter and others, 1979)
[ft, feet; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; a dash indicates no data available]

Aquifer age	Aquifer	Well number	Well depth (ft)	Altitude of total depth of well (ft)	Chloride (mg/L)	Specific conductance (µS/cm)	Dissolved solids (mg/L)	Remarks
				Water-supply wells				
Pennsylvanian	Allegheny Group	36	60	1,655	0.8	104	59	
	Do	65	65	1,695	-	180	-	
	Do	69	42	1,538	-	325	-	
	Do	70	65	1,600	-	200	-	
	Do	77	115	1,685	-	160	-	
	Do	104	110	1,270	160	840	390	
	Pottsville Group	38	295	1,330	1.1	76	57	Sampling depth 252 feet
				Test wells				
Pennsylvanian	Allegheny Group	23	101	1,559	2.5	575	361	Sampling depth 70 feet
	Do	67	699	1,211	2.5	125	-	Sampling depth 200 feet
Mississippian	Lower Mississippian Series (undifferentiated)	Do	Do	Do	144	700	-	Sampling depth 640 feet
Pennsylvanian	Allegheny Group	68	891	924	-	265	-	Sampling depth 600 feet
Mississippian	Lower Mississippian Series (undifferentiated)	Do	Do	Do	1,670	5,500	-	Sampling depth 800 feet

reported in gas well-completion records are discussed in more detail in a succeeding section concerned with surface-casing depths and the fresh ground-water system.

Samples of brines from eight shallow gas wells in Jefferson County had chloride concentrations ranging from 105,000 to 160,000 mg/L and a median concentration of 140,000 mg/L (Waite and Blauvelt, 1983).

Warren Quadrangle

Few ground-water quality data are available in published form for the Warren quadrangle (Warren County). No data are available in Leggette (1936) or Koester and Miller (1980). Ground-water quality sampling for major cations, anions, and selected trace constituents of principle aquifers of the area is being done by the Pennsylvania Topographic and Geologic Survey, Warren County Commissioners, and the U.S. Geological Survey for a study that is scheduled for completion in 1993. The depths of about 70 water-supply wells on the Warren quadrangle ranged from 17 to 220 ft; the median was about 47 ft. Specific conductance of water in 12 wells tapping outwash deposits adjacent to the Allegheny River on the Warren quadrangle ranged from 510 to 1,650 μS/cm and the median was 690 μS/cm. The outwash deposits are the most important aquifer of the study area. Specific conductance data indicate that the dissolved-solids concentrations for several springs in the Pottsville and Venango Groups were less than 100 mg/L. The specific conductance of a brine produced from an oil well near Warren tapping the oil sands of the Bradford Group was 132,500 μS/cm. Saltwater in the interval between land surface and the oil sands of the Bradford Group rarely was reported in the oil and gas well-completion records selected for review.

Pittsburgh East Quadrangle

Information obtained on about 170 water wells included aquifer identification, well depth, and location in the Pittsburgh East quadrangle (Allegheny County). Wells tap unconsolidated deposits of Quaternary age and bedrock of the Conemaugh and Allegheny Groups of Pennsylvanian age. The unconsolidated deposits are the major aquifer of the study area. Water wells range in depth from 25 to 450 ft, and the median depth is 73 ft; about 90 percent are less than 175 ft. The information on these wells was collected mostly in the 1940's and 1950's and published in a report by Gallaher (1973). The chloride and dissolved-solids concentrations of water in five wells tapping Pleistocene outwash indicate that the ground water is fresh (table 5).

Reports of salty water in water wells are uncommon. Salty water was reported in only 3 of the 170 water wells reviewed. Salty water was noted in well WW-212, which taps the Saltsburg Sandstone and Buffalo Sandstone of the Conemaugh Group and is 168 ft deep (altitude of total depth-582 ft) (pl. 1). Salty water also was noted in another well tapping the same units and having a depth of 165 ft (altitude of total depth-574 ft). This well was in a stream valley about 1,000 ft from the Monongahela River. The third water well reporting salty water at a depth of 202 ft (altitude of total depth-548 ft) was on valley fill deposits about 800 ft from the Allegheny River.

Limited documentation (Piper, 1983; Johnson, 1928) indicates that heads of some salty water aquifers were sufficient to cause the salty water to rise into and above freshwater aquifers. Piper described two locations in Allegheny County where saltwater coming from the Saltsburg Sandstone at depths of 128 ft and 225 ft rose to 3 and 65 ft below land surface, respectively. Piper also noted that any well that passes more than 50 or 100 ft below the level of the major streams is likely to encounter saltwater. Johnson compiled data on freshwater and saltwater in wells on the Pittsburgh 15-minute quadrangle; most of these were oil and gas wells with depths of less than 1,000 ft below land surface. (The Pittsburgh 15-minute quadrangle includes the Pittsburgh East 7-1/2-minute quadrangle). Levels of saltwater in 11 gas wells ranged from 180 ft to 890 ft below land surface; the median was 435 ft. In another six gas wells, the depth of the top bed in which saltwater was observed ranged from 127 ft to 750 ft below land surface.

The preceding data and meager information indicate that heads of some saltwater bearing zones were sufficient to allow saltwater to rise into and occasionally above freshwater aquifers. Thus, improperly plugged or abandoned oil or gas wells may have allowed salty water to enter shallow aquifers. Other factors that may account for salty water in water wells include increased ground-water pumpage, poor brine disposal practices, or naturally occurring connate water at shallow depth.

Table 5.--Ground-water quality of wells on Pittsburgh East 7-1/2-minute quadrangle (modified from Koester and Miller, 1980)

[ft, feet; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

Aquifer age	Aquifer	Well number	Well depth (ft)	Altitude of total depth of well (ft)	Chloride (mg/L)	Specific conductance (µS/cm)	Dissolved solids (mg/L)
			Water-supply wells				
Quaternary	Pleistocene outwash	330	54	661	54	686	406
	Do	367	74	671	36	558	330
	Do	447	63	672	67	540	389
	Do	701	75	656	24	390	208
	Do	702	74	671	39	460	314

Gallaher (1973) noted that during the search for oil and gas, thousands of wells were drilled and that many of the well casings have been removed or had become severely corroded. Gallaher stated that saltwater under artesian pressure has, in many areas of Allegheny County, moved up the boreholes and into the shallower freshwater aquifers. When oil and gas formation pressures have been depleted from production, then heads on brines in the oil and gas sands probably will not be sufficient to move the brine the hundreds of feet vertically to the freshwater aquifers.

Analyses of three samples of brine from Devonian oil and gas sands of Allegheny County were reported in Poth (1962). The dissolved-solids concentration of the brines ranged from 108,000 to 166,000 mg/L. Depths of the sandstones producing the brine averaged 2,170 ft below land surface.

ESTIMATION OF MINIMUM SURFACE-CASING DEPTHS

Procedure

The depth of the fresh ground-water system needs to be established prior to the commencement of discussions on how deep surface-casing of oil and gas wells should be installed to prevent dewatering the freshwater system and prevent contamination of freshwater aquifers by oil, gas, brines, or other chemicals from oil and gas wells. Because specific data concerning the base of the freshwater system were found to be essentially nonexistent, any available data concerning ground water for the study areas were compiled and analyzed to provide the best possible description of the ground-water system. The four major types of data (oil and gas well-completion reports, water well-completion reports, geophysical logs, and water-quality data) and their accuracy and limitations were discussed in a prior section.

The scope of the attempted delineation of the base of the freshwater system included a literature review of geology and ground-water reports of western Pennsylvania and particularly of reports concerning the study areas. Locations of oil and gas wells in the study areas were plotted and altitudes of total depths of surface casing were determined from oil and gas well-completion records. Geophysical logs were evaluated with emphasis on locating ground water and delineating changes in ground-water quality with depth. Locations of water wells in the study areas were plotted and total depths tabulated. Water-well depths were compared to surface-casing depths of oil and gas wells. Ground-water quality data were compiled from water wells, core holes, and oil and gas wells. Examination of the relations of freshwater and saline water was an emphasis of interpretation of water-quality data. Hydrogeologic sections were prepared for study areas showing relations of surface casing depths of oil and gas wells, water-well depths, and altitudes of freshwater and saltwater reports of oil and gas wells. All of the preceding information and data were comprehensively evaluated for the study areas to attempt to estimate the location of the base of the fresh ground-water system. Depths of surface casing of shallow oil and gas wells generally proved to be the most valuable data for estimating the location of the base of the fresh ground-water system.

Relation of Surface-Casing Depths to the Base of the Fresh Ground-Water System

Geneva Quadrangle

Records of 13 deep gas wells in the Geneva quadrangle indicate surface-casing depths range from 459 to 531 ft, and the median depth is 498 ft. These surface-casing depths of deep gas wells are prescribed by law and are dependent on well depth as discussed on page 3. Figure 17 and plate 1 show that the total depths of surface casing of these deep gas wells generally are deeper than most water wells. Thus, the surface-casing lengths probably would provide some protection for most shallow aquifers being tapped for water supply. The median depth of 290 water wells on the Geneva quadrangle is about 70 ft.

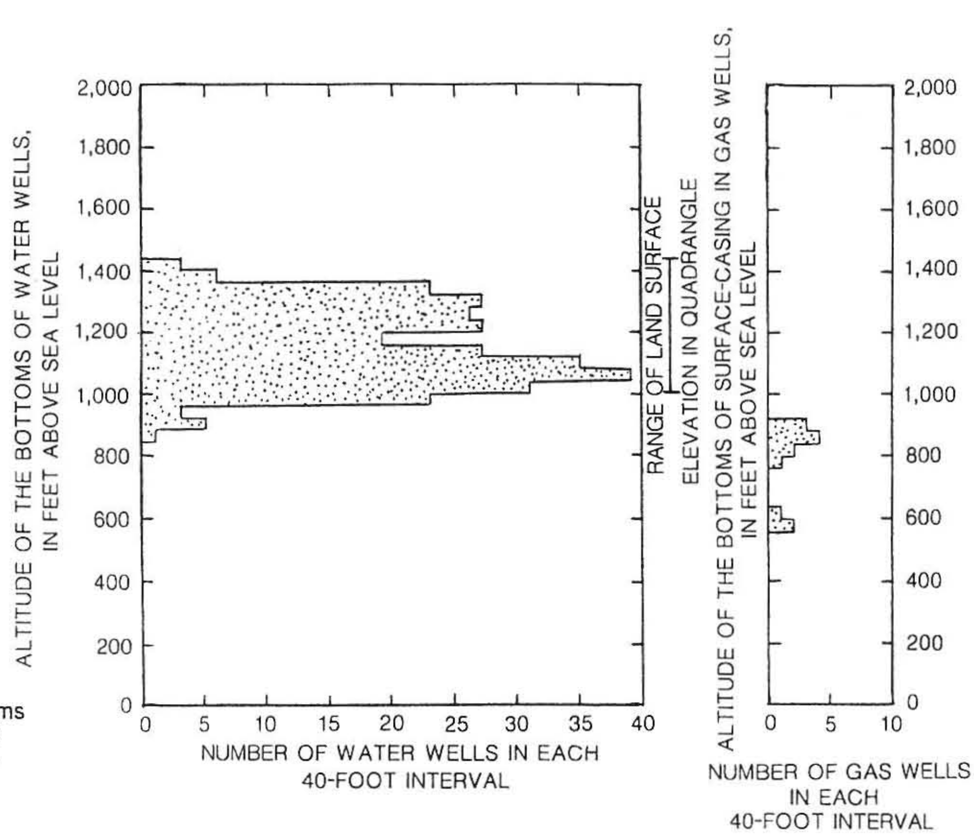


Figure 17. Relations of the altitudes of water-well bottoms and surface-casing bottoms of gas wells, Geneva 7-1/2-minute quadrangle.

Most deep gas wells on the Geneva quadrangle were drilled with modern air- or mud-rotary techniques and any large freshwater producing zones probably would have been cased off to permit efficient drilling of the rest of the well. Small volumes of deep freshwater may not have been observed with the modern drilling techniques. Only 2 of the 13 gas well-completion records had reports of freshwater (95 ft and 35 to 180 ft). Surface casing for these deep gas wells is not much longer than the minimum legally prescribed. Thus, there are probably no high yielding water-bearing zones below the surface-casing strings at the deep gas well sites because their presence would have interfered with efficient drilling rates. A line connecting surface-casing bottoms may in some places be lower in altitude than the base of freshwater since some data indicate saline water at depths of less than 300 ft, and freshwater at depths greater than 500 ft is not reported in water- or gas-well records.

Because of the lack of definitive data, the approximate base of the fresh ground-water system was not indicated on plate 1. Without knowing accurately the base of the fresh ground-water system, minimum surface-casing depths cannot be suggested with confidence. In summary, because most ground-water use is from depths less than 250 ft, surface casings of gas wells are probably of adequate depth to protect nearby freshwater wells.

Hazen and Reynoldsville Quadrangles

Well-completion records for about 200 mostly shallow gas wells were examined for information on surface-casing depths and freshwater and saltwater for the Hazen and Reynoldsville quadrangles. Altitudes of bottoms of about 100 water wells were compared to the altitudes of bottoms of the surface casings of gas wells (fig 18). Surface casings of gas wells were generally considerably deeper than water wells. These casing lengths would provide protection to the shallow freshwater aquifers in use. The following statistics indicate the relative depths of water wells and surface-casing depths of gas wells.

	Hazen quadrangle	Reynoldsville quadrangle
Water well depth		
Range (feet)	18-298	27-385
Median (feet)	80	95
Number of wells	57	46
Surface casing depths of gas wells		
Range (feet)	534-1,129	547-1,362
Median (feet)	738	918
Number of wells	140	53

Depths of surface casing of gas wells for this study area are the depths of the water string of figure 13 or intermediate casing string (see Glossary). The purpose of the water string is to case off ground water. Cement is commonly placed in part or all of the annulus of the water string for support and to restrict movement of fluids.

Reports of freshwater at depths of slightly over 1,000 ft below land surface were made on several gas well-completion records in the Reynoldsville quadrangle. These were the deepest of all the freshwater reported in any study area; flows were reported as 1-in. streams. Comparison of altitudes of freshwater and saltwater reported in gas-well records indicated that some saltwater occurs at the altitude of zones of freshwater (fig. 18).

Gas well-completion records showed reports of freshwater at lower altitudes than the freshwater being tapped by water wells (fig. 18). Thus, for this study area, water-well depths provide inaccurate estimates of the base of freshwater. Because of the lack of comprehensive quality and quantity data concerning these deep freshwater reports, it is unknown if this ground water may be feasibly developed for water supply.

Because of the efforts of gas-well drillers (especially operators of cable-tool drilling rigs) to case off ground water, the base of the freshwater may be roughly estimated from the altitudes of the bottom of the water-string casings. The contoured surface of the base of the water strings would probably be deeper than the base of freshwater because drillers generally run the casing deeper than the deepest freshwater observed. Some water strings also case off saltwater, but the extent of this practice is not known. Because of the unreliability in much of the data in the study area, the approximate base of the fresh ground-water system was not drawn on plate 1.

The reasons for the freshwater and corresponding water strings being deeper in the Reynoldsville quadrangle than in the Hazen quadrangle are unclear. Probable causes may include geologic structure and the presence of lineaments. In the Reynoldsville quadrangle, the pronounced folds, inclined beds, and bedding-plane openings probably have facilitated movement of freshwater to the Mississippian bedrock as much as 800 ft below valley floors. The deep water strings of both the Hazen and Reynoldsville quadrangles provide considerably more protection to the shallow freshwater aquifers than the smaller casing lengths of the Warren or Geneva quadrangles.

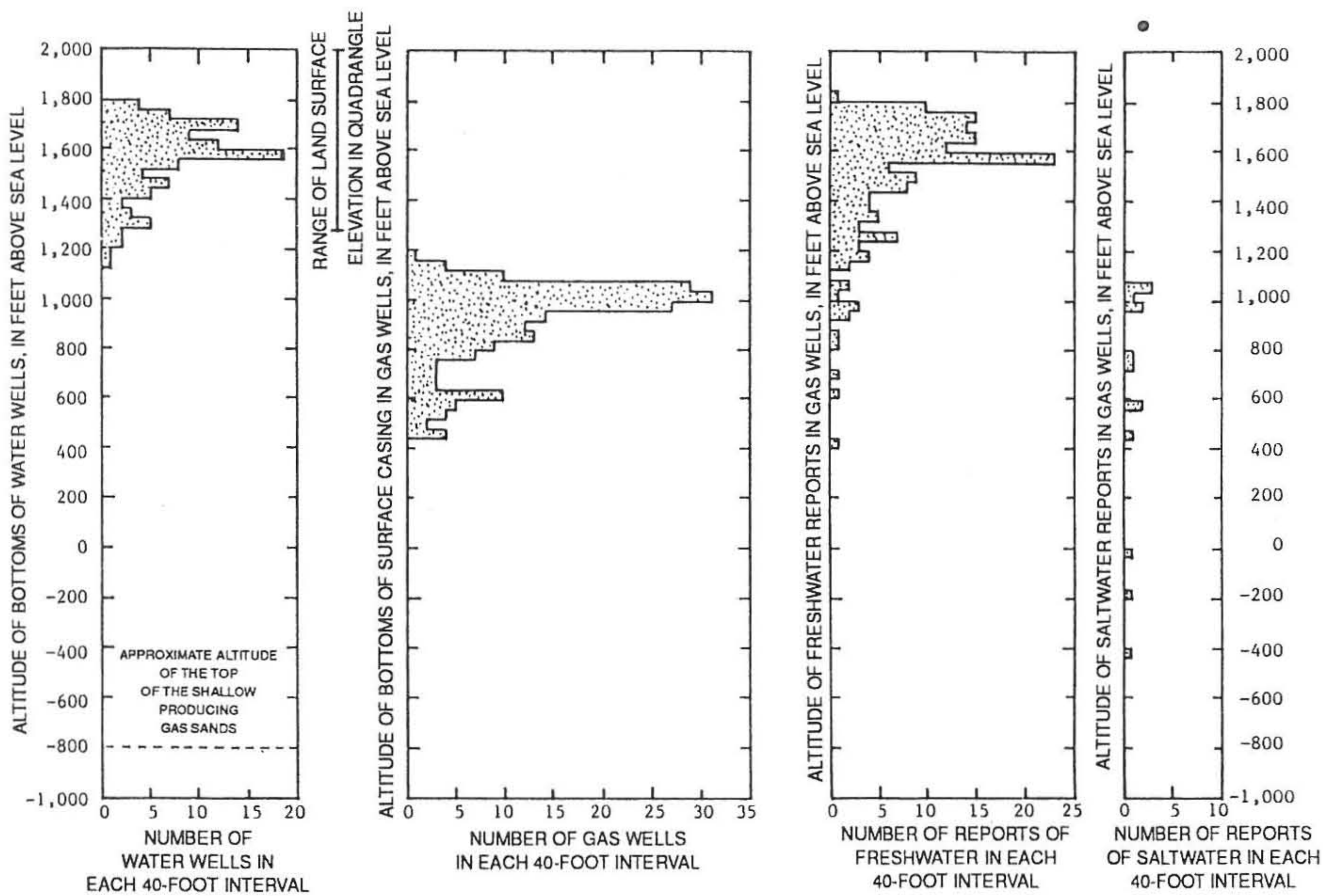


Figure 18. Relations of the altitudes of water-well bottoms, surface-casing bottoms, and reported freshwater and saltwater in gas wèlls, Hazen and Reynoldsville 7-1/2-minute quadrangles.

Figure 19 shows that the altitudes of the base of the surface casing of many oil and gas wells are higher than the altitudes of the bottom of many water wells. (The term "oil and gas well" is used in this study area because oil is the major product; however, marketable quantities of gas may be produced simultaneously with the oil in some wells, and gas may be produced after oil depletion.) The distribution of altitudes of bottoms of water wells (fig. 19) reflects the high density of shallow domestic wells tapping outwash deposits next to the Allegheny River. Water wells generally are shallow in these outwash deposits and average 40 to 50 ft in depth.

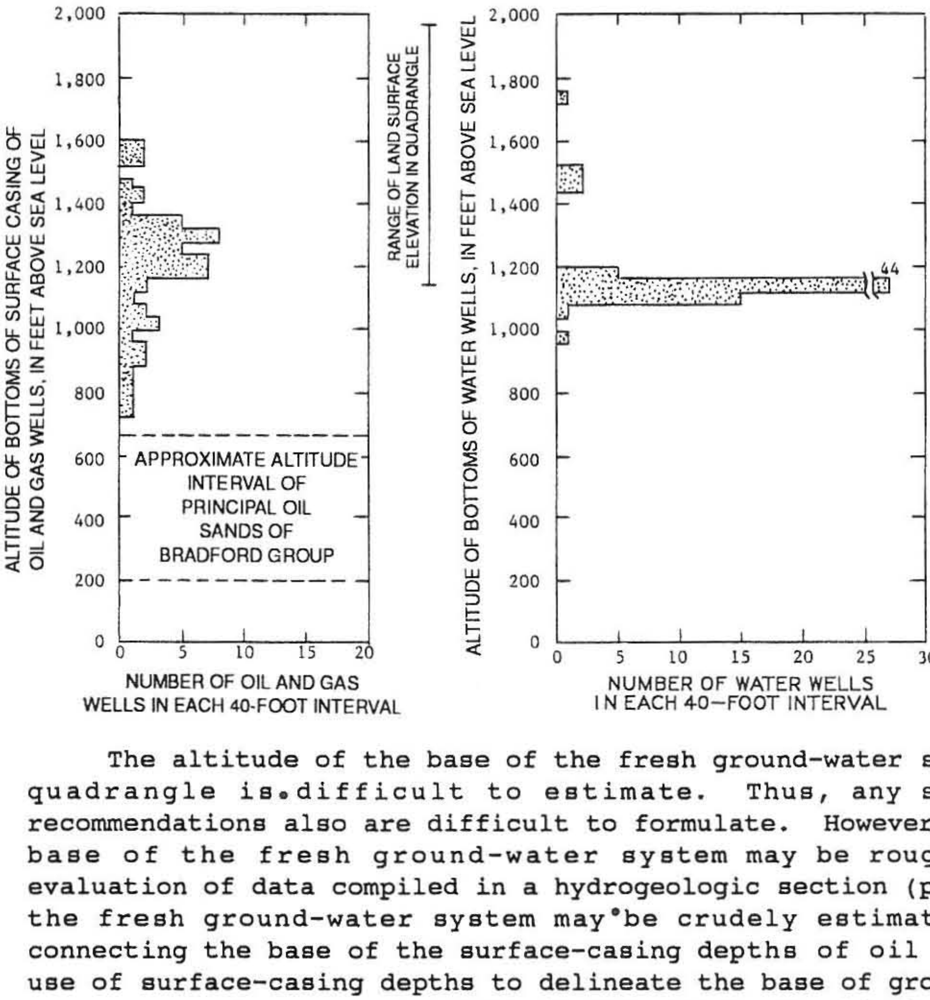


Figure 19. Relations of the altitudes of water-well bottoms and surface-casing bottoms of oil and gas wells, Warren 7-1/2-minute gradrangle.

The altitude of the base of the fresh ground-water system on the Warren quadrangle is difficult to estimate. Thus, any surface-casing depth recommendations also are difficult to formulate. However, the altitude of the base of the fresh ground-water system may be roughly approximated by evaluation of data compiled in a hydrogeologic section (plate 1). The base of the fresh ground-water system may be crudely estimated by drawing a line connecting the base of the surface-casing depths of oil and gas wells. The use of surface-casing depths to delineate the base of ground-water circulation was proposed by Westlund (1976) in the nearby Bradford oil field of McKean County, Pa. Available data did not merit the drawing of even a dashed line on plate 1 indicating the approximate base of the fresh ground-water system because of the lack of reliable data. A line connecting the bottom of the surface casings of oil and gas wells would show a subdued replica of the topography. As discussed previously, oil wells generally have surface casing installed to the "casing point" or point below which freshwater is no longer encountered. Thus, any hypothetical line connecting surface-casing bottoms would probably be slightly deeper than the base of the fresh ground-water system.

The relations of land surface elevations of oil and gas wells to surface-casing depths and altitudes of the bottom of surface casing are shown for about 55 randomly selected oil and gas wells in figures 20 and 21. The range of surface-casing depths from 185 to 603 ft (fig. 20) is similar to the range of 180 to 600 ft given by Lytle (1965) for the Warren 15-minute quadrangle and to the range of 350 to 600 ft given by Waite and Blauvelt (1983) for surface-casing depths of oil wells of the Bradford District, which includes Warren County. Figure 20 shows a generally wide range of surface-casing depths for any given altitude. The depths of surface casing aren't dependent on topography; hilltop, hillside, and valley oil and gas wells show only minor differences in ranges of casing depth. Hilltop and hillside oil and gas wells were not cased more than a maximum of about 600 ft, inasmuch as ground water was not found below that depth.

Few reports of freshwater below 600 ft from land surface were found in oil and gas well-completion reports of the Warren 7-1/2-minute quadrangle probably because of decreasing secondary permeability with depth and the low permeability of the Devonian bedrock (particularly shales).

Generally, the first saltwater noted in oil well-completion records is at the horizons of the target oil sands, mainly the Glade and Clarendon sands of the Upper Devonian Bradford Group. The general lack of reports of saltwater in the bedrock between the base of fresh ground water (approximately 200 to 600 ft below land surface) and the oil sands are substantiated by oil operators of the area. Quaker State has drilled many shallow oil wells in the Warren, Pa., area; little to no water is produced during drilling once the top hole water has been eliminated (Barber, 1982). Pennzoil, another active oil producer in the Bradford District (includes Warren County) has encountered negligible connate water during drilling (Kardos, 1982).

Various theories have been advanced to explain the existence of "dry" Upper Devonian and Mississippian formations despite studies showing the strata to be porous and permeable. Most of the water that occurs in these "dry sands" is absorbed moisture. Reeves (1917) and Mills and Wells (1919) postulated that the sediments may have dried out subsequent to deposition and that air entrapped in the pores had prevented water from reentering the rocks.

The effects of the gentle geologic structure of the bedrock on the ground-water flow system in the Warren quadrangle are unknown, but because of the nearly flat-lying beds there are probably few major effects. Major controls on the ground-water flow system include topography and secondary permeability. Lack of major folds may tend to limit infiltration of freshwater to deeper horizons. For example, if steeply dipping bedrock with permeable bedding planes were present above the altitude of the major drainage (such as the Allegheny River), then observations of freshwater below 600 ft would be expected.

The bedrock of the Warren quadrangle is nearly horizontally bedded and cyclic in nature (sandstone, siltstone, shale). Therefore, when fractures and joints become closed within a modest depth because of overburden pressure, the downward movement of infiltrating water virtually ceases in the low permeability shales and siltstones. This represents the base of the fresh ground-water system.

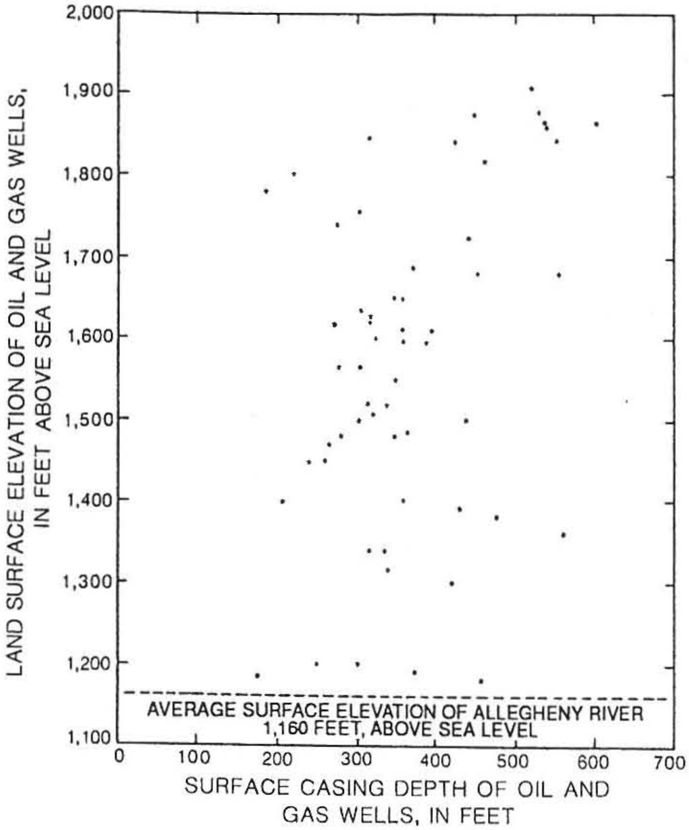


Figure 20. Relations between surface-casing depth and land surface elevation of oil and gas wells, Warren 7-1/2-minute quadrangle.

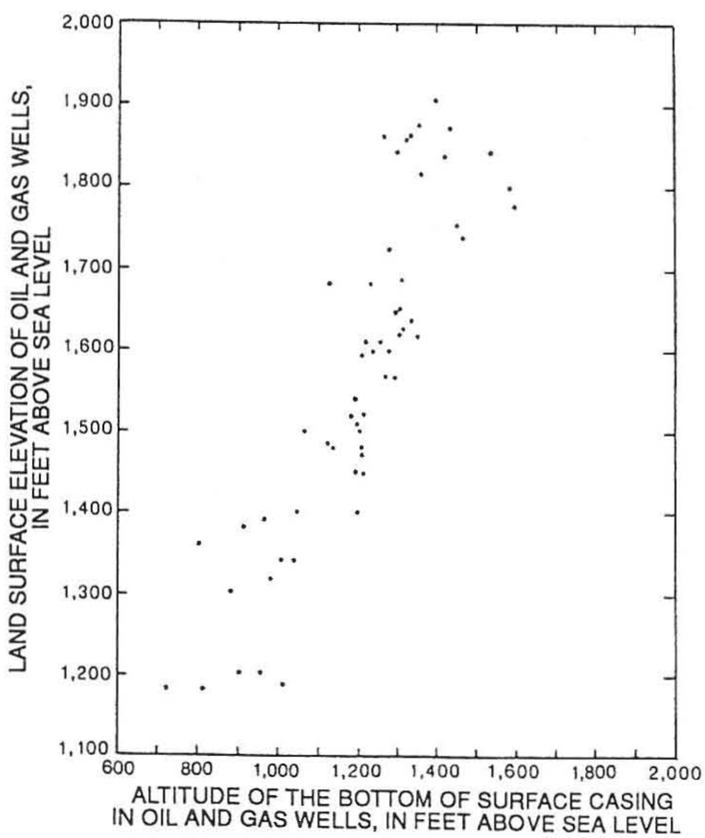


Figure 21. Relations between altitude of bottom of surface casing and land surface elevation of oil and gas wells, Warren 7-1/2-minute quadrangle.

Pittsburgh East Quadrangle

The base of the fresh ground-water system could not be delineated because of the meager and unreliable data base. Consequently, minimum surface-casing depths for gas wells could not be determined or even estimated. If PaDER conducts an in-house survey of the base of the fresh ground-water system in western Pennsylvania, many other quadrangles in western Pennsylvania also may have similar data bases.

The range of altitudes of bottoms of about 170 water wells are shown in the histogram in figure 22. The median depth of water wells was 73 ft. Most freshwater is probably at altitudes ranging from 400 to 1,200 ft above sea level assuming most water wells yield freshwater. How much (if any) freshwater occurs below the 400 ft altitude is unknown. The average altitude of bottoms of water wells for the Pittsburgh East quadrangle is lower than those for other study areas in this report (plate 1). This is related to the drainage basin characteristics of the Ohio River Basin in western Pennsylvania and the corresponding low land-surface elevations of the Pittsburgh East quadrangle.

Reports of saltwater at altitudes where freshwater is consistently reported are noted on Plate 1 (water well WW-212) and figure 22. Saltwater at these altitudes is not inconceivable because heads on selected brine-producing aquifers have been shown to be sufficient to force brine to shallow freshwater aquifers. However, other factors, including increased ground-water pumpage, poor brine-disposal practices, or naturally occurring connate water at shallow depths, also may be responsible.

The Pittsburgh East quadrangle contains two principal rivers--the Allegheny and Monongahela Rivers--that are major points for ground-water discharge. Freshwater reported in gas well records generally was deeper below land surface in the Hazen and Reynoldsville quadrangles located near a major divide of the Ohio and Susquehanna River Basins than in the Pittsburgh East quadrangle (figs. 18 and 22). This difference may be because of the difference in the locations of the study areas in the Ohio River Basin or perhaps to a combination of other factors including geologic structure, lithology, secondary permeability, and data availability.

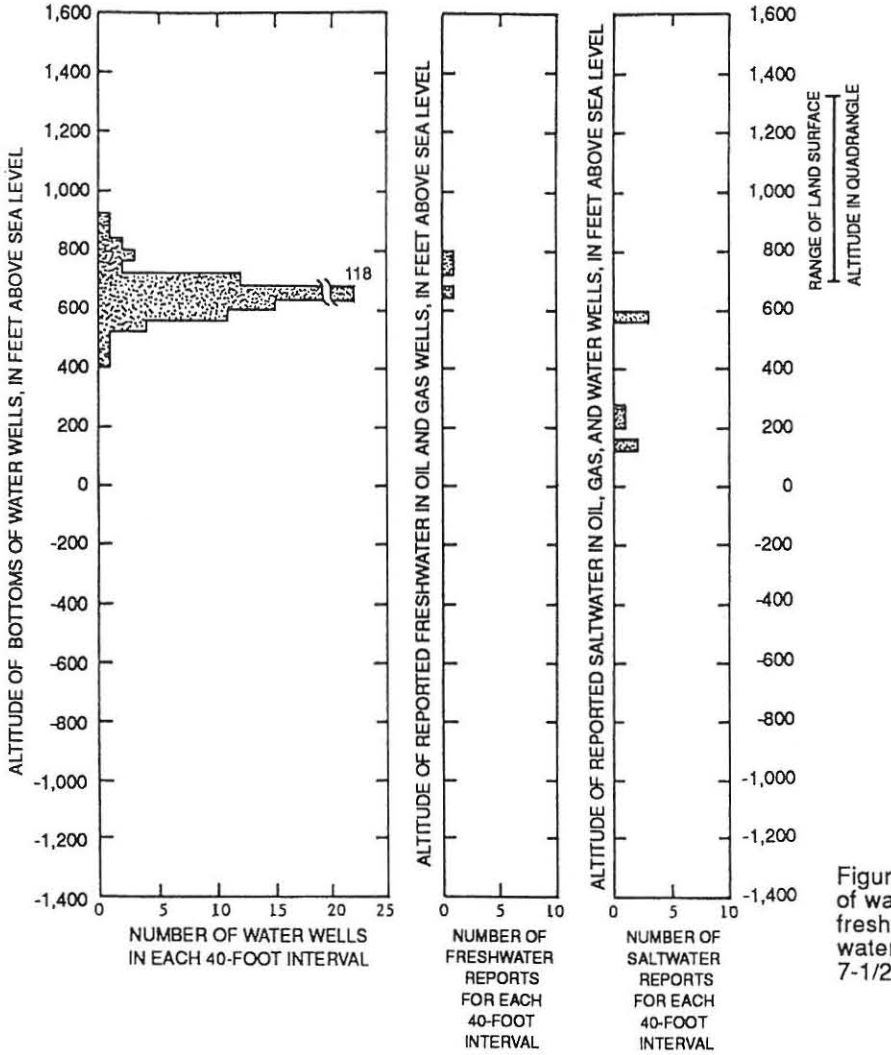


Figure 22. Relations between altitudes of water-well bottoms and reported freshwater and saltwater in oil, gas, and water wells, Pittsburgh East 7-1/2-minute quadrange.

Results

The maximum protection of fresh ground water would require the installation of casing to immediately above the hydrocarbon producing zones and cementation of the annular space to land surface. This method would virtually stop upward movement of gas, oil, or brines to freshwater aquifers and prevent most aquifer dewatering. However, the cost precludes this method as a practical measure especially for shallow oil wells. Also, the casing and cementing of wells to hydrocarbon producing zones would generally only protect massive intervals of dry rock.

For shallow oil and gas wells drilled with air rotary rigs, total lengths of surface casing are selected mostly to maximize drilling efficiency. Discharges of fresh or saline ground water, especially at high rates, are cased off early in drilling to permit optimum air drilling for the remainder of the hole. Cable-tool rigs, commonly used in the past and still in use in some areas of western Pennsylvania, also case off ground water to maximize bit penetration during the drilling of the lower parts of the hole. Thus, past and present drilling methods commonly result in installation of surface casing to below the base of readily observed freshwater. Casing depths are selected generally for maximizing drilling efficiency and to stop freshwater from entering the well and subsequently interfering with hydrocarbon recovery. The depths of surface casing generally are not selected for ground-water protection. However, based on existing hydrologic data, most freshwater aquifers in use are protected with current casing depths. Minimum surface-casing depths for the recent increase in deep gas drilling are prescribed by PaDER regulations and appear to be adequate to prevent ground-water contamination, in most respects, for the only study area with deep gas fields examined in Crawford County.

To protect all ground water that the U.S. Environmental Protection Agency considers potentially usable for drinking, a hypothesis was evaluated that proposed that surface casing be long enough to reach ground water having a dissolved-solids concentration greater than 10,000 mg/L. Data mostly from oil and gas well-completion records commonly showed intervals of "dry" rock as thick as several thousand feet below the altitude of the deepest reported freshwater. Reports of salty ground water in water, oil, and gas wells are uncommon and differ from study area to study area. However, the first observations of salty water in oil and gas well-completion reports are commonly associated with the deep oil and gas producing zones. Thus, requiring installation of surface-casing lengths to the top of the first very saline water found in drilling, would likely protect only massive intervals of "dry" rock at prohibitive surface-casing costs.

The findings of this report indicate that contamination of most freshwater aquifers by leakage of oil, gas, and brines in boreholes of oil and gas wells probably would be prevented if the following PaDER guidelines were followed: (1) The surface casing should extend at least 50 ft below the deepest fresh ground-water-bearing strata; (2) the surface casing should be pressure cemented along its entire outer length to the surface; and (3) the surface casing should be installed prior to drilling into any strata that contain oil or gas (Pennsylvania Department of Environmental Resources, written commun., 1985).

Most surface casing of oil and gas wells extends below the elevation of first-order streams, but, where topography is rugged, surface casings of oil and gas wells located on hilltops and valley walls may not extend below the altitude of the base of those freshwater aquifers beneath adjacent major streams (generally third-order streams) or rivers (generally fourth-order streams such as the Allegheny River). However, there probably is little chance of any harm to the fresh ground-water resources because of a generally poor hydraulic connection between the deep (400 to 500 ft below land surface), mostly "dry" bedrock under hilltops and the unconsolidated and shallow bedrock aquifers under the major stream valleys.

FUTURE STUDIES

The altitude of the base of the fresh ground-water system in the four study areas cannot be accurately delineated because of the unreliability of much of the hydrologic data. Field investigations including geophysical logging (cased and uncased hole), straddle packer testing (especially in deep freshwater aquifers), and comprehensive laboratory chemical analyses of ground water are some of the techniques that would assist in reliable delineations of the base of the fresh ground-water system.

Additional head measurements in oil and gas wells of brine, produced from a variety of formations throughout western Pennsylvania, would aid in the identification of areas prone to upward movement of brine into freshwater aquifers. Special casing and cementing techniques may be needed to protect fresh ground water in these identified areas. The role of pressurized gas (especially in the annular space of wells) in moving brine, oil, or stimulation fluids is also in need of further study.

Conscientious and reliable reporting of freshwater and saltwater during drilling of oil and gas wells would expand the existing data base. Reporting of field specific conductance of ground water would greatly enhance the value of the reports of ground water in oil and gas well-completion records.

SUMMARY AND CONCLUSIONS

Hydrologic data were evaluated from four areas of western Pennsylvania to estimate the minimum depth of surface casing for oil and gas wells that is necessary to protect most of the freshwater resources. The areas are representative of the different types of oil and gas activities and of the ground-water hydrology of most sections of the Appalachian Plateaus Physiographic Province in western Pennsylvania. Approximate delineation of the base of the freshwater system was attempted by interpreting the following hydrologic data: (1) freshwater and saltwater reports in oil and gas well-completion reports; (2) water well-completion reports; (3) geophysical logs, and (4) chemical analyses from water wells. Data densities were highly variable and ranged from no data points to 50 per square mile.

Most of the data were considered inadequate or unreliable because only the presence of freshwater was shown and not the actual base of the fresh ground-water system. Also, water wells are completed when adequate supplies are obtained--not when the base of the system is reached. Most commercial geophysical logs on file with PaDER were made after surface casing had been installed; this prevented the electric logs from indicating freshwater. Many logs are only run in deep oil- and gas-producing zones. Few water-quality analyses from deep freshwater-bearing zones are available; as a result, estimations were not determined for minimum surface-casing depths in these instances.

Reports of ground water in oil and gas well-completion reports are nonexistent for many wells and, if any are available, represent major producing zones, water from which was identified as being fresh or saline mostly by subjective taste tests. Because of the high air pressures of modern air-rotary drilling rigs, the location or presence of minor freshwater-bearing zones may not be observed during drilling and, therefore, are not considered during the installation and cementing of surface casing.

Freshwater-bearing zones in bedrock are controlled mostly by the number, size, and distribution of secondary openings. Primary permeability is probably minor in most bedrock aquifers of western Pennsylvania. The deepest freshwater report in an oil and gas well-completion record is probably the deepest secondary opening containing freshwater. The vertical and horizontal discontinuity of secondary openings in the bedrock between adjacent oil or gas wells may be responsible, in part, for large differences in altitudes of freshwater noted on oil and gas well-completion records.

In northwestern Pennsylvania Geneva and Warren quadrangles, the Pennsylvanian, Mississippian, and Devonian bedrock is horizontally bedded and composed mostly of sandstone, siltstone, and shale. The fractures and joints generally become closed within a modest depth mainly because of overburden pressure. Thus, the downward movement of infiltrating water essentially stops in the low permeability shales and siltstones. Similarly, in Greene County, southwestern Pennsylvania, a digital ground-water flow model (Stoner and others, 1987) of gently dipping Permian and Pennsylvanian rocks indicated that only 0.5 percent of total ground-water circulation occurs in aquifers located deeper than 175 ft.

To protect all ground water that the U.S. Environmental Protection Agency considers potentially usable for drinking, a hypothesis was evaluated that proposed that surface casing be long enough to reach ground water having a dissolved-solids concentration greater than 10,000 mg/L. Depths of saline ground water (including brines) are rarely reported; however, the first observations in oil and gas well-completion reports are commonly associated with the deep oil- and gas-producing zones. Oil and gas well-completion records usually indicate the presence of as much as several thousand feet of dry rock below the deepest reported freshwater. Thus, surface casing set to the depth of the first observation of very saline ground water found in drilling would likely provide a costly protection to massive intervals of dry rock.

In upland and hilltop topographies, depths to the base of the freshwater ranged from several hundred feet below land surface to slightly over 1,000 ft below land surface. The deep freshwater is noted in oil and gas well-completion records and is not substantiated by laboratory analyses of dissolved-solids concentrations or field measurements of specific conductance.

Preparation of hydrogeologic sections showed the variability of the depths of water-supply wells (18 to 494 ft; median depth about 75 ft) and their relations to surface-casing depths of oil and gas wells. The bottoms of surface casings of most oil and gas wells are considerably deeper than the bottoms of nearby water wells, although the vertical separation differs within and between study areas. In areas of minor geologic structure with gently dipping strata (Geneva and Warren quadrangles), analysis of hydrogeologic sections indicates that topography is a predominant control on the altitude of the base of the freshwater system. However, in the Hazen and Reynoldsville quadrangles, pronounced folding, inclined beds, and bedding-plane openings probably allowed movement of fresh ground water to the Mississippian bedrock, which is as much as 800 ft below valley floors.

Casing depths are selected generally for maximizing drilling efficiency and to stop freshwater from entering the well and subsequently interfering with hydrocarbon recovery. For shallow oil and gas wells drilled with air-rotary rigs, the length of surface casing is selected mainly to maximize drilling efficiency. Permeable zones of fresh or saline ground water, especially those that can yield water at high rates, are cased off early during air drilling to reduce loss of air pressure and maximize the drilling rate for the remainder of the hole. Cable-tool rigs commonly used in the past and still in use in some areas of western Pennsylvania, also case off ground water to maximize bit penetration during the drilling of the lower parts of the hole. Thus, past and present drilling methods commonly result in installation of surface casing to below the base of readily observed freshwater. The depths of surface casing generally are not selected to protect ground water. However, on the basis of existing hydrologic data most freshwater aquifers in use are protected with current casing depths. Minimum surface-casing depths for the recent increase in deep gas drilling are prescribed by PaDER regulations and appear to be adequate to prevent ground-water contamination, in most respects, for the only study area with deep gas fields examined in Crawford County.

The maximum protection of freshwater would require the installation of casing to immediately above the hydrocarbon producing zones and the cementation of the annular space to land surface. This method would virtually stop upward movement of gas, oil, or brines to freshwater aquifers and would prevent most aquifer dewatering. However, the costs preclude this method as practical, especially for shallow oil and gas wells commonly showing little or no profit after drilling, development, and operating expenses. Also, casing and cementing of wells to hydrocarbon-producing zones generally would protect only massive intervals of dry rock.

In producing gas wells that tap the Silurian Tuscarora Formation (10,000 to 12,000 ft in depth) and in some other deep gas wells, surface casing is typically 1,400 to 1,600 ft long and is cemented to land surface. Additionally, intermediate casing strings as long as 9,000 ft and production casing commonly are cemented. High pressures and strength requirements for supporting the heavy weight of casing and tubing in some of these deep wells requires the filling of annular spaces with cement. Freshwater is protected by these well-construction techniques.

The findings of this report generally indicate that most contamination of freshwater aquifers by leakage of oil, gas, and brines in boreholes of oil and gas wells probably would be prevented if the following PaDER guidelines were followed: (1) The surface casing should extend at least 50 ft below the deepest fresh ground-water-bearing strata; (2) the surface casing should be pressure cemented along its entire length to the surface; and (3) the surface casing should be installed prior to drilling into any strata that contain oil or gas.

Most surface casing of oil and gas wells extend below the elevation of first-order streams, but, where topography is rugged, surface casings of oil and gas wells located on hilltops and valley walls may not extend below the altitude of the base of those fresh ground-water aquifers beneath adjacent major streams (generally third-order streams) or rivers (generally fourth-order streams such as the Allegheny River). However, there probably is little chance of any harm to the freshwater resources because of a generally poor hydraulic connection between the deep (400 to 1,500 ft below land surface), mostly "dry" bedrock under hilltops, and the unconsolidated and shallow bedrock aquifers of the major stream valleys.

One phase of the literature review examined the theories and evidence of prior delineations of the base of the freshwater system; contradictory theories and little substantial data were found. Literature review also documented significant thicknesses of "dry" bedrock separating the base of freshwater from deep saline or salty ground water. The review also indicated that parts of some of the Upper Devonian and Mississippian formations may contain very little or no water, despite the fact that studies have shown the strata to be porous and permeable. Most of the water in these "dry sands" is present as absorbed moisture. Several of the theories found in the review note that the sediments may have been dried out after deposition and that air trapped in the pores had prevented water from reentering the rocks.

The altitude of the base of the freshwater system in the four study areas cannot be accurately described because of the poor quality of much of the hydrologic data. Geophysical logging (cased and uncased hole), straddle packer testing (especially in deep freshwater aquifers), and comprehensive laboratory analyses of ground water are some of the techniques that would assist in reliable delineations of the base of the freshwater system.

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GLOSSARY

Air drilling.--Drilling using air as the circulation medium. The conventional method of removing cuttings from the well bore is to use a flow of water or drilling mud. Since about 1955 it has been known that compressed air (sometimes natural gas) removes the cuttings with equal or greater efficiency. In many cases the rate of penetration is increased appreciably. The principal problems in air drilling are related to the penetration of formations containing water.

Annular space.--The open space surrounding a cylindrical object within a cylinder. The open space around a pipe suspended in a wellbore is often termed the annulus, and its outer wall may be either the wall of the borehole or the casing.

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

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

Casing.--Steel pipe placed in an oil or gas well as drilling progresses. The function of casing is to prevent the wall of the hole from caving during drilling, to provide a means of extracting the oil if the well is productive, and to exclude fluids from the bore hole.

Casing cementing.--The practice of filling the annulus between casing and drill hole wall with cement in order to prevent fluid migration between permeable zones and to support the casing.

Cementing.--The application of a liquid slurry of cement and water to various points in an oil or gas well, inside or outside the casing. Primary cementing refers to the cementing operation that takes place immediately after the casing has been run into the hole, and that provides a protective sheath around the casing, segregates the producing formation, and prevents the migration of undesirable fluids. After the primary cementing operation has been completed, any subsequent cementing operation is generally referred to as secondary cementing. Among the most useful of secondary cementing methods is that of squeeze cementing, in which the slurry is squeezed out through perforations in the casing by the application of great pressure. Squeeze cementing is used to isolate a producing formation, to seal off water, or to repair casing leaks. Other secondary cementing methods include a plug back job, in which a plug of cement is positioned at the desired point and allowed to set. Wells are plugged back to shut off bottom water or to reduce the depth of the well.

Conductor casing.--A short string of casing of large diameter which is used on offshore and marshy locations and under certain other conditions. Its principal function is to keep the top of the well bore open and to provide means of conveying the upflowing drilling fluid from the well bore to the slush pit. Conductor casing or conductor pipe is also commonly called drive pipe.

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

Conservation wells.--Include all wells drilled to penetrate formations below the top of the Devonian Onondaga Formation except in areas where the top of the Onondaga is shallower than 3,800 ft or is not present at all; in such areas, all wells penetrating formations below 3,800 are included. Where strata older than the top of the Onondoga Formation are exposed at the surface the term Onondoga horizon shall mean the surface. [Pennsylvania Department of Environmental Resources, Bureau of Oil and Gas Management written commun., 1985.]

Dip.--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.

Deep oil or gas well.--See shallow and deep oil and gas wells.

Drive pipe.--See conductor casing.

Fault.--A fracture or a zone of fractures along which there has been displacement of sides relative to one another parallel to the fracture.

Freshwater-bearing zone.--A discrete interval in bedrock or unconsolidated materials producing measurable amounts of fresh ground water.

Intermediate casing string.--The string of casing set in a well after the surface casing; sometimes called protection casing or water string. Purposes include keeping the hole from caving, affording a strong string of pipe for attachment of blowout preventers, or casing off fresh or salt-water bearing zones.

Lineaments.--Linear features on aerial photographs or imagery formed by the alignment of stream channels or tonal features in soil, vegetation, or topography.

Oil or gas well-completion report.--A form filed with the Pennsylvania Department of Environmental Resources by the well operator which includes well construction, production, formations, location, elevation, and frequently depths to fresh or salt water-bearing zones.

Packer.--A device used for blocking material transfer through the annular space between two strings of pipe or between the pipe and the wall of the borehole by sealing off the space between them. "Open-hole packers" are used to seal the space between drill pipe or casing and the wall of the hole, as when taking a drill-stem test. "Production packers" may be retrievable or permanent.

Permeability.--The capacity of a porous rock, sediment, or soil to transmit a fluid under a hydraulic head; it is the relative ease of fluid flow under unequal pressure.

Primary permeability.--The permeability of a material due to its soil or rock matrix.

Secondary openings.--Voids produced in rocks subsequent to their formation by solution, weathering, or breaks in the rocks.

Secondary permeability.--The permeability developed in a rock after its deposition or emplacement through such processes as solution or fracturing.

Shallow and deep oil and gas wells.--This report uses the Pennsylvania Geological Survey definition of shallow and deep oil or gas well: Oil and gas wells are classified as shallow or deep, not depending on depth, but on whether or not the Upper-Middle Devonian boundary was penetrated in the well. Wells that penetrate the boundary (normally the top of the Middle Devonian Tully Limestone, but may be an equivalent shale) are considered deep. Wells that do not penetrate the boundary are considered shallow, regardless of depth. Because of the wedge-shaped character of the sedimentary package deposited in the Appalachian Basin, absolute drilling depth is not instrumental. A well in the Lower Silurian Medina Group in Erie County along the lake shore may be only 2,500 ft deep, and a well in the Upper Devonian Bradford Group in Clearfield County may be as much as 4,000 ft deep. Yet, the well in the Medina is considered deep and the well in the Bradford is considered shallow on the basis of geologic age. Shallow wells, which account for the greatest number of wells drilled in Pennsylvania, may produce oil or gas; deep wells most commonly produce gas, but there are some wells in Erie and Crawford Counties that produce small amounts of oil as well (Harper, 1984).

Stimulation fluids.--A variety of fluids used during processes designed to increase oil or gas production. Examples of stimulation fluids include concentrated acids, water, diesel fuel, crude oil, nitrogen, and carbohydrate polymer gels.

Surface casing.--The first string of casing to be set in a well. The length will vary in different areas from a few hundred ft to three or four thousand ft. On some wells, it is necessary to set a temporary conductor pipe which should not be confused with surface casing as described here.

Water-bearing zone.--A discrete interval in bedrock or unconsolidated materials producing measurable amounts of ground water. Water-well drillers commonly report water-bearing zones on water well-completion reports. Water-bearing zones in bedrock wells are mostly reported by well drillers at precise depths such as 65 ft, 115 ft, and 150 ft.

Water string.--See intermediate casing string.