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Evaluation of Geophysical Logs, Phase I, at Willow Grove Naval Air Station, Montgomery County, Pennsylvania

by Randall W. Conger

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CONVERSION FACTORS AND VERTICAL DATUM

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
foot (ft)	0.3048	meter
gallon per minute (gal/min)	0.00006309	cubic meter per second

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

Evaluation of Geophysical Logs, Phase I, at Willow Grove Naval Air Station, Montgomery County, Pennsylvania

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ABSTRACT

Between April and June 1997, the U.S. Navy contracted Brown and Root Environmental, Inc., to drill 20 monitor wells at the Willow Grove Naval Air Station in Horsham Township, Montgomery County, Pa. The wells were installed to monitor water levels and allow collection of water samples from shallow, intermediate, and deep water-bearing zones. Analysis of the samples will determine the horizontal and vertical distribution of any contaminated ground water migrating from known contaminant sources. Eight wells were drilled near the Fire Training Area (Site 5), five wells near the 9th Street Landfill (Site 3), four wells at the Antenna Field Landfill (Site 2), and three wells near Privet Road Compound (Site 1). Depths range from 73 to 167 feet below land surface.

The U.S. Geological Survey conducted borehole-geophysical and borehole-video logging to identify water-bearing zones so that appropriate intervals could be screened in each monitor well. Geophysical logs were run on the 20 monitor wells and 1 existing well. Video logs were run on 16 wells.

Caliper and video logs were used to locate fractures, inflections on fluid-temperature and fluid-resistivity logs were used to locate possible water-bearing fractures, and flowmeter measurements verified these locations. Single-point-resistance and natural-gamma logs provided information on stratigraphy. After interpretation of geophysical logs, video logs, and driller's notes, all wells were screened such that water-level fluctuations could be monitored and discrete water samples collected from one or more shallow and intermediate water-bearing zones in each borehole.

INTRODUCTION

The Willow Grove Naval Air Station (NAS) is located in Montgomery County, Pa., on the U.S. Geological Survey (USGS) Ambler 7.5-minute topographic quadrangle map (fig. 1). In addition to its primary use as a reserve Naval Air Station, this 1,000-acre facility also supports U.S. Marine and U.S. Army activities. The U.S. Air Force has property holdings within the NAS boundary and shares common facilities with the NAS. Four major contaminated sites within the NAS (fig. 2) were identified as part of a Remedial Investigation (Halliburton NUS Environmental Corporation, 1993). A hydrogeological investigation is being conducted as part of the U.S. Navy's Installation Restoration Program to address ground-water contamination at these (and other) sites at the NAS. The U.S. Navy requested that the USGS provide technical assistance to their hydrological investigation. Specifically, the USGS was asked to conduct borehole-geophysical logging to identify water-bearing zones that could be monitored by properly completed wells.

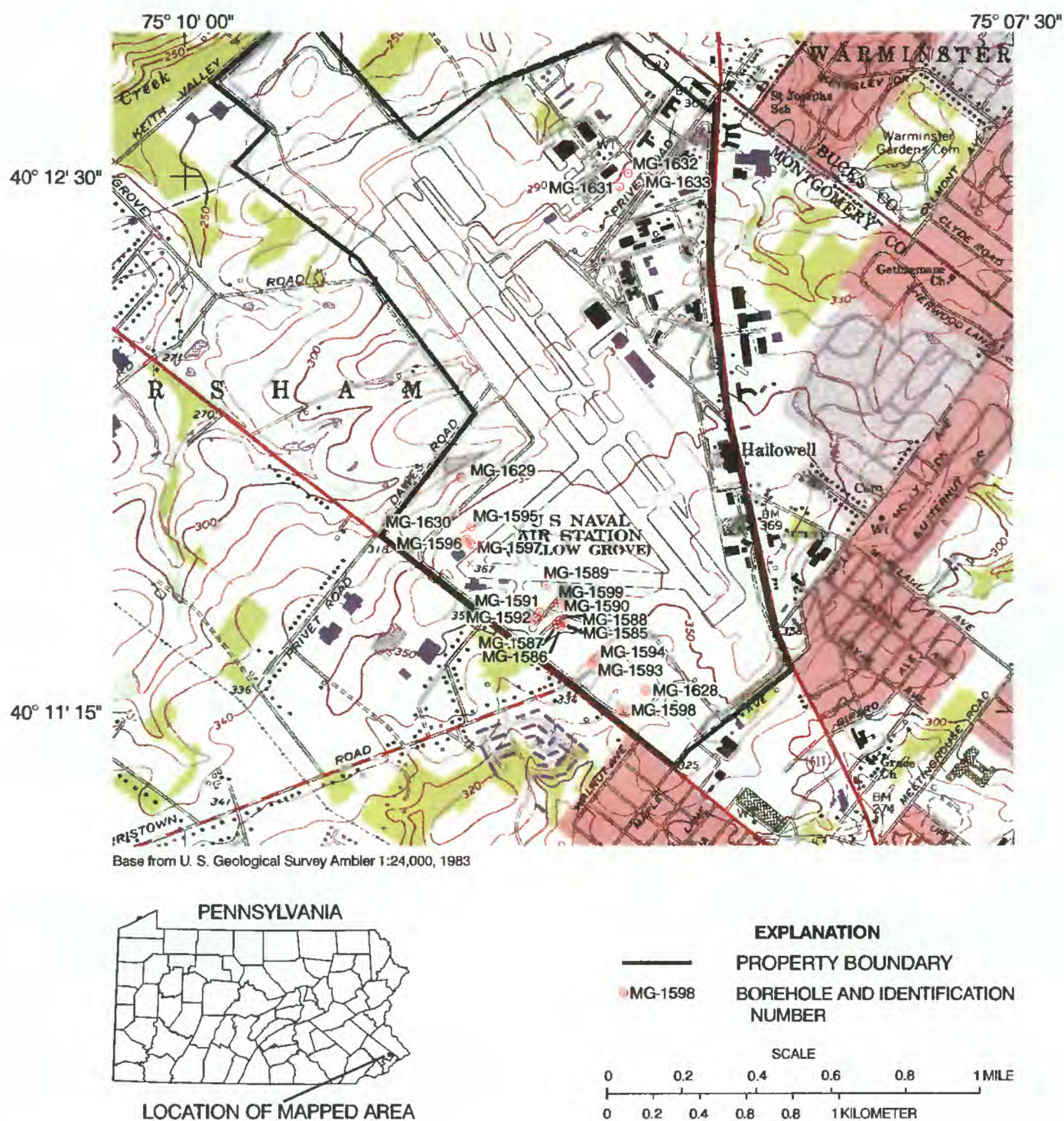


Figure 1. Location of the Willow Grove Naval Air Station, Montgomery County, Pennsylvania, and boreholes described in this report.

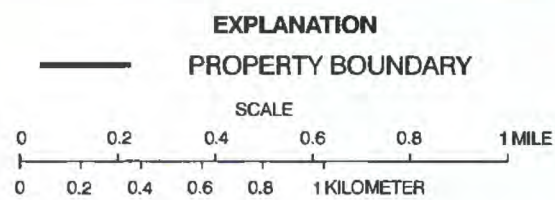
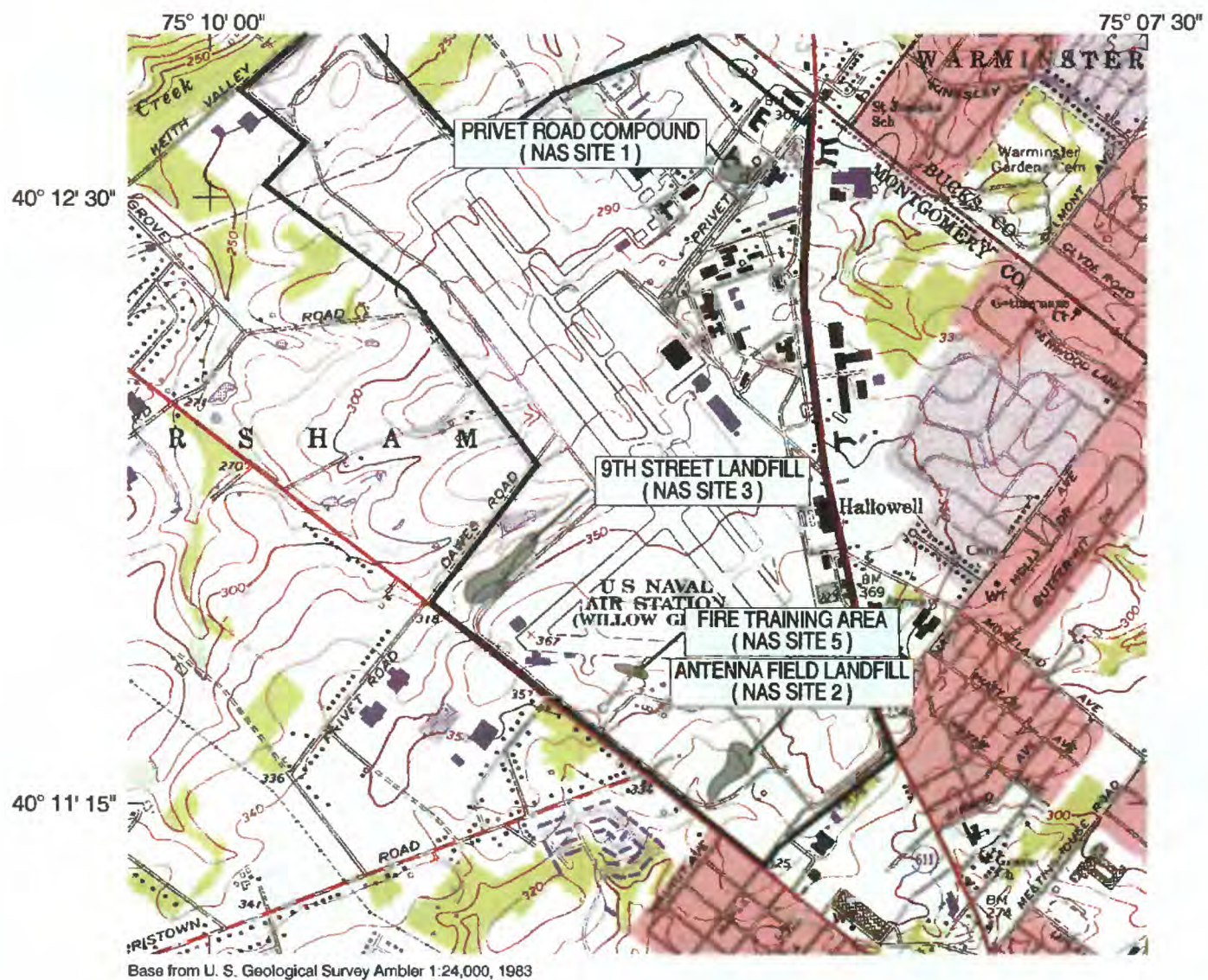


Figure 2. Location of four contaminated sites at the Willow Grove Naval Air Station, Montgomery County, Pennsylvania.

Purpose and Scope

This report evaluates borehole-geophysical and borehole-video logs run by the USGS in 21 boreholes at the NAS from April 14, 1997, to June 5, 1997 (table 1 and fig. 1). One or more water-bearing zones in each well are identified on the basis of geophysical and video-log data. Caliper, natural-gamma, single-point-resistance, fluid-resistivity, fluid-temperature, and borehole-flow (heat-pulse-flowmeter) logs were run in 20 boreholes. Borehole-video logs were run in 16 boreholes. Natural-gamma only was run in borehole MG-1590 for the purpose of stratigraphic correlation. A cross-reference between the USGS borehole-identification numbers and Brown and Root Environmental, Inc. (B&R), borehole-identification numbers and a list of logs run in each borehole are shown in table 1.

Table 1. Boreholes logged at Willow Grove Naval Air Station, Montgomery County, Pennsylvania

[B, borehole-video log; C, caliper log; G, natural-gamma log;
R, single-point-resistance log; F, fluid-resistivity log;
T, fluid-temperature log; V, borehole-flow measurement]

U.S. Geological Survey borehole- identification number	Brown and Root Environmental, Inc.	Depth logged (feet)	Geophysical logs run
MG-1585	05-MW-8S	74	B, C, G, R, F, T, V
MG-1586	05-MW-8I	149	B, C, G, R, F, T, V
MG-1587	05-MW-9I	149	B, C, G, R, F, T, V
MG-1588	05-MW-9S	74	B, C, G, R, F, T, V
MG-1589	05-MW-3I	167	B, C, G, R, F, T, V
MG-1590	05-MW-1I	84	G
MG-1591	05-MW-10S	93	B, C, G, R, F, T, V
MG-1592	05-MW-10I	127	B, C, G, R, F, T, V
MG-1593	02-MW-04S	73	B, C, G, R, F, T, V
MG-1594	02-MW-04I	148	B, C, G, R, F, T, V
MG-1595	03-MW-05I	149	B, C, G, R, F, T, V
MG-1596	03-MW-06S	84	B, C, G, R, F, T, V
MG-1597	03-MW-06I	148	B, C, G, R, F, T, V
MG-1598	02-MW-01I	104	B, C, G, R, F, T, V
MG-1599	05-MW-01I	148	B, C, G, R, F, T, V
MG-1628	02-MW-03I	148	B, C, G, R, F, T, V
MG-1629	03-MW-02I	143	B, C, G, R, F, T, V
MG-1630	03-MW-07S	73	C, G, R, F, T, V
MG-1631	01-MW-03I	98	C, G, R, F, T, V
MG-1632	01-MW-01I	98	C, G, R, F, T, V
MG-1633	01-MW-08I	98	C, G, R, F, T, V

Location and Physiography

The NAS is in the Gettysburg-Newark Lowlands Section of the Piedmont Physiographic Province. The site and surrounding area are underlain by the Stockton Formation, which consists of sedimentary rocks of Triassic age. The Stockton Formation is subdivided into three lithologic units known as the lower arkose, middle arkose, and upper shale members (Rima and others, 1962). The middle arkose member crops out at the site. At the NAS, this unit consists of fine- to medium-grained arkosic sandstone interbedded with red siltstone and mudstone. Quartz, calcite, and feldspar are predominant.

The Stockton Formation is approximately 6,000 ft thick at the Bucks-Montgomery County line. At this location, the middle arkose member has a maximum thickness of about 4,200 ft (Rima and others, 1962). Bedding planes in the Stockton Formation at the NAS generally strike NE-SW and dip an average of 12° NW (Rima and others, 1962). Vertical fractures are common. Primary ground-water storage and movement within the Stockton Formation occurs through secondary openings such as interconnected fractures, bedding planes separations, and joints (Sloto and others, 1995). Deeper wells may penetrate several water-bearing zones with different hydraulic properties that are under different hydraulic head. Thus, wells penetrating more than one water-bearing zone are multiaquifer wells (Sloto and others, 1995). The hydraulic head in a multiaquifer well is a composite of the heads of all water-bearing zones it includes. In areas where the hydraulic head differs between water-bearing zones, water either flows up or down the well bore in the direction of lower head (Sloto and others, 1995).

Ground water at the NAS originates from infiltration of precipitation and inflow of ground water from upgradient areas. Ground-water levels fluctuate with seasonal variations in recharge and also are influenced by pumping of nearby wells. Water in the upper part of the aquifer generally is under unconfined (water table) conditions; water in the deeper part of the aquifer may be confined or partly confined. Local artesian conditions are common.

Borehole-Geophysical Logs

Geophysical logs provide information on location of fractures (caliper and video logs), water-bearing and water-receiving zones and intervals of vertical borehole flow (fluid-resistivity and fluid-temperature logs), quantification of borehole flow (heat-pulse-flowmeter logs), lithologic correlation (gamma and electric logs), and well construction (caliper and electric logs).

Caliper logs record the average borehole diameter, which may be related to fractures, lithology, or drilling methods. Caliper logs can be used to identify fractures and possible water-producing openings and to correct other geophysical logs for changes in borehole diameter. They also can be correlated with fluid-resistivity and fluid-temperature logs to identify fractures, water-producing zones, water-receiving zones, and to measure water velocity.

The term fracture used in association with the caliper-log interpretations might identify a change in borehole diameter that may not necessarily indicate a bedding-plane separation, lithologic contact, or fluid-producing or fluid-receiving zones but may simply indicate an enlargement of the borehole.

The natural-gamma or gamma log measures the natural-gamma radiation (photons) emitted from all rocks. The most common emitters of gamma radiation are uranium-238 and thorium-232 and their daughter elements and potassium-40. These radioactive elements are concentrated in clays by adsorption, precipitation, and ion exchange. Fine-grained sediments such as shale or siltstone usually emit more gamma radiation than sandstone, limestone, or dolomite. The gamma log can be run in or out of water or casing. However, casing does reduce the gamma response. The gamma log is used to correlate geologic units between wells (Keys, 1988).

The single-point-resistance log records the electrical resistance of a formation between the probe in a water-filled borehole below casing and an electrical ground at land surface. Generally, electrical resistance increases with formation grain size and decreases with borehole diameter, water-bearing fractures, and increasing dissolved-solids concentration of borehole water. The single-point-resistance log is used to correlate geology and lithology between wells and may help identify formation water-bearing zones (Keys and MacCary, 1971).

Fluid resistivity is the inverse of fluid conductivity. The fluid-resistivity log measures the electrical resistivity of the water column in the well. The fluid-resistivity probe measures the resistivity of borehole water between electrodes in the probe. Fluid-resistivity logs reflect changes in the dissolved-solids concentration of water in the borehole. Fluid-resistivity logs are used to identify water-producing and water-receiving zones and to determine intervals of vertical borehole flow. Water-producing and water-receiving zones are usually identified by distinct changes in resistivity. Intervals of vertical borehole flow usually are identified by a low-resistivity gradient between a water-producing and a water-receiving zone. Also, zones of salt water intrusion and some types of contaminant plumes can be identified.

Fluid-temperature logs provides a continuous record of the temperature of vertical variation in the water in a borehole. Temperature logs are used to identify water-producing and water-receiving zones and to determine zones of vertical borehole flow. Intervals of vertical borehole flow are characterized by little or no temperature gradient (Williams and Conger, 1990).

The direction and rate of borehole-water movement was determined by the use of a heat-pulse flowmeter. The heat-pulse flowmeter operates by heating a small sheet of water between two sensitive thermistors (heat sensors). A measurement of direction and rate is computed when a peak temperature is recorded by one of the thermistors. The range of flow measurement is about 0.01-1.5 gal/min in a 2- to 10-in.-diameter borehole (Conger, 1996).

Some heat-pulse-flowmeter measurements may be influenced by (1) an incomplete seal between the borehole and heat-pulse flowmeter, and (2) contributions of water from storage within the borehole. If the seal between the borehole and flowmeter is not complete, some water can bypass the flowmeter, resulting in measurements of flow that are less than the actual rate. Although the heat-pulse flowmeter is a calibrated probe, the data are used primarily as a relative indicator to identify water-producing zones.

Borehole-television logging was conducted by lowering a waterproof camera down the borehole and recording the image on video tape. The depth indicated on the video log may not correspond exactly to the geophysical logs because of some minor slippage of the television cable.

EVALUATION OF BOREHOLE-GEOPHYSICAL LOGS

The locations of boreholes logged are shown on figure 1. The reference measuring point for all geophysical and video logs is the land surface. Depth of wells, casing lengths, and water levels at the time of logging are given in table 2.

Table 2. Well depth, casing length, and depth to water for boreholes logged by the U.S. Geological Survey at Willow Grove Naval Air Station, Montgomery County, Pennsylvania

U.S. Geological Survey borehole-identification number	Brown and Root Environmental, Inc.	Depth of well below land surface (feet)	Length of casing below land surface (feet)	Depth to water below land surface (feet)	Date water level measured
MG-1585	05-MW-8S	74	18	17.87	4/14/97
MG-1586	05-MW-8I	149	18	17.72	4/14/97
MG-1587	05-MW-9I	149	24	18.71	4/14/97
MG-1588	05-MW-9S	74	24	18.32	4/15/97
MG-1589	05-MW-3I	167	29	23.32	4/15/97
MG-1590	05-MW-1I	84	¹ 84	20.73	4/15/97
MG-1591	05-MW-10S	93	19	18.78	4/15/97
MG-1592	05-MW-10I	127	19	19.24	4/16/97
MG-1593	02-MW-04S	73	30	27.08	4/29/97
MG-1594	02-MW-04I	148	24	24.34	4/29/97
MG-1595	03-MW-05I	149	27	24.60	4/29/97
MG-1596	03-MW-06S	84	25	28.24	4/30/97
MG-1597	03-MW-06I	148	20	No data	
MG-1598	02-MW-01I	104	13	37.00	4/30/97
MG-1599	05-MW-01I	148	24	21.51	5/15/97
MG-1628	02-MW-03I	148	13	12.44	5/15/97
MG-1629	03-MW-02I	143	13	8.52	5/15/97
MG-1630	03-MW-07S	73	14	10.97	6/5/97
MG-1631	01-MW-03I	98	19	9.66	6/5/97
MG-1632	01-MW-01I	98	25	11.62	6/5/97
MG-1633	01-MW-08I	98	25	11.38	6/5/97

¹ Well reconstructed with plastic screen.

MG-1585 (05-MW-8S)

The caliper log shows the total depth of the borehole is 74 ft and it is cased with 6-in.-diameter casing to 18 ft bls (below land surface) (fig. 3). The caliper log shows major fractures at 56, 59, and 69 ft bls and minor fractures at 32-33, 43, and 49-51 ft bls. The fluid-resistivity log shows changes in slope at 30, 44, 65, and 73 ft bls that correlate to fractures shown on the caliper log. Under ambient conditions, the heat-pulse flowmeter measured downward flow at 38, 46, and 54 ft bls and no flow at 26 and 66 ft bls (table 3). The borehole-video log shows the borehole water becomes cloudy abruptly at 66 ft bls, which indicates that little or no borehole flow exists below that depth. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 32-33 and 43 ft bls and moves downward. Most of the water then exits the borehole through fractures at 55-65 ft bls; a minor quantity of water exits the borehole at 49-51 ft bls. The driller's log shows the largest water-producing zone in the borehole is at approximately 60 ft bls. Screens were placed at 26-36 and 55-65 ft bls to include the water-producing fractures at 32-33 and 60 ft bls.

Table 3. *Summary of heat-pulse-flowmeter measurements for borehole MG-1585 (05-MW-8S) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
26	No flow	
38	0.28	Down
46	.75	Down
54	.60	Down
66	No flow	

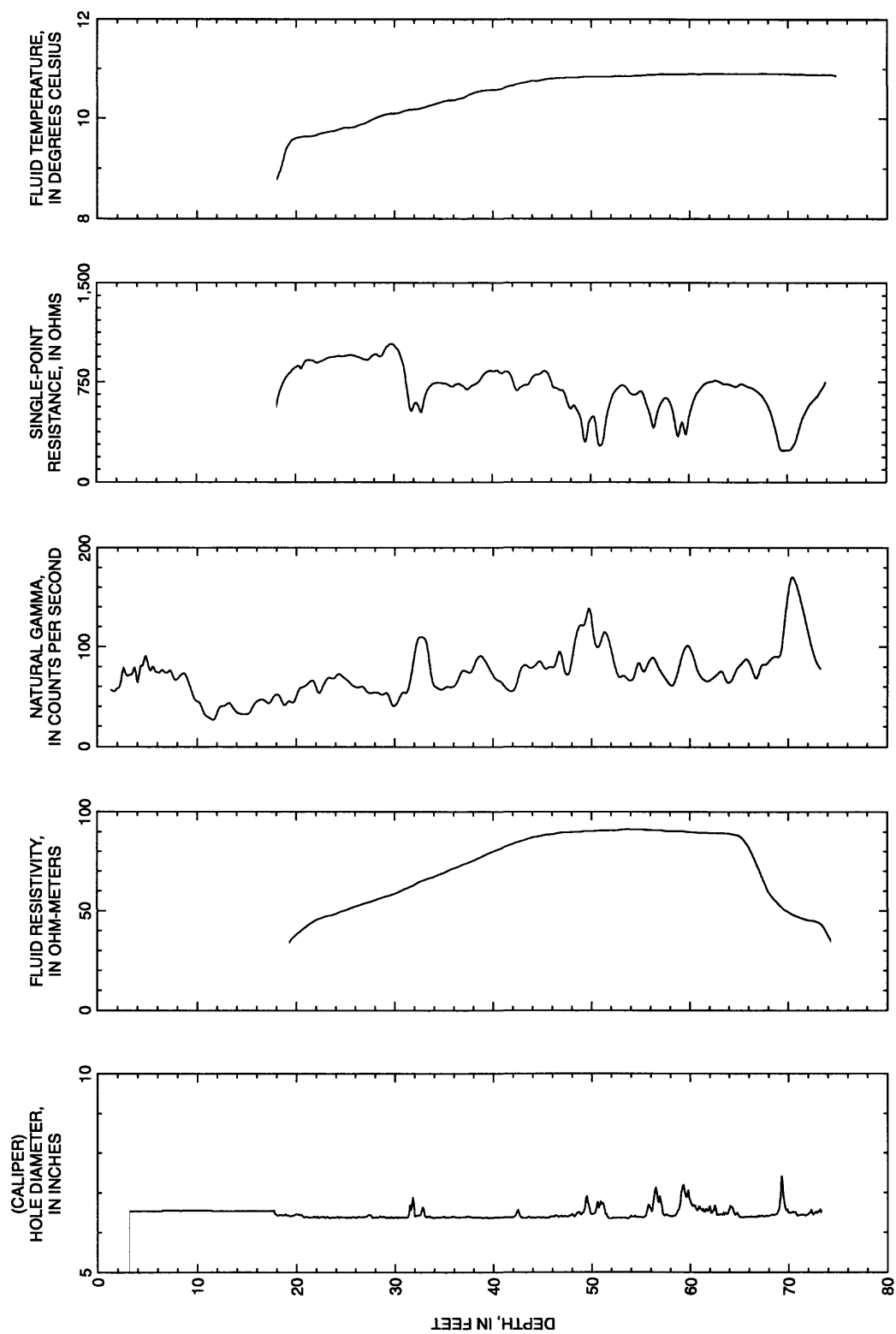


Figure 3. Borehole-geophysical logs for borehole MG-1585 (05-MW-8S), Willow Grove Naval Air Station.

MG-1586 (05-MW-8I)

The caliper log shows the total depth of the borehole is 149 ft and it is cased with 6-in.-diameter casing to about 18 ft bls (fig. 4). The caliper log shows major fractures at 54-62 and 93-95 ft bls and numerous minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 22, 42, 108, and 133 ft bls that correlate to fractures on the caliper log. Also, the fluid-temperature log shows a change in slope at 42 and 60 ft bls that correlates to fractures on the caliper log. Under ambient conditions, the heat-pulse-flowmeter measurements indicated downward borehole flow at 36, 52, 88, and 102 ft bls (table 4). The borehole-video log shows the borehole water becomes cloudy at 116 ft bls, which indicates that little or no borehole flow exists below that depth. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through the fractures at 20, 41, and 60 ft bls, moves downward, and exits the borehole at 93-95 and 104-116 ft bls. The driller's log shows the greatest water-producing zone in the borehole is at approximately 93-95 ft bls. A screen was placed at 89-99 ft bls to include the fractures from 93-95 ft bls.

Table 4. *Summary of heat-pulse-flowmeter measurements for borehole MG-1586 (05-MW-8I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
36	0.96	Down
52	1.2	Down
88	1.5	Down
102	.90	Down

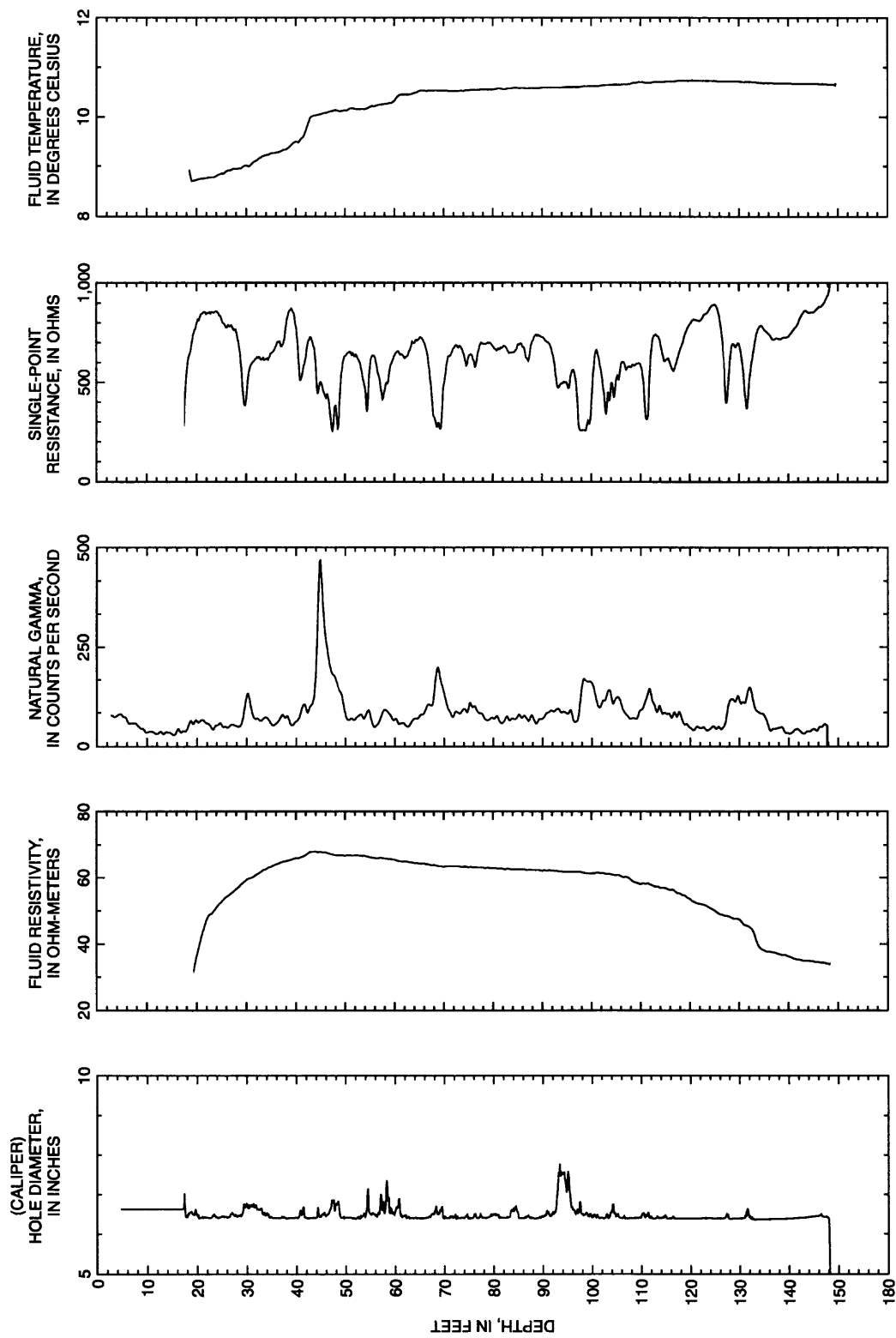


Figure 4. Borehole-geophysical logs for borehole MG-1586 (05-MW-8I), Willow Grove Naval Air Station.

MG-1587 (05-MW-9I)

The caliper log shows the total depth of the borehole is 149 ft and it is cased with 6-in.-diameter casing to 24 ft bls (fig. 5). The caliper log shows a major fracture at 70-74 ft bls plus numerous minor fractures throughout the open-hole interval. Also, the caliper log shows a constriction within the borehole at 101-103 ft bls that may be caused by the shifting of loose formation rock. The fluid-resistivity log shows changes in slope at 25, 42, 72, and 105 ft bls that correlate to fractures shown on the caliper log. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 35, 50, 66, 78, and 89 ft bls and no flow at 110 ft bls (table 5). The borehole-video log shows the borehole water becomes cloudy abruptly at 120 ft bls indicating little or no borehole flow exists below that depth. The geophysical logs and the heat-pulse-flowmeter and video data indicate water enters the borehole through fractures at 25 ft bls, moves downward, and exits the borehole through fractures at approximately 105 ft bls. The driller's log shows the greatest water-producing zone in the borehole is at approximately 104-106 ft bls. A screen was placed at 96-106 ft bls to include these fractures.

Table 5. *Summary of heat-pulse-flowmeter measurements for borehole MG-1587 (05-MW-9I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
35	1.5	Down
50	1.4	Down
66	1.5	Down
78	1.5	Down
89	1.5	Down
110	No flow	

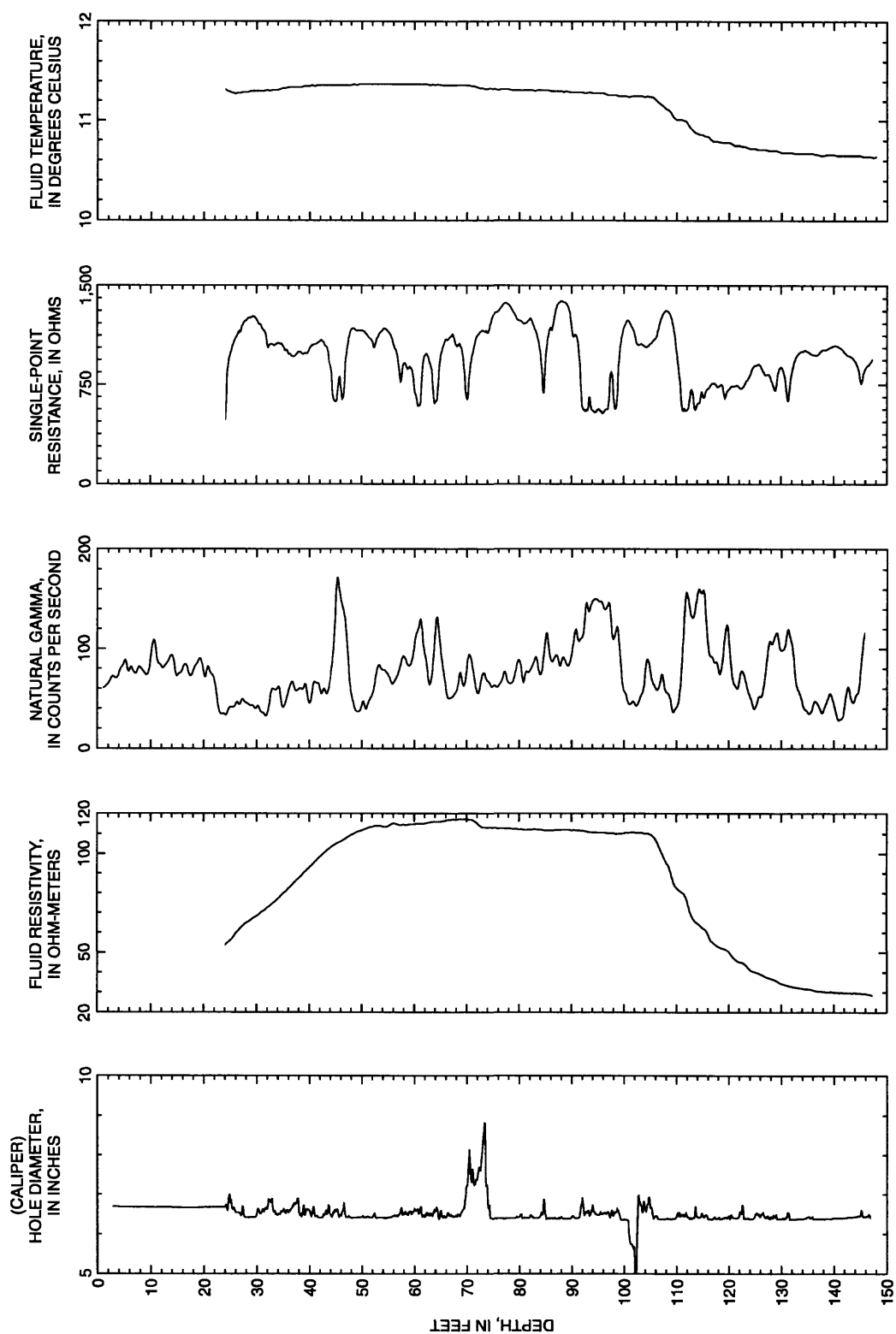


Figure 5. Borehole-geophysical logs for borehole MG-1587 (05-MW-91), Willow Grove Naval Air Station.

MG-1588 (05-MW-9S)

The caliper log shows the total depth of the borehole is 74 ft and it is cased with 6-in.-diameter casing to 24 ft bls (fig. 6). The caliper log shows only minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 26, 38-40, and 70 ft bls that correlate to minor fractures shown on the caliper log. The fluid-temperature log shows almost no change in gradient with depth to about 70 ft bls indicating borehole flow. The natural-gamma log shows a shale unit with elevated gamma readings at 55-57 ft bls that might be used for stratigraphic correlation of geologic units with other wells. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 27, 36, 58, and 65 ft bls and no flow at 71 ft bls (table 6). The borehole-video log shows the borehole water becomes cloudy at 71 ft bls indicating little or no borehole flow exists below that depth. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures just below casing about 27 ft bls, moves downward, and exits the borehole through fractures at approximately 68-70 ft bls. The driller's log reports 2 gal/min of water is produced between 60-70 ft bls. A screen and sand pack was placed at 27-32 and 59-74 ft bls to include the water-producing fractures at 27 ft bls and between 60-70 ft bls.

Table 6. *Summary of heat-pulse-flowmeter measurements for borehole MG-1588 (05-MW-9S) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*
[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
27	0.86	Down
36	1.0	Down
58	.99	Down
65	.97	Down
71	No flow	No flow

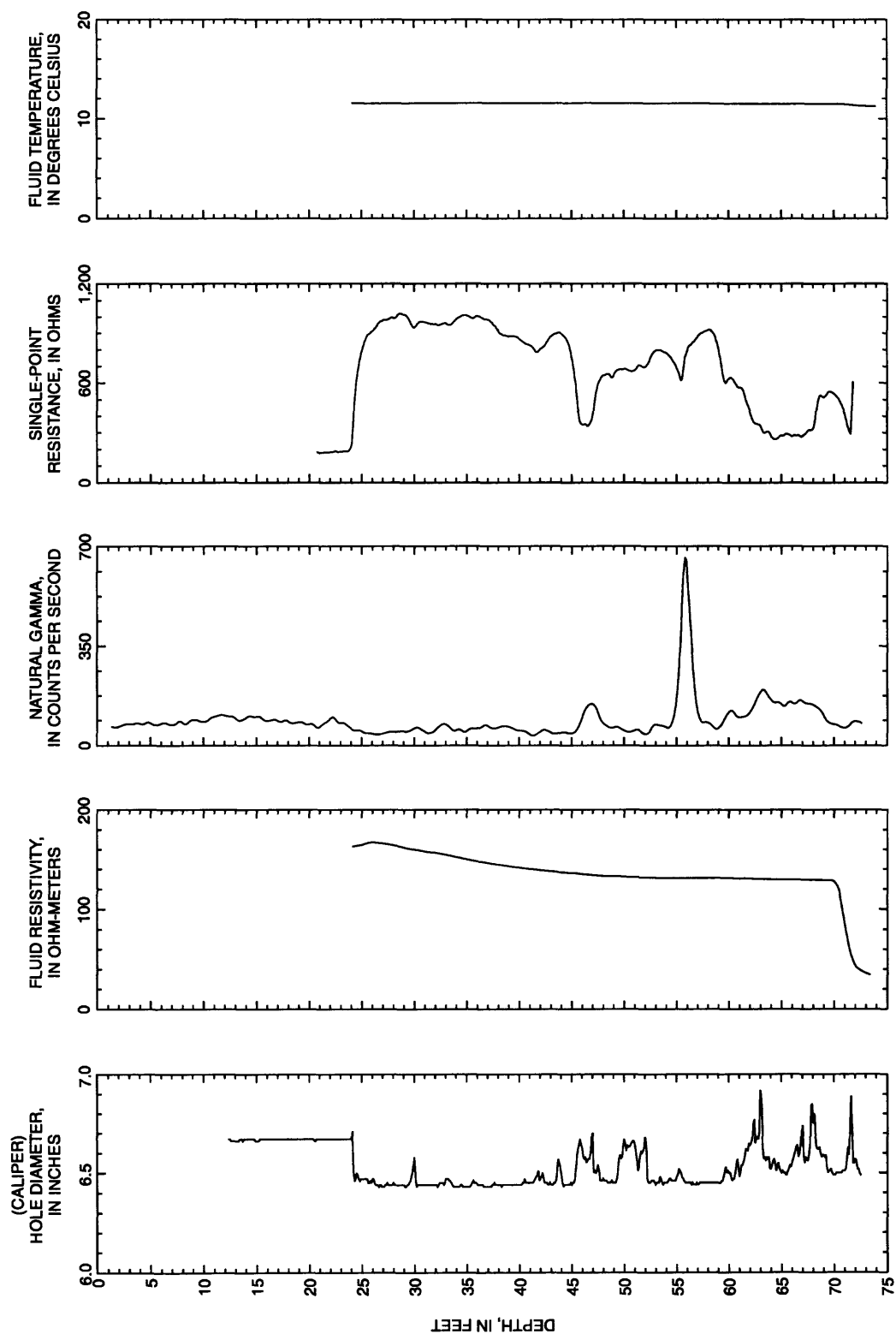


Figure 6. Borehole-geophysical logs for borehole MG-1588 (05-MW-9S), Willow Grove Naval Air Station.

MG-1589 (05-MW-3I)

The caliper log shows the total depth of the borehole is 167 ft and it is cased with 6-in.-diameter casing to 29 ft bls (fig. 7). The caliper log shows major fractures at 71-75 and 119-127 ft bls plus numerous smaller fractures. Also, a constriction within the borehole is indicated at 121 ft bls that may be caused by the shifting of loose formation rock. The fluid-resistivity and fluid-temperature logs show changes in slope at 39, 50, 132, 149, and 155 ft bls that correlate to minor fractures shown on the caliper log. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 45, 60, and 100 ft bls, upward flow at 138 and 152 ft bls, and no flow at 160 ft bls (table 7). The borehole-video log shows the borehole water becomes cloudy at 158 ft bls indicating little or no borehole flow exists below that depth. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at about 40 ft bls, moves downward, and exits the borehole through fractures at approximately 115-132 ft bls. Additional water is produced near the bottom at 154-156 ft bls, moves upward, and exits the borehole at 146-149 and 115-132 ft bls. The driller's log reports that during drilling approximately 30 gal/min of water was produced at 128 ft bls. A screen and sand pack were placed at 118-128 ft bls to capture the water-producing fractures at 128 ft bls.

Table 7. *Summary of heat-pulse-flowmeter measurements for borehole MG-1589 (05-MW-3I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
45	1.4	Down
60	1.3	Down
100	1.4	Down
138	.09	Up
152	.13	Up
160	No flow	No flow

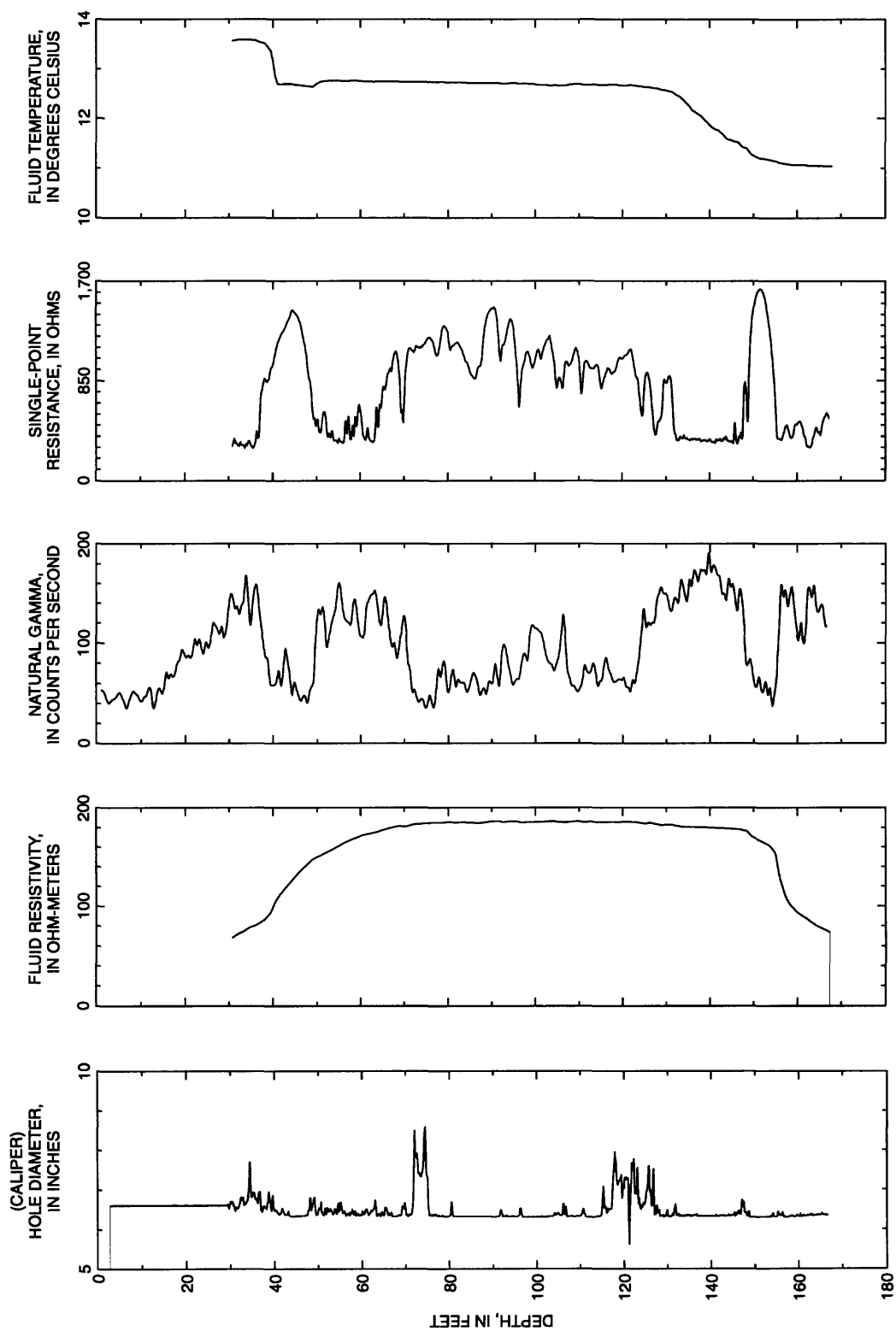


Figure 7. Borehole-geophysical logs for borehole MG-1589 (05-MW-3I), Willow Grove Naval Air Station.

MG-1590 (05-MW-1I)

This existing borehole was already screened. Therefore, only the gamma log was run for the purpose of stratigraphic correlation. The gamma log shows the total depth of the borehole is 84 ft bls (fig. 8). The gamma log shows a large spike at 53-56 ft bls that indicates a distinct shale unit and may be useful for correlation.

MG-1591 (05-MW-10S)

The caliper log shows the total depth of the borehole is 93 ft and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 9). The caliper log shows numerous fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 28, 38, 86, and 90 ft bls. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 36, 44, 58, and 76 ft bls (table 8). The borehole-video log shows the borehole water becomes cloudy at 86 ft bls indicating little or no borehole flow exists below that depth. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 27-32 ft bls, moves downward, and exits the borehole through fractures at 54, 70, and 85 ft bls. Screens were placed at 22-32 and 79-94 ft bls to include the water-producing fracture at 28 ft bls and water-receiving fracture at 85 ft bls.

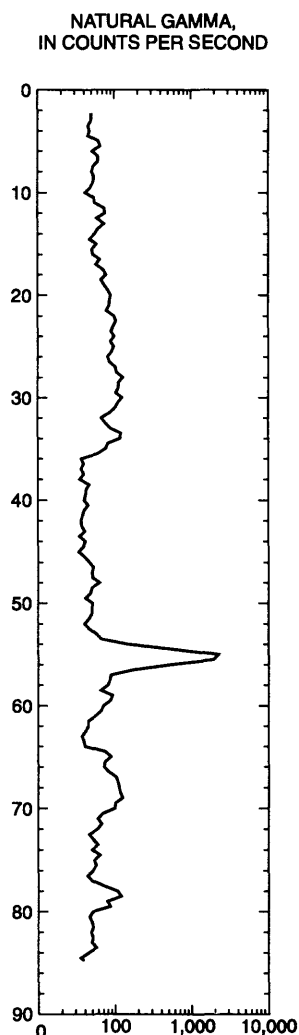


Figure 8. Natural-gamma log for borehole MG-1590 (05-MW-1I), Willow Grove Naval Air Station.

Table 8. Summary of heat-pulse-flowmeter measurements for borehole MG-1591 (05-MW-10S) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
36	0.39	Down
44	.51	Down
58	.34	Down
76	.22	Down

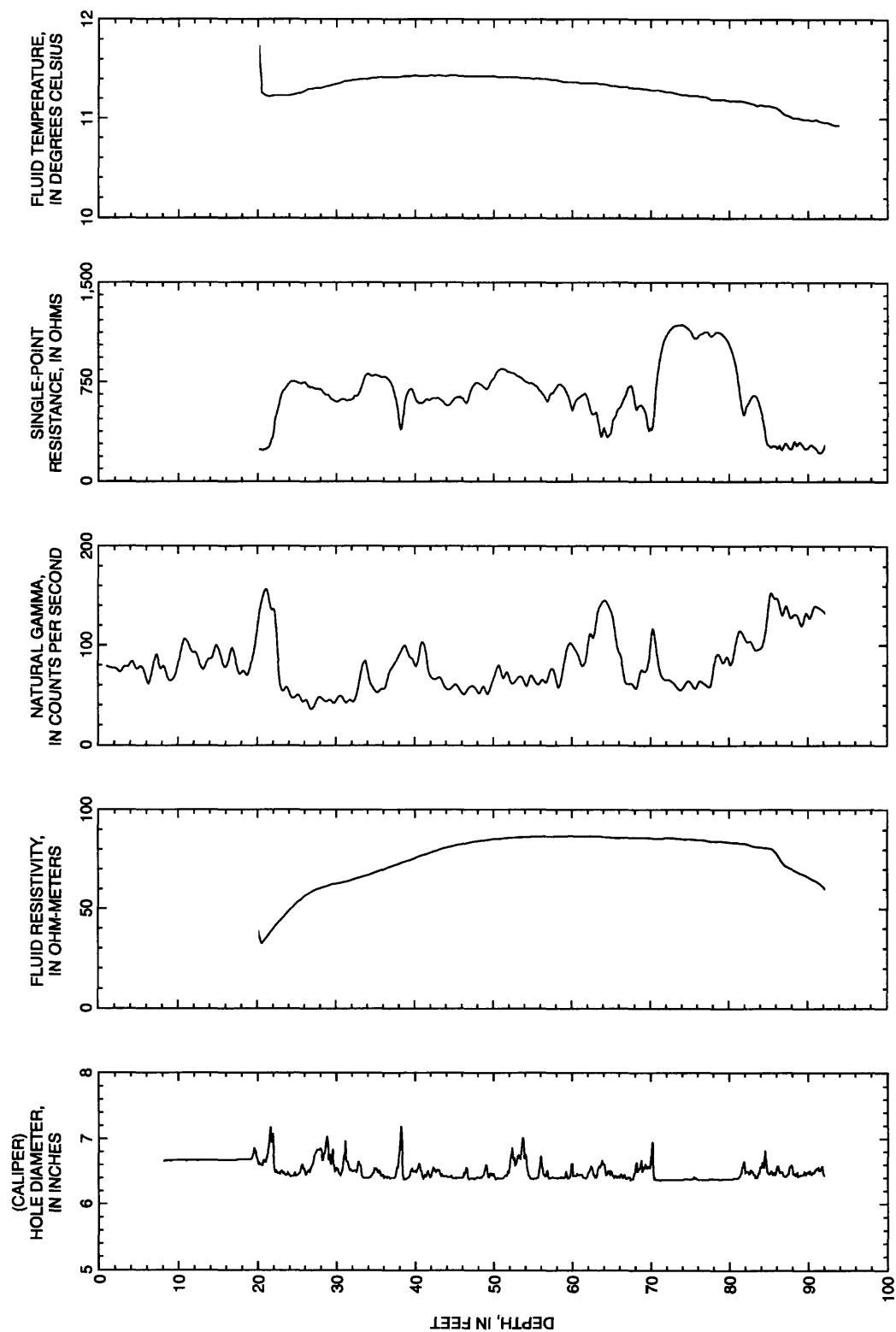


Figure 9. Borehole-geophysical logs for borehole MG-1591 (05-MW-10S), Willow Grove Naval Air Station.

MG-1592 (05-MW-10I)

The caliper log shows the total depth of the borehole is 127 ft and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 10). The caliper log shows major fractures at 19-20, 27-30, 32-35, 74-77, and 98 ft plus numerous minor fractures throughout the open-hole interval. The fluid-resistivity and fluid-temperature logs show changes in slope at 32, 80, and 122 ft bls that correlate to fractures shown on the caliper log. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 42, 54, 66, 82, 92, 102, and 117 ft bls (table 9). The borehole-video log shows the borehole water becomes cloudy at 121 ft bls indicating little or no borehole flow exists below that depth. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at about 32 ft bls and at 74-77 and 98 ft bls, moves downward, and exits the borehole through fractures at 118-121 ft bls. The driller's log reports 4-9 gal/min of water production at 128 ft bls, which probably is produced from the fractures at 118-121 ft bls. A screen was placed at 116-126 ft bls to include the water-producing fractures at 118-121 ft bls.

Table 9. *Summary of heat-pulse-flowmeter measurements for borehole MG-1592 (05-MW-10I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
42	0.12	Down
54	.13	Down
66	.13	Down
82	.47	Down
92	.62	Down
102	.80	Down
117	.74	Down

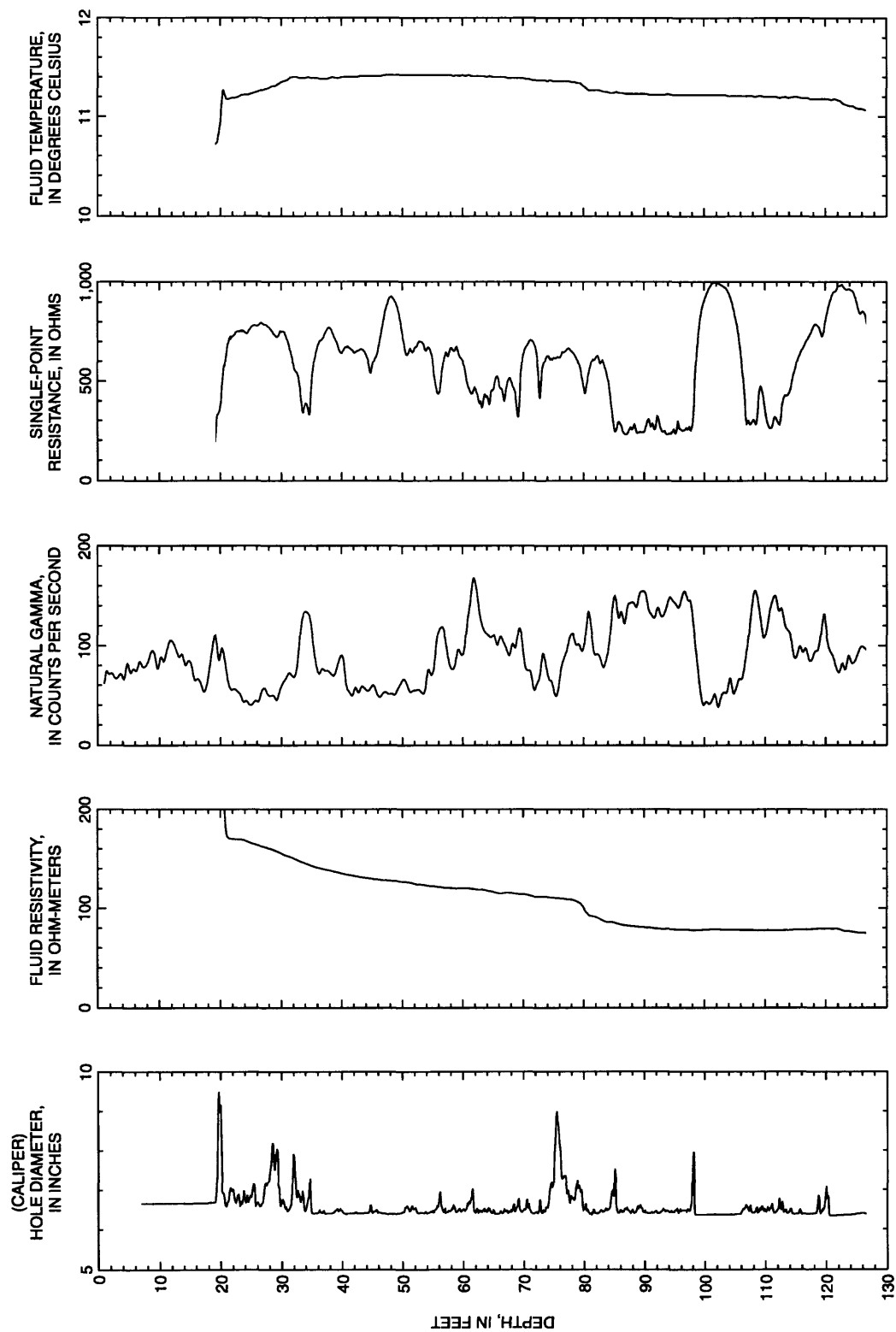


Figure 10. Borehole-geophysical logs for borehole MG-1592 (05-MW-10I), Willow Grove Naval Air Station.

MG-1593 (02-MW-04S)

The caliper log shows the total depth of the borehole is 73 ft and it is cased with 6-in.-diameter casing to 30 ft bls (fig. 11). The caliper log shows major fractures at 33 and 61 ft bls. The fluid-resistivity and fluid-temperature logs show a change in slope at 60 ft bls that correlates to a fracture shown on the caliper log. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 36 ft bls, upward flow at 50 ft bls, and no flow at 64 ft bls (table 10). The borehole-video log shows the borehole water becomes cloudy beginning at 56 ft bls. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 33 and 61 ft bls, moves downward and upward, respectively, and exits the borehole through fractures at 38–48 ft bls. A screen was placed at 34–44 ft bls, and a sand pack was placed at 33–45 ft bls to capture the water-producing fracture at 33 ft bls.

Table 10. Summary of heat-pulse-flowmeter measurements for borehole MG-1593 (02-MW-04S) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
36	0.43	Down
50	.12	Up
64	No flow	

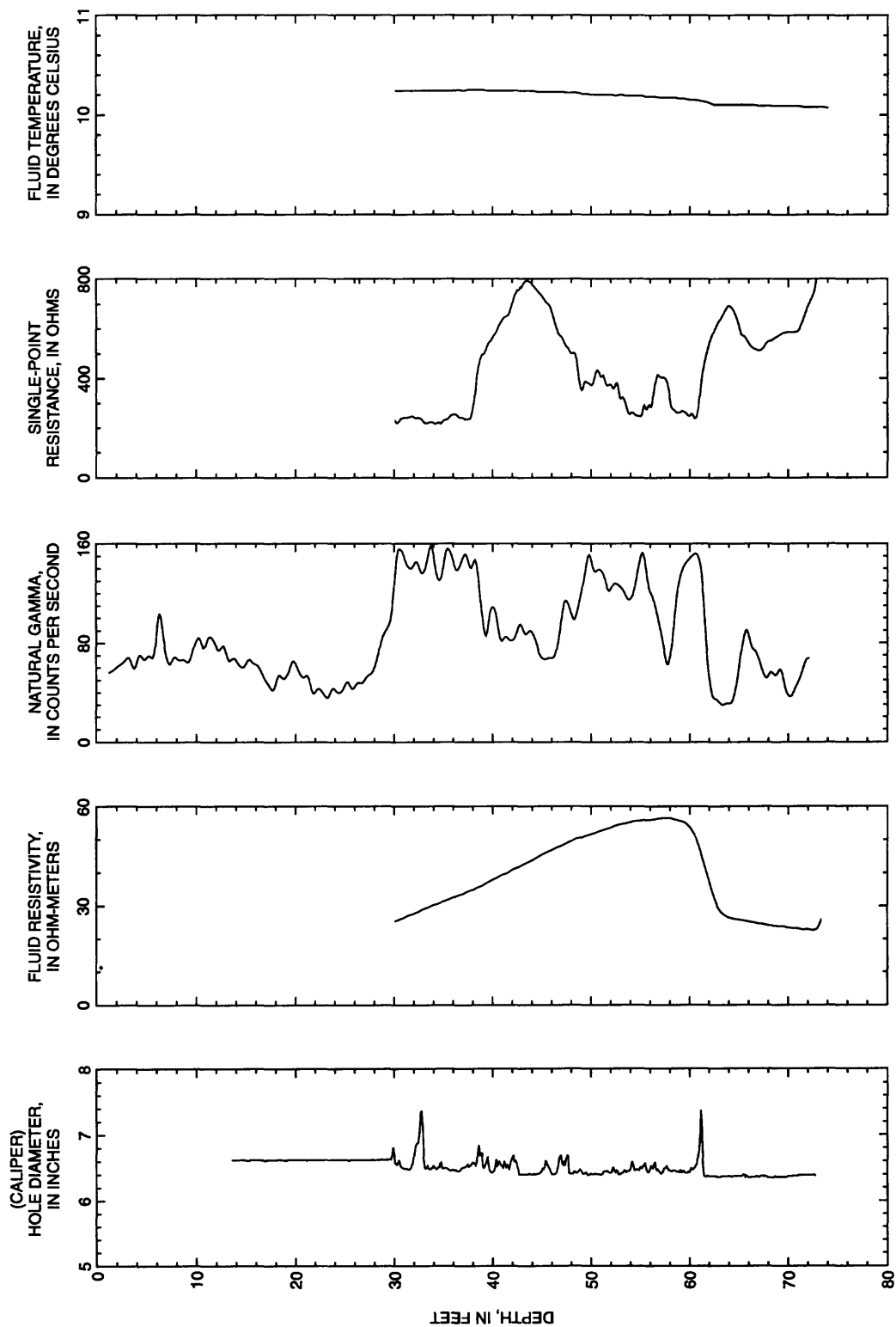


Figure 11. Borehole-geophysical logs for borehole MG-1593 (02-MW-04S), Willow Grove Naval Air Station.

MG-1594 (02-MW-04I)

The caliper log shows the total depth of the borehole is 148 ft and it is cased with 6-in.-diameter casing to 24 ft bls (fig. 12). The caliper log shows major fractures at 25 and 31 ft bls plus numerous minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 52 and 60 ft bls that may indicate water-producing fractures. The fluid-resistivity and fluid-temperature logs show a change in slope at 131 ft bls that correlates to a fracture shown on the caliper log. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 39, 51, 72, 95, 104, 114, and 122 ft bls (table 11). The borehole-video log shows the borehole water becomes cloudy at 136 ft bls indicating little or no borehole flow exists below that depth. The geophysical logs, video log, and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 27 ft bls, moves downward, and exits the borehole through fractures at 110 and 130 ft bls. A screen was placed at 105-115 ft bls to include the water-receiving fractures at 110 ft bls.

Table 11. Summary of heat-pulse-flowmeter measurements for borehole MG-1594 (02-MW-04I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
39	1.5	Down
51	1.5	Down
72	1.4	Down
95	1.5	Down
104	1.5	Down
114	.90	Down
122	.93	Down

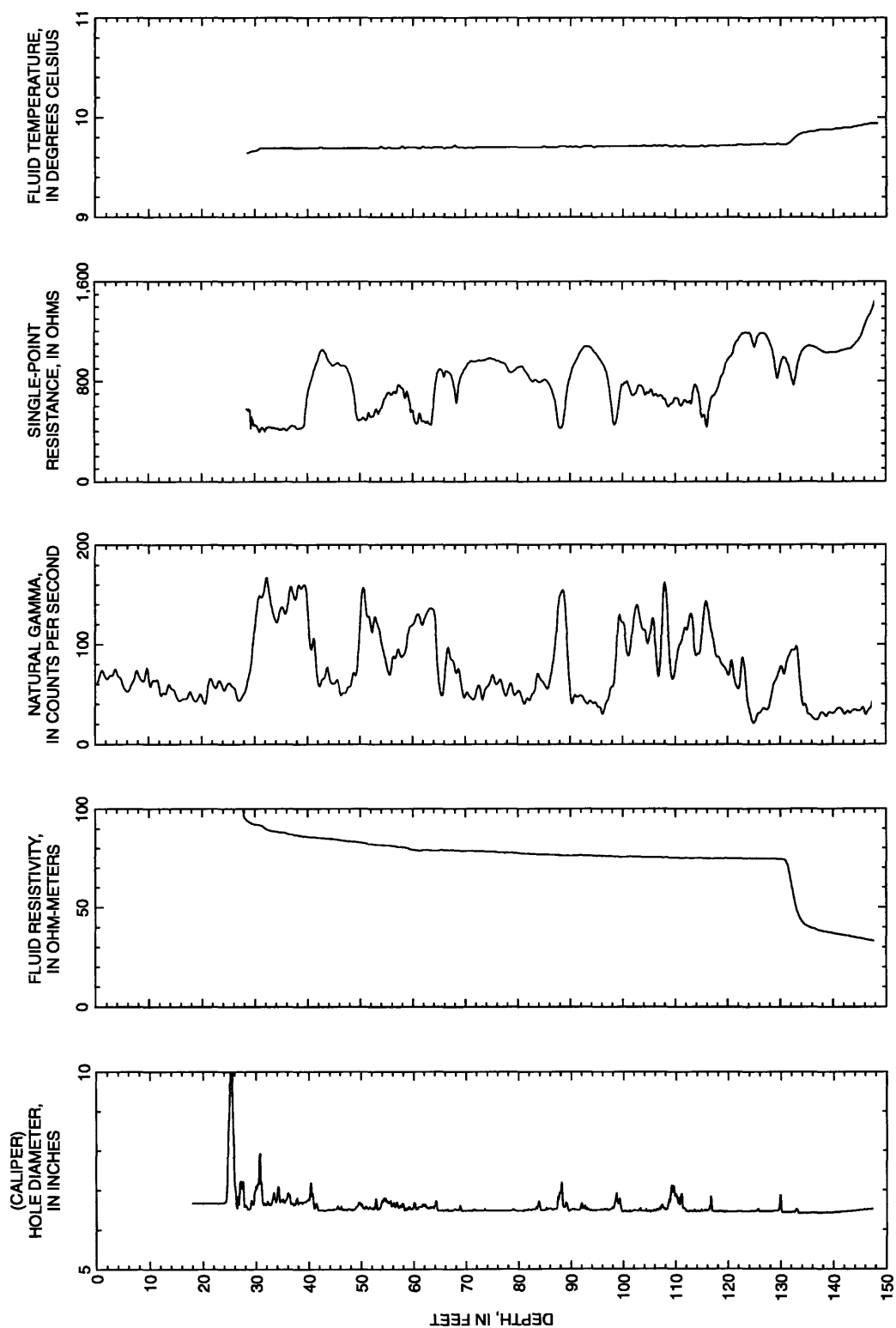


Figure 12. Borehole-geophysical logs for borehole MG-1594 (02-MW-04), Willow Grove Naval Air Station.

MG-1595 (03-MW-051)

The caliper log shows the total depth of the borehole is 149 ft and it is cased with 6-in.-diameter casing to 27 ft bls (fig. 13). The caliper log shows major fractures at 58-61, 65-66, 67-69, 74, 78 and 86 ft bls plus numerous minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 60, 94, 112, 135, and 145 ft bls that correlate to fractures shown on the caliper log and may indicate water-producing zones. Under ambient conditions, the heat-pulse flowmeter measured upward borehole flow at 46, 63, 83, 100, 124, and 140 ft bls (table 12). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 145, 110-116, 94, and 60 ft bls, moves upward, and exits the borehole through fractures at approximately 30 ft bls. The driller's log reports 2 gal/min of water production at about 90 ft bls and 4 gal/min at 135-145 ft bls. Screens placed at 80-95 and 130-145 ft bls would include the water-producing fractures at 90 and 135-145 ft bls. A screen was placed at 82-92 ft bls to include the water-producing fractures at 90 ft bls.

Table 12. *Summary of heat-pulse-flowmeter measurements for borehole MG-1595 (03-MW-051) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
46	0.18	Up
63	.17	Up
83	.17	Up
100	.15	Up
124	.11	Up
140	.13	Up

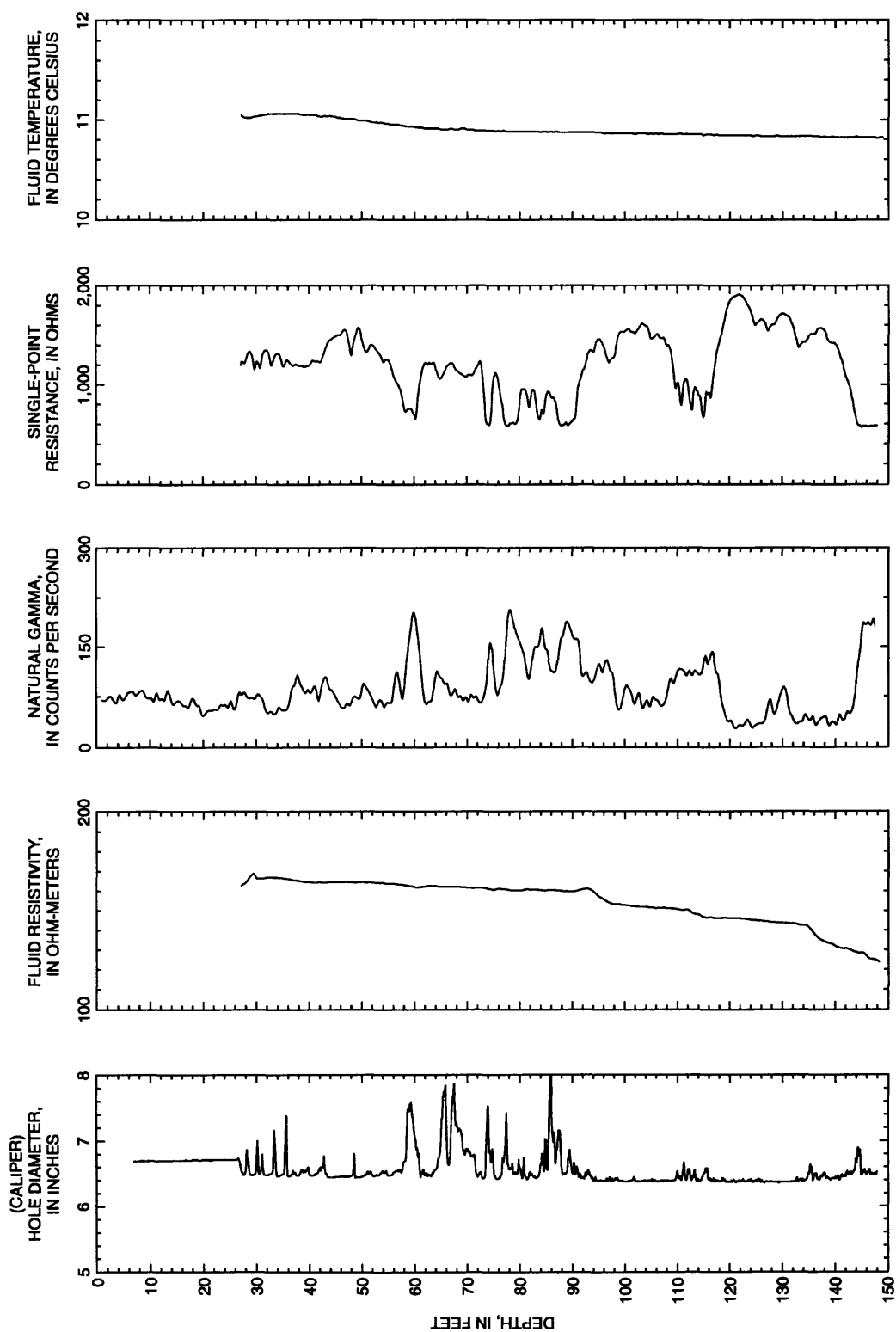


Figure 13. Borehole-geophysical logs for borehole MG-1595 (03-MW-051), Willow Grove Naval Air Station.

MG-1596 (03-MW-06S)

The caliper log shows the total depth of the borehole is 84 ft and it is cased with 6-in.-diameter casing to 25 ft bls (fig. 14). The caliper log shows major fractures at 39-44 and 80-83 ft bls plus numerous minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 39 and 80 ft bls that correlate to fractures shown on the caliper log. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 35, 52, 68, and 75 ft bls (table 13). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 31, 39-44, and 55-65 ft bls, moves downward, and exits the borehole through fractures at 80-83 ft bls. Screens were placed at 26-36 and 75-85 ft bls to include the water-producing fracture at 31 ft bls and water-receiving fractures at 80-83 ft bls.

Table 13. *Summary of heat-pulse-flowmeter measurements for borehole MG-1596 (03-MW-06S) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
35	0.19	Down
52	.15	Down
68	.30	Down
75	.33	Down

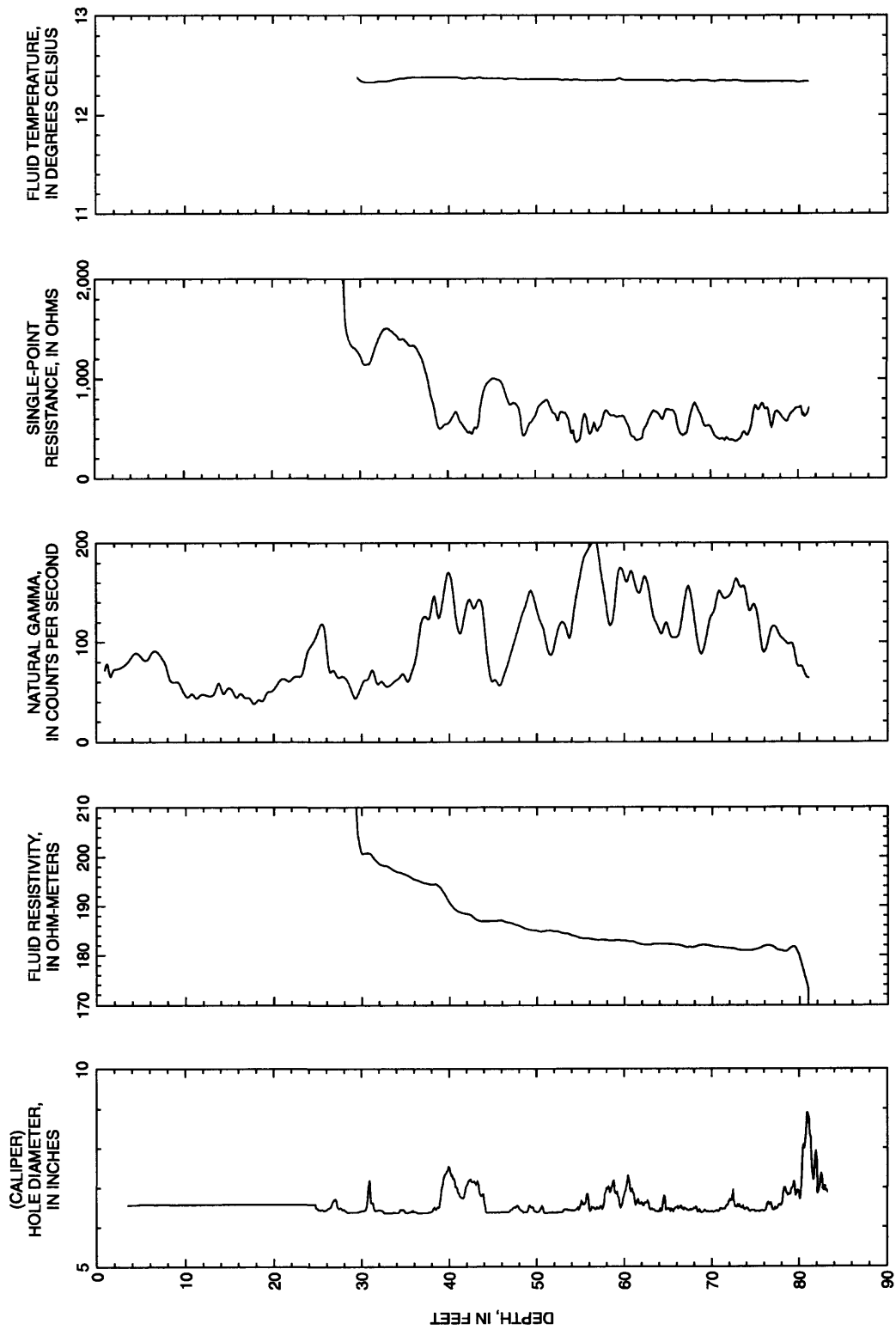


Figure 14. Borehole-geophysical logs for borehole MG-1596 (03-MW-06S), Willow Grove Naval Air Station.

MG-1597 (03-MW-06I)

The caliper log shows the total depth of the borehole is 148 ft and it is cased with 6-in.-diameter casing to 20 ft bls (fig. 15). The caliper log shows major fractures at 35-37, 103-106, and 118 ft bls plus other minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 60, 92, 106, 112, 118, 122, and 144 ft bls that correlate to fractures shown on the caliper log and may indicate water-producing zones. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 47, 63, 82, 94, 128, and 140 ft bls (table 14). The borehole-video log shows the borehole water becomes very cloudy at 124 ft bls. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 35-37 ft bls, moves downward, and exits the borehole through the fracture at 143 ft bls. The driller's log reports the greatest quantity of water is produced at about 103-106 ft bls. A screen placed at 100-115 ft bls would include the water-producing fractures at 103-106 ft bls. A screen was placed at 140-150 ft bls.

Table 14. *Summary of heat-pulse-flowmeter measurements for borehole MG-1597 (03-MW-06I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
47	0.24	Down
63	.19	Down
82	.19	Down
94	.19	Down
128	.23	Down
140	.25	Down

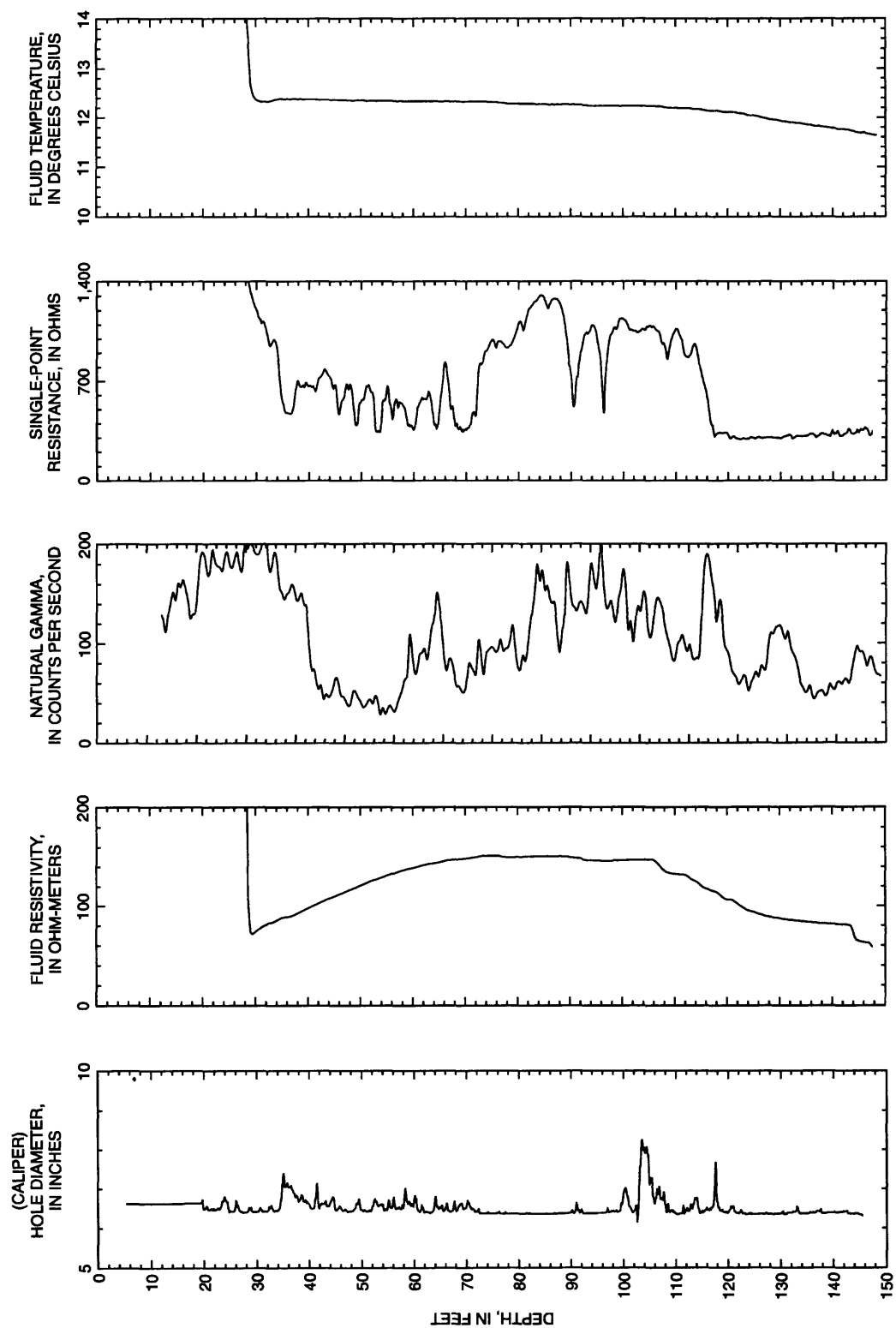


Figure 15. Borehole-geophysical logs for borehole MG-1597 (03-MW-06), Willow Grove Naval Air Station.

MG-1598 (02-MW-011)

The caliper log shows the total depth of the borehole is 104 ft and it is cased with 6-in.-diameter casing to 13 ft bls (fig. 16). The caliper log shows major fractures at 14, 15, and 74-78 ft bls plus numerous minor fractures throughout the open-hole interval. The fluid-temperature log shows a sharp change in slope at 98 ft bls that correlates to a fracture shown on the caliper log and indicates a water-producing zone. Under ambient conditions, the heat-pulse flowmeter measured upward borehole flow at 43, 68, 81, and 93 ft bls (table 15). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 97 and 74-78 ft bls, moves upward, and probably exits the borehole through the fracture at 46 ft bls. A screen was placed at 70-80 ft bls to include the water-producing fracture at 74-78 ft bls.

Table 15. *Summary of heat-pulse-flowmeter measurements for borehole MG-1598 (02-MW-011) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
43	0.77	Up
68	.89	Up
81	.76	Up
93	.73	Up

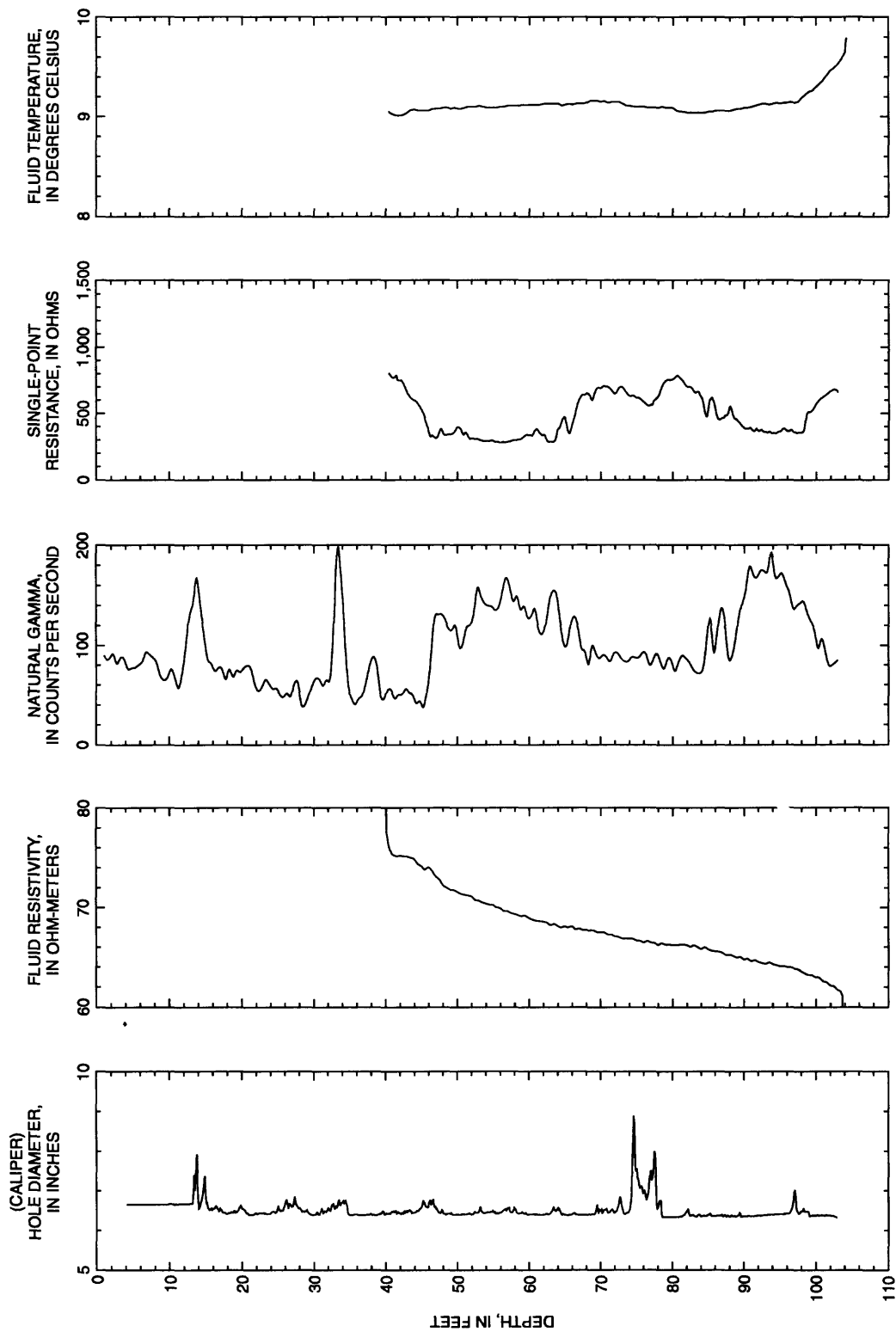


Figure 16. Borehole-geophysical logs for borehole MG-1598 (02-MW-011), Willow Grove Naval Air Station.

MG-1599 (05-MW-01I)

The caliper log shows the total depth of the borehole is 148 ft and it is cased with 6-in.-diameter casing to 24 ft bls (fig. 17). The caliper log shows major fractures at 27, 72, and 76-92 ft bls plus other minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 38, 102, 108, 112, 120, and 130 ft bls that approximately correlate to fractures shown on the caliper log and may indicate water-producing zones. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 42 and 66 ft bls and no flow at 95 and 118 ft bls (table 16). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures between 30-62 ft bls, moves downward, and exits the borehole through the fractures at 76-92 ft bls. The driller's log reports 3 gal/min is produced at 126-130 ft bls. A screen was placed at 125-135 ft bls to include the water-producing fracture at 126-130 ft bls.

Table 16. *Summary of heat-pulse-flowmeter measurements for borehole MG-1599 (05-MW-01I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
42	0.37	Down
66	.69	Down
95	No flow	
118	No flow	

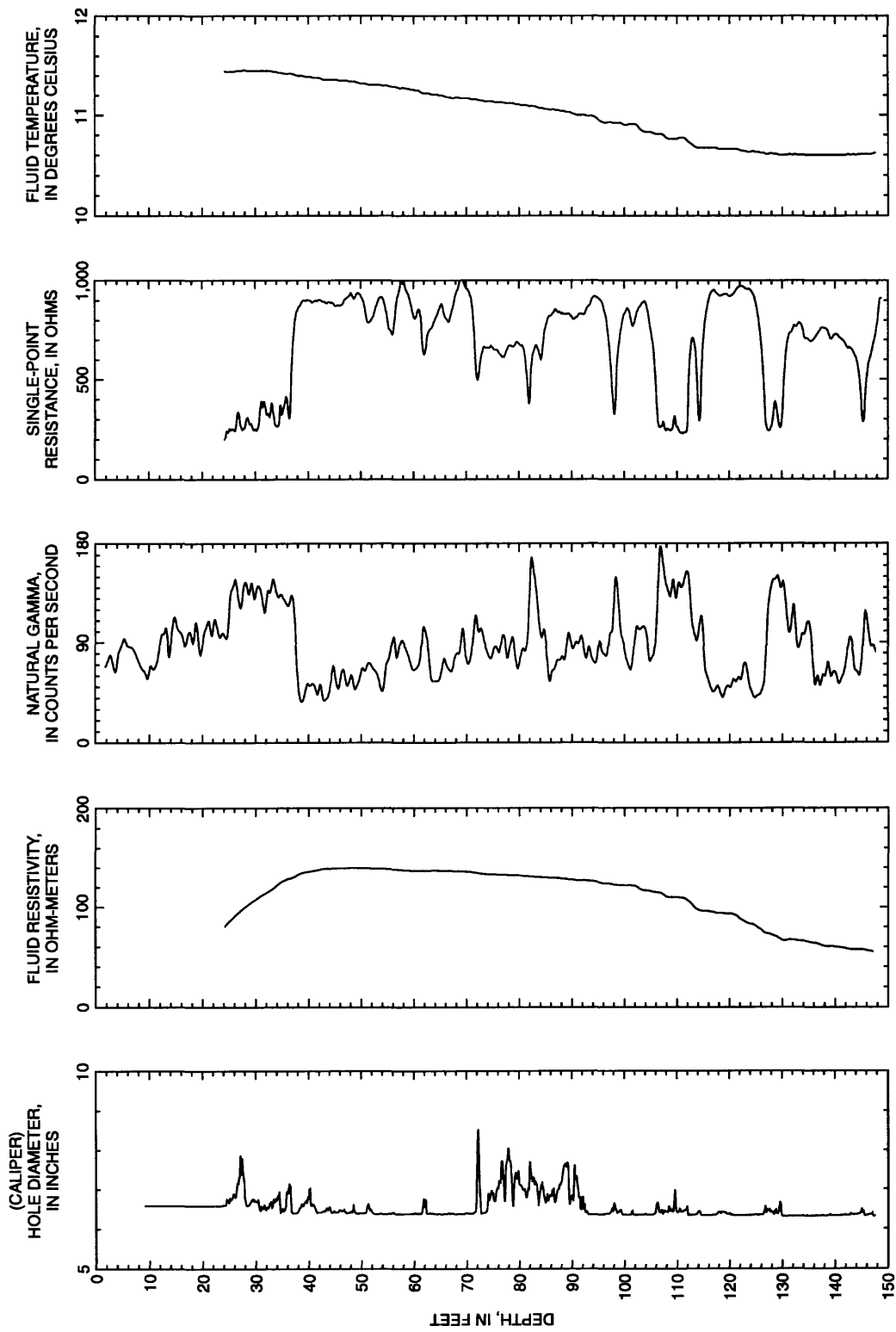


Figure 17. Borehole-geophysical logs for borehole MG-1599 (05-MW-011), Willow Grove Naval Air Station.

MG-1628 (02-MW-03I)

The caliper log shows the total depth of the borehole is 148 ft and it is cased with 6-in.-diameter casing to 13 ft bls (fig. 18). The caliper log shows major fractures at 13-16, 24-27, 64-70, and 144-146 ft bls plus other minor fractures throughout the open-hole interval. The fluid-temperature and fluid-resistivity logs show changes in slope at 44 and 51 ft bls that correlate to fractures shown on the caliper log and indicate a water-producing zone. Under ambient conditions, the heat-pulse flowmeter measured upward borehole flow at 35 ft bls and downward flow at 61, 98 and 130 ft bls (table 17). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures between 42-54 ft bls, moves upward and downward, and exits the borehole through the fractures at 14-32 and 144-146 ft bls. Screens placed at 40-55 and 140-150 ft bls would include the water-producing fractures at 42-54 ft bls and the water-receiving fracture at 144-146 ft bls.

Table 17. *Summary of heat-pulse-flowmeter measurements for borehole MG-1628 (02-MW-03I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
35	0.16	Up
61	1.4	Down
98	1.3	Down
130	1.4	Down

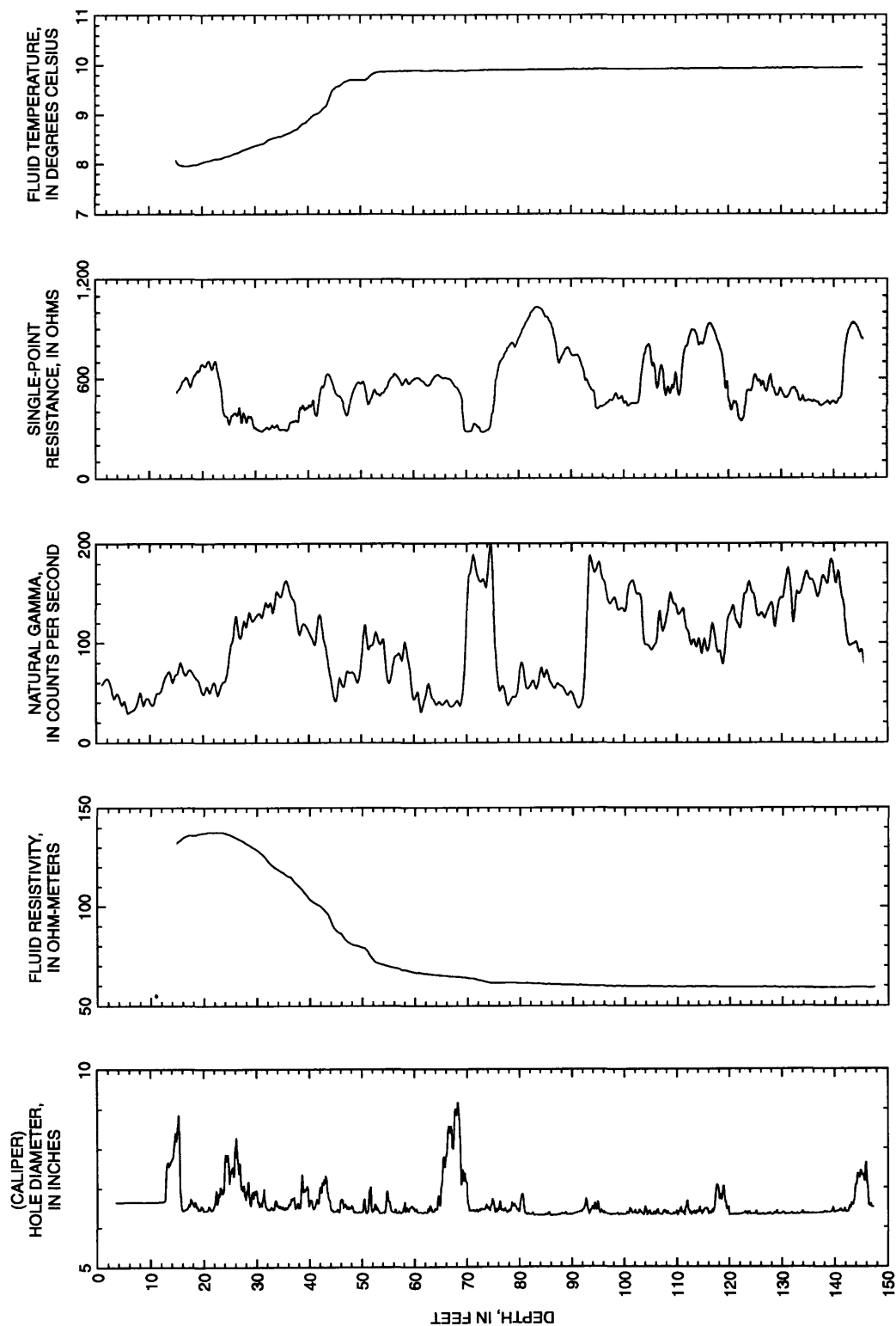


Figure 18. Borehole-geophysical logs for borehole MG-1628 (02-MW-031), Willow Grove Naval Air Station.

MG-1629 (03-MW-02I)

The caliper log shows the total depth of the borehole is 143 ft and it is cased with 6-in.-diameter casing to 13 ft bls (fig. 19). The caliper log shows major fractures at 13-21 and 22-24 ft bls plus other minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 25, 62, 82, and 92 ft bls that correlate to fractures shown on the caliper log and may indicate water-producing zones. Under ambient conditions, the heat-pulse flowmeter measured upward borehole flow at 28, 87, 106, and 130 ft bls (table 18). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures between 140-143 ft bls, moves upward, and exits the borehole through fractures at about 24 ft bls. The driller's log reports a 2 gal/min water-production zone at 60 ft bls. A screen and sand pack was placed at 55-65 and 134-144 ft bls to include the water-producing fractures at 60 and 140-143 ft bls.

Table 18. *Summary of heat-pulse-flowmeter measurements for borehole MG-1629 (03-MW-02I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
28	1.2	Up
87	1.2	Up
106	1.1	Up
130	1.0	Up

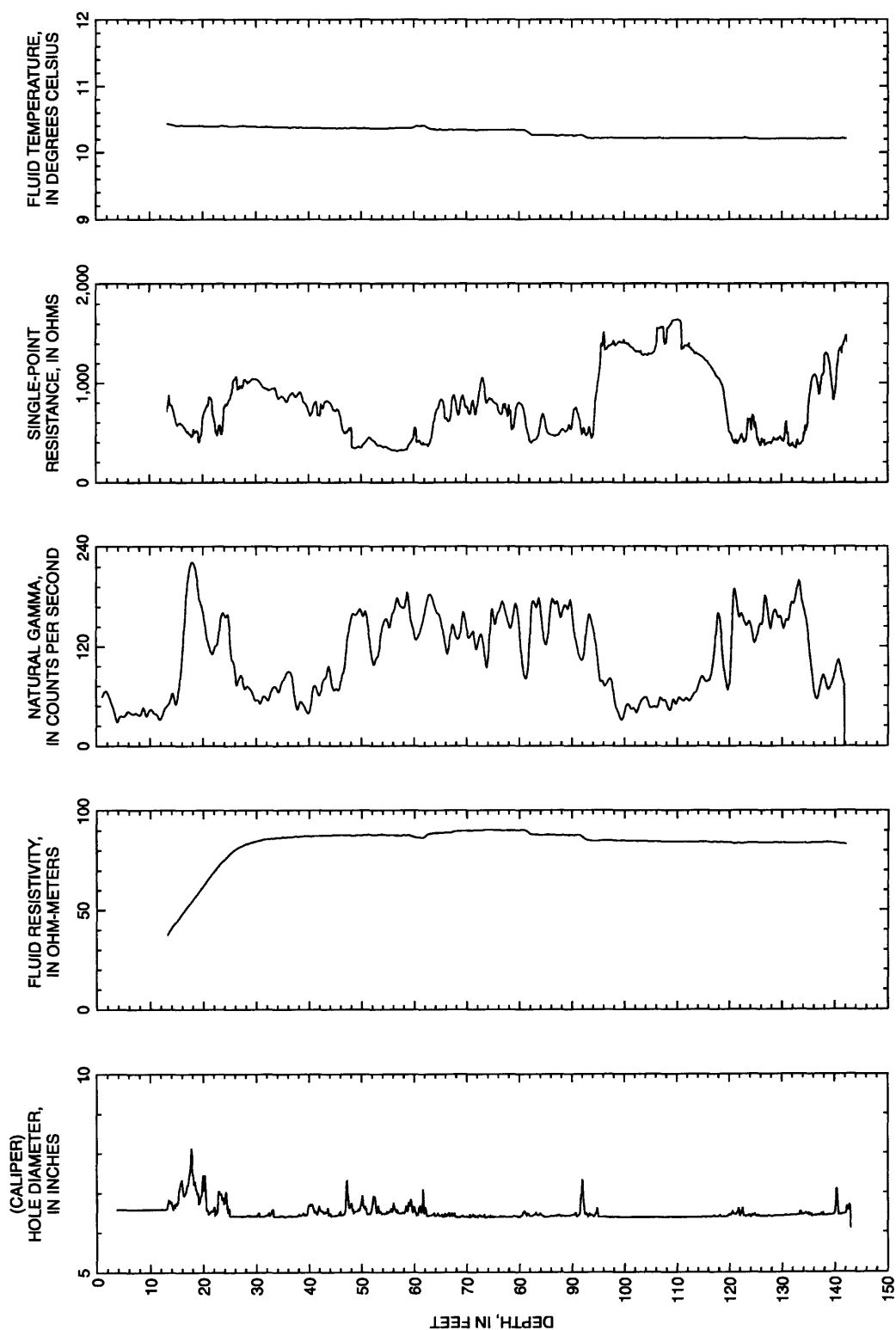


Figure 19. Borehole-geophysical logs for borehole MG-1629 (03-MW-021), Willow Grove Naval Air Station.

MG-1630 (03-MW-07S)

The caliper log shows the total depth of the borehole is 73 ft and it is cased with 6-in.-diameter casing to 14 ft bls (fig. 20). The caliper log shows a major fracture at 40-41 ft bls plus minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 20, 42, 58, and 64 ft bls that correlate to fractures shown on the caliper log and indicate water-producing zones. Under ambient conditions, the heat-pulse flowmeter measured upward borehole flow at 31, 45, and 56 ft bls and no flow at 62 and 68 ft bls (table 19). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 58 and 52 ft bls, moves upward, and exits the borehole through fractures at 40-41 and 14-30 ft bls. The driller's log indicates 5-7 gal/min of water production at about 44 ft bls that probably is derived from the fracture at 40-41 ft bls. A screen was placed at 34-44 ft bls to include the water-producing fracture at 40-41 ft bls.

Table 19. *Summary of heat-pulse-flowmeter measurements for borehole MG-1630 (03-MW-07S) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
31	0.19	Up
45	.33	Up
56	.13	Up
62	No flow	
68	No flow	

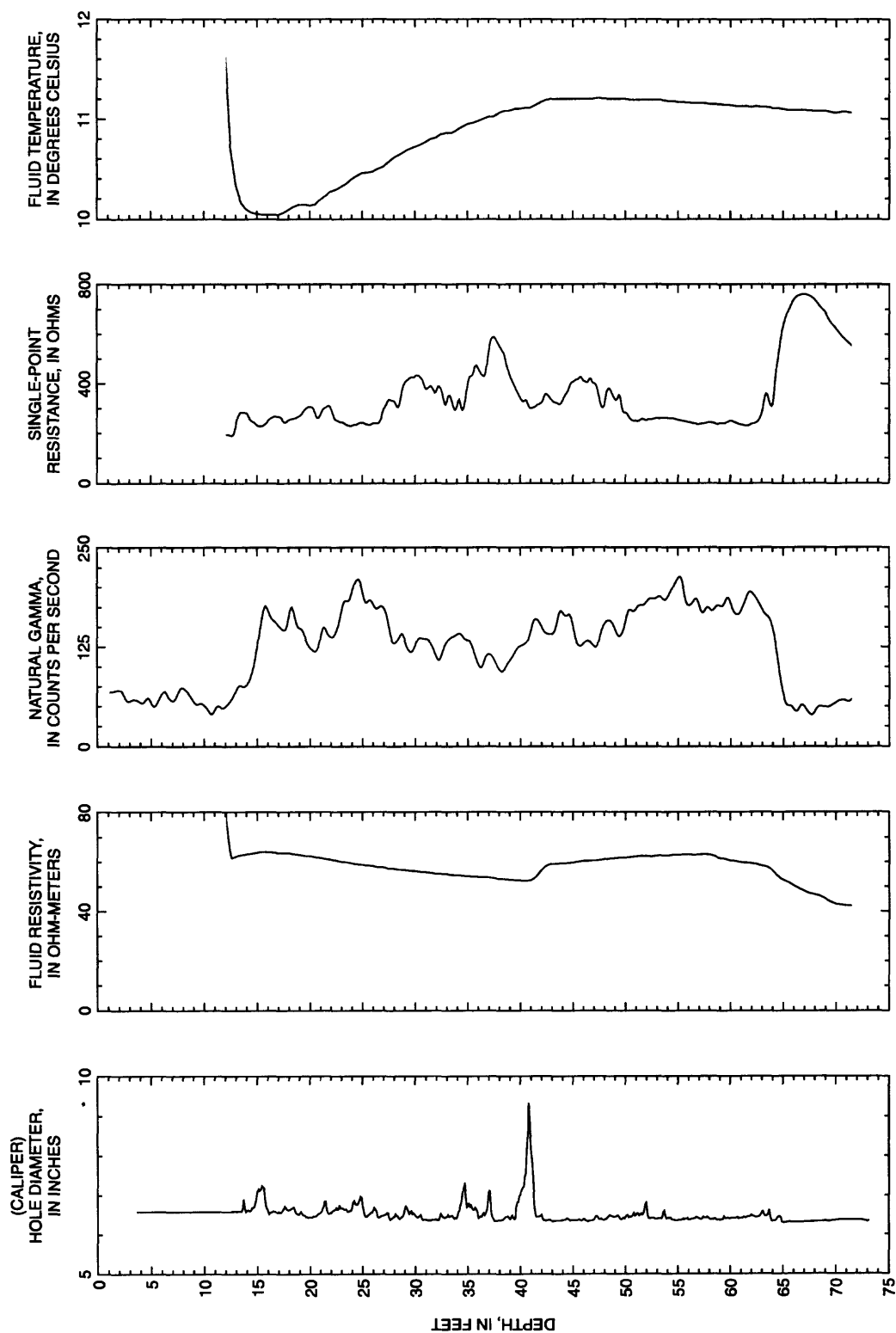


Figure 20. Borehole-geophysical logs for borehole MG-1630 (03-MW-07S), Willow Grove Naval Air Station.

MG-1631 (01-MW-03I)

The caliper log shows the total depth of the borehole is 98 ft and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 21). The caliper log shows major fractures at 19-20, 70-72, and 84-86 ft bls plus other minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 24 and 93 ft bls that correlate to fractures shown on the caliper log and indicate water-producing zones. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 30, 54, 68, and 80 ft bls (table 20). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 19-28 ft bls, moves downward, and exits the borehole through fractures at 40-50, 70-78, and 94 ft bls. The driller's log indicates 20-25 gal/min of water is produced from 50-98 ft bls that probably is derived from fractures at 70-94 ft bls. A screen placed at 69-79 ft bls would include the water-receiving fractures at 70-78 ft bls.

Table 20. *Summary of heat-pulse-flowmeter measurements for borehole MG-1631 (01-MW-03I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
30	0.32	Down
54	1.0	Down
68	1.1	Down
80	.51	Down

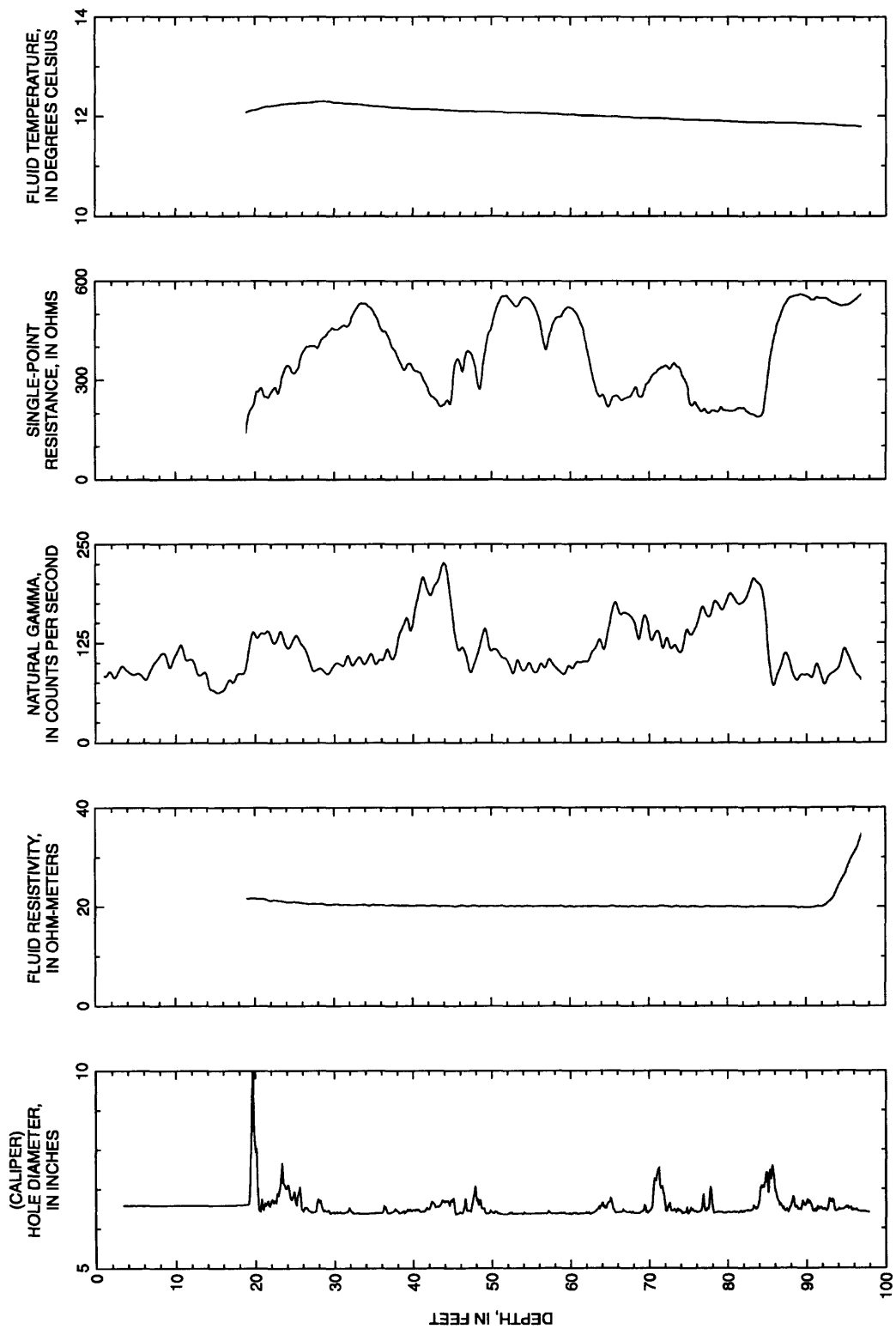


Figure 21. Borehole-geophysical logs for borehole MG-1631 (01-MW-03I), Willow Grove Naval Air Station.

MG-1632 (01-MW-01I)

The caliper log shows the total depth of the borehole is 98 ft and it is cased with 6-in.-diameter casing to 25 ft bls (fig. 22). The caliper log shows a major fracture at 38-40 ft bls plus numerous minor fractures throughout the open-hole interval. The fluid-resistivity log shows a change in slope at 93 ft bls that correlates to fractures shown on the caliper log and indicates a water-receiving zone. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 31, 43, 56, 70, and 88 ft bls (table 21). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 27-30 ft bls, moves downward, and exits the borehole through fractures at 33-40, 60-66, 80-83, and 94 ft bls. The driller's log indicates about 4 gal/min of water is produced from 82 ft bls. A screen was placed at 75-85 ft bls to include the water-producing fracture at 82 ft bls.

Table 21. *Summary of heat-pulse-flowmeter measurements for borehole MG-1632 (01-MW-01I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
31	1.4	Down
43	.68	Down
56	.63	Down
70	.37	Down
88	.24	Down

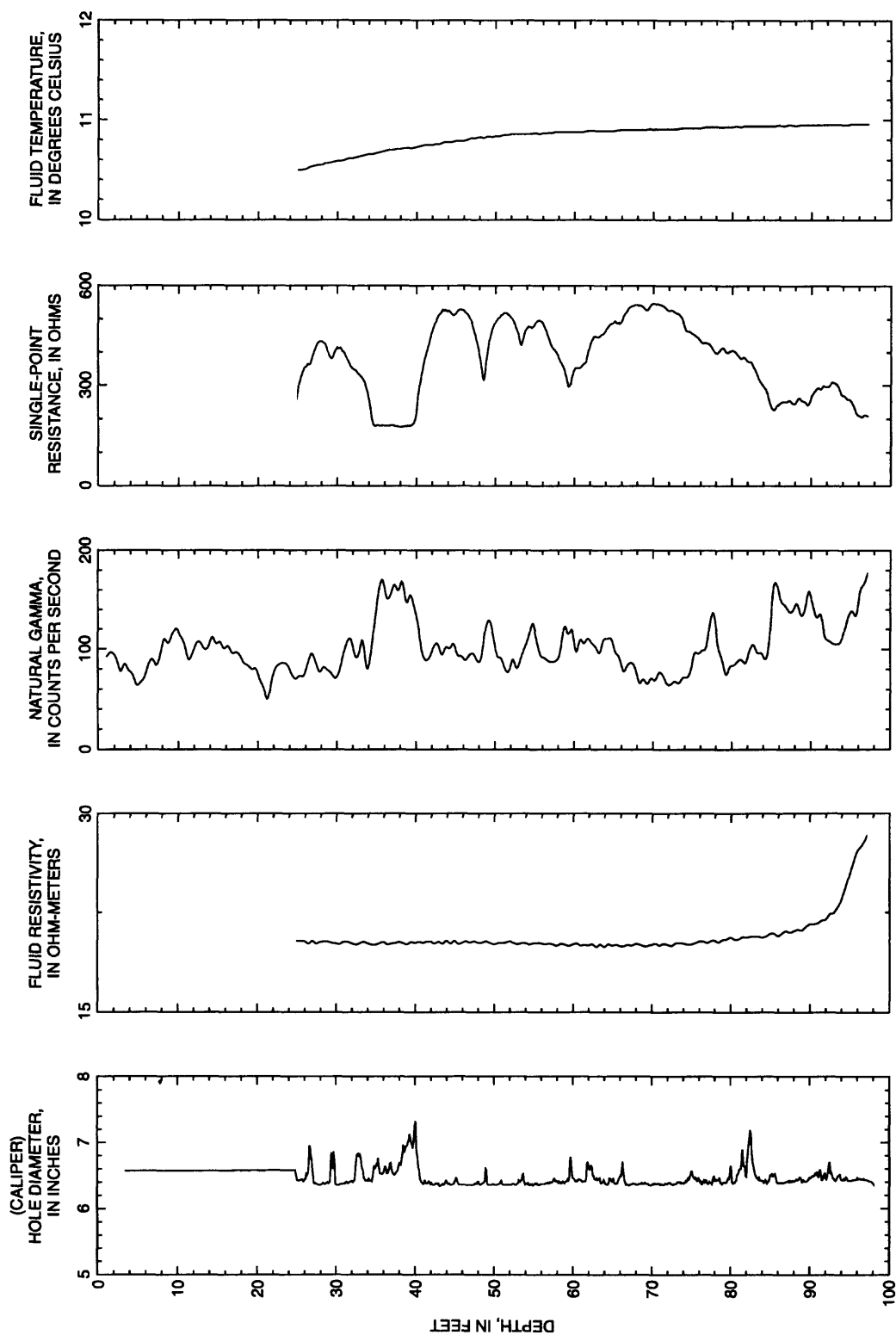


Figure 22. Borehole-geophysical logs for borehole MG-1632 (01-MW-011), Willow Grove Naval Air Station.

MG-1633 (01-MW-08I)

The caliper log shows the total depth of the borehole is 98 ft and it is cased with 6-in.-diameter casing to 25 ft bls (fig. 23). The caliper log shows numerous minor fractures throughout the open-hole interval. The fluid-temperature and fluid-resistivity logs show changes in slope at 26 and 80 ft bls that correlate to fractures shown on the caliper log and indicate a water-producing and a water-receiving zone, respectively. Under ambient conditions, the heat-pulse flowmeter measured downward borehole flow at 30, 44, 58, and 76 ft bls and no flow at 86 ft bls (table 22). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures just below casing at 25 ft bls, moves downward, and exits the borehole through fractures at 64-73 and 80 ft bls. The driller's log indicates about 5 gal/min of water is produced at 80 ft bls. A screen was placed at 76-86 ft bls to include the water-producing fracture at 80 ft bls.

Table 22. *Summary of heat-pulse-flowmeter measurements for borehole MG-1633 (01-MW-08I) at Willow Grove Naval Air Station, Montgomery County, Pennsylvania*

[ft bls, feet below land surface; gal/min, gallon per minute]

Depth (ft bls)	Flow rate under ambient conditions (gal/min)	Flow direction under ambient conditions
30	1.2	Down
44	1.2	Down
58	1.1	Down
76	.50	Down
86	No flow	

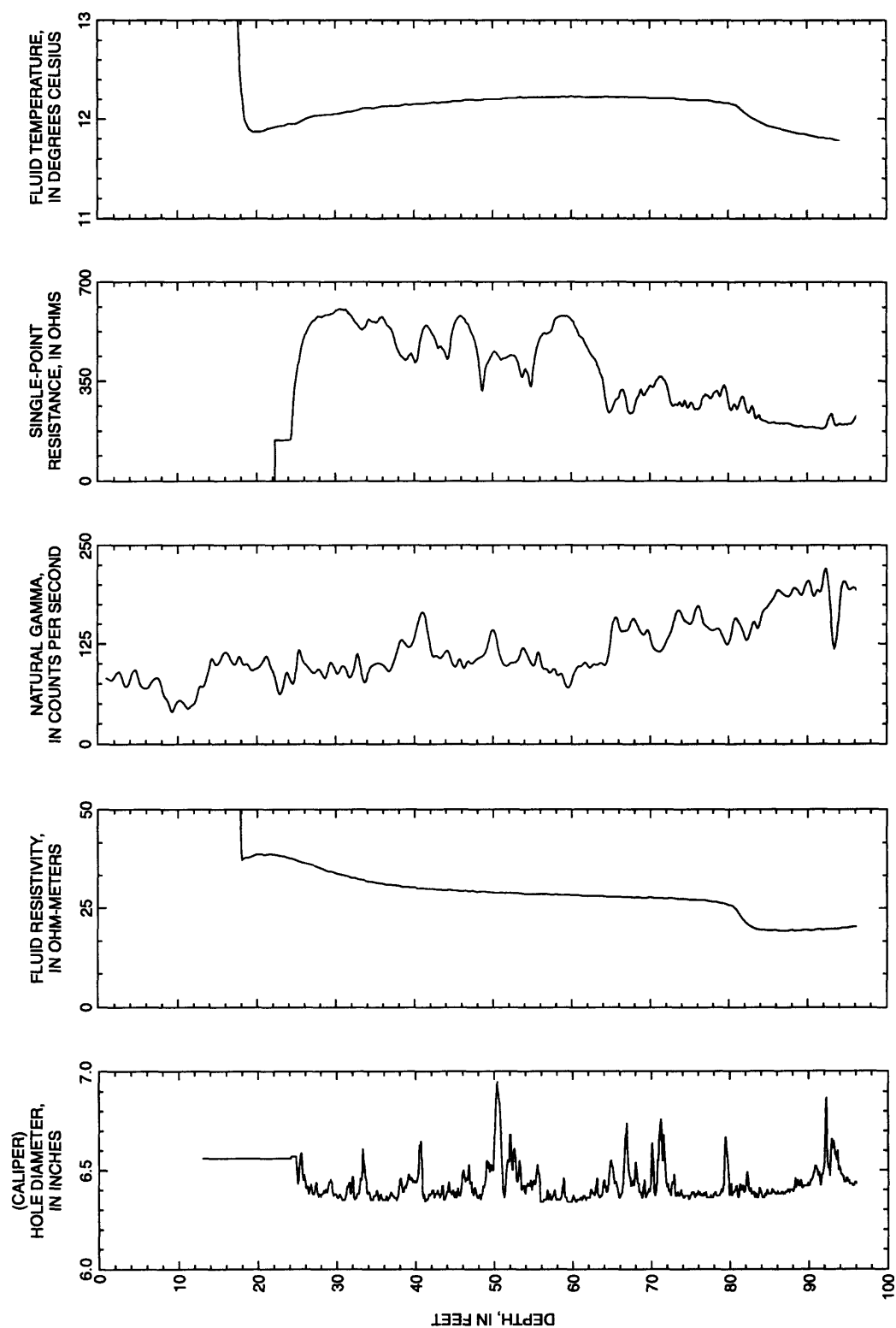


Figure 23. Borehole-geophysical logs for borehole MG-1633 (01-MW-081), Willow Grove Naval Air Station.

CONCLUSIONS

Water-producing zones, water-receiving zones, and intervals of vertical borehole flow were identified by the use of geophysical logs, heat-pulse-flowmeter data, video logs, and driller's notes. This enabled Brown and Root to place screens at selected water-producing intervals so that these intervals could be sampled.

All boreholes flowmetered near NAS Site 1, NAS Site 5, and wells MG-1596 and MG-1597 at NAS Site 3 showed downward ambient flow. In these boreholes, water is generally produced through fractures between 18-49 ft bls, moves downward, and exits the borehole through fractures between 53-128 ft bls. The deepest borehole [MG-1589 (05-MW-3I), located at NAS Site 5], showed downward flow from the top and upward flow near the bottom.

Boreholes MG-1595, MG-1629, and MG-1630 in NAS Site 3 and borehole MG-1598 in NAS Site 2 showed consistent upward borehole flow. These wells are located topographically lower than wells at NAS Sites 1, 2, and 5 and are in areas of ground-water discharge.

Not all water-producing zones in the wells at NAS are under different head pressure. For example, during drilling of MG-1599, well yield increased about 8 gal/min from depths of 88 to 129 ft bls. No flow was detected between the water-producing zones at 95 or 118 ft bls with the heat-pulse flowmeter. This indicates that the water-producing zones reported on the driller's log at 90, 100, 112, and 127-129 ft bls are essentially under the same head. Identification of zones such as these are correlated between the geophysical logs and the driller's notes.

The video logs show that most wells become distinctly cloudy immediately below the last water-receiving or water-producing zone. Heat-pulse-flowmeter data indicate all boreholes penetrate 2-3 water-bearing zones depending on well depth: a shallow, unconfined zone and two semiconfined or confined zones. The shallow boreholes near NAS Site 5 are reported to produce 3-20 gal/min, and the intermediate boreholes produce from 25 to 70 gal/min. Generally, water yield increases with depth to about 150 ft bls. The vertical direction of ambient borehole flow in an open borehole is dependant upon depth and elevation of the water-producing intervals.

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