U.S. Department of the Interior
U.S. Geological Survey

Identification of Water-Bearing Zones by the Use of Geophysical Logs and Borehole Television Surveys, Collected February to September 1997, at the Former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania

by Randall W. Conger

Open-File Report 98-86

prepared in cooperation with the
U.S. DEPARTMENT OF THE NAVY

Lemoyne, Pennsylvania
1998

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.40	millimeter
foot (ft)	0.3048	meter
acre	0.4047	hectare
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.

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ABSTRACT

Between February 1997 and September 1997, 10 monitor wells were drilled near the site of the former Naval Air Warfare Center, Warminster, Bucks County, Pa., to monitor water levels and sample ground-water contaminants in the shallow, intermediate, and deep water-bearing zones. The sampling will determine the horizontal and vertical distribution of contaminated ground water migrating from known or suspected contaminant sources. Four wells were drilled north of the property adjacent to Area A, three wells along strike located on Lewis Drive, and three wells directly down dip on Ivyland Road. Well depths range from 69 feet to 300 feet below land surface.

Borehole-geophysical logging and television surveys were used to identify water-bearing zones so that appropriate intervals could be screened in each monitor well. Geophysical logs were obtained at the 10 monitor wells. Borehole television surveys were obtained at the four monitor wells adjacent to Area A.

Caliper and borehole television surveys were used to locate fractures, inflections on fluid-temperature and fluid-resistivity logs were used to locate possible water-bearing fractures, and heat-pulse-flowmeter measurements verified these locations. Natural-gamma logs provided information on stratigraphy. After interpretation of geophysical logs, borehole television surveys, and driller's logs, all wells were screened such that water-level fluctuations could be monitored and water samples collected from discrete water-bearing zones in each borehole.

INTRODUCTION

The former Naval Air Warfare Center (NAWC) is located in Warminster, Bucks County, Pa., on the U.S. Geological Survey (USGS) Hatboro 7.5-minute topographic quadrangle map (fig. 1). The NAWC occupies approximately 734 acres. It was commissioned by the Navy in 1942 and was previously operated by the Brewster Aircraft Company. On September 30, 1995, the Navy officially closed the NAWC facility to all activity except environmental remediation. During the operation of the NAWC, numerous wastes were generated during the maintenance and repair of aircraft, machine-shop operations, spray painting, pest control, fire-fighting training, and laboratory research activities.

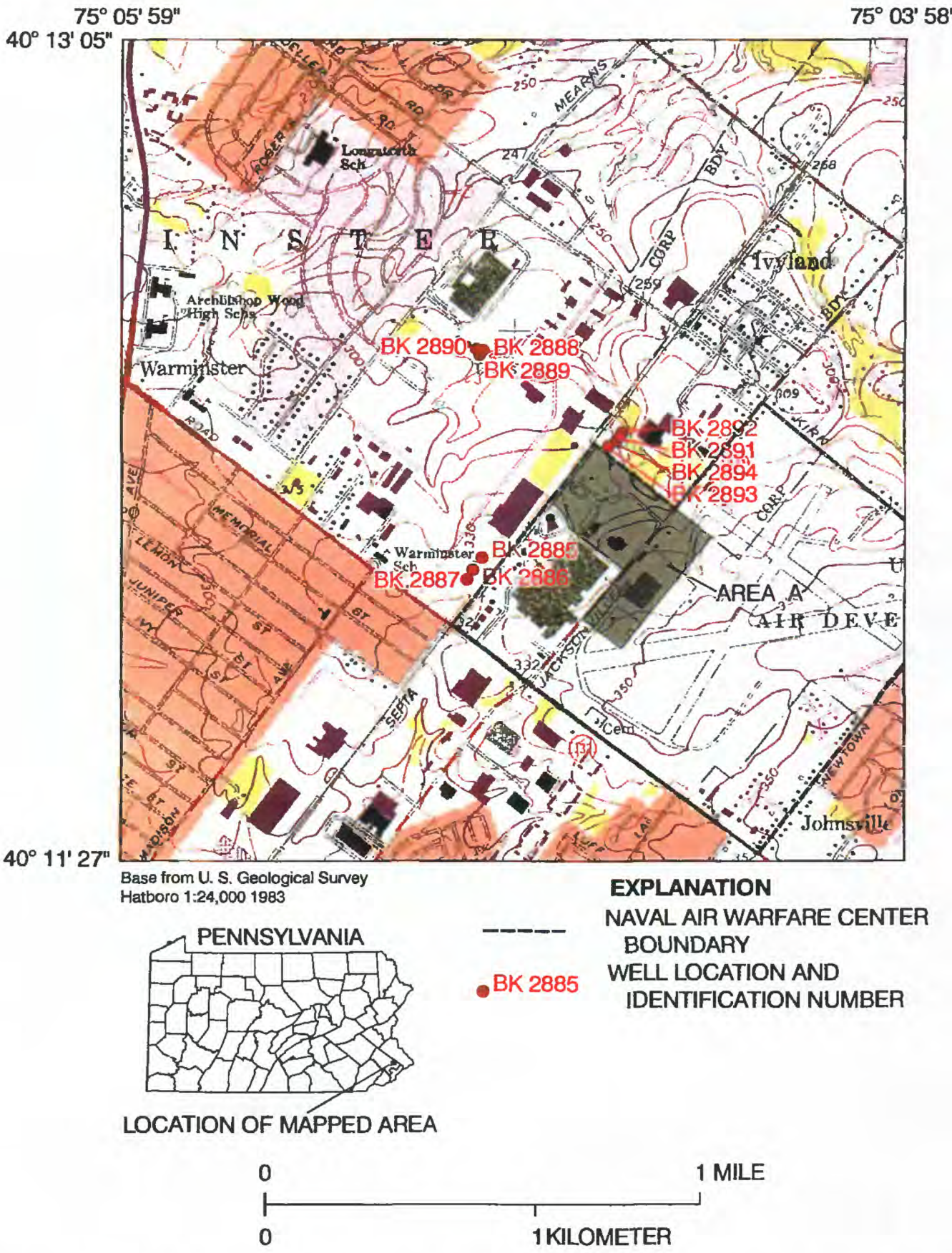

Figure 1. Location of boreholes where geophysical logging was conducted near the Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

Boreholes were installed to monitor water levels and sample for ground-water contaminants in the shallow, intermediate, and deep water-bearing zones adjacent to Area A (fig. 1). Area A is located on the northwestern side of the NAWC and includes disposal sites 1, 2, and 3. It is one of four major contaminated sites within the NAWC that was described in the Phase II Remedial Investigation Report by Halliburton NUS Environmental Corporation (1992). Wells BK-2891, BK-2892, BK-2893, and BK-2894 were drilled as monitor wells hydraulically down gradient from Area A. Four wells were drilled on the property north of and adjacent to Area A, three wells along strike from Area A on Lewis Drive, and three wells directly down dip from Area A located on Ivyland Road (fig. 1). Depths range from 69 to 300 ft bls (below land surface).

A hydrogeological investigation is being conducted by Brown and Root Environmental, Inc., as part of the Navy's Installation Restoration Program to address ground-water contamination at Area A and other sites. The U.S. Navy requested that USGS provide technical assistance to their hydrological investigation and conduct borehole-geophysical logging to identify water-bearing zones that could be monitored by properly completed wells.

Purpose and Scope

This report evaluates borehole-geophysical logs and borehole television surveys run by the USGS in 10 boreholes near the NAWC from February to September 1997 (table 1 and fig. 1). This report identifies one or more water-bearing zones in each well on the basis of geophysical logs and borehole television surveys. Caliper, natural-gamma, single-point-resistance, fluid-resistivity, and fluid-temperature logs were run and heat-pulse-flowmeter measurements were made in 10 boreholes. Borehole television surveys were run in four boreholes. A cross-reference between USGS borehole-identification numbers and U.S. Navy borehole-identification numbers and a list of logs run in each borehole are given in table 1.

Table 1. *Boreholes logged at the former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

[B, borehole television survey; C, caliper; G, natural-gamma; R, single-point-resistance; F, fluid-resistivity; T, fluid-temperature; V, heat-pulse-flowmeter measurements]

USGS borehole-identification number	U.S. Navy borehole-identification number	Depth logged (feet)	Geophysical logs obtained
BK-2885	HN-54-S	69	C, G, R, F, T, V
BK-2886	HN-54-I	121	C, G, R, F, T, V
BK-2887	HN-54-D	222	C, G, R, F, T, V
BK-2888	HN-65-D	300	C, G, R, F, T, V
BK-2889	HN-65-I	200	C, G, R, F, T, V
BK-2890	HN-65-S	100	C, G, R, F, T, V
BK-2891	HN-14-I	113	B, C, G, R, F, T, V
BK-2892	HN-14-S	114	B, C, G, R, F, T, V
BK-2893	HN-59-I	98	B, C, G, R, F, T, V
BK-2894	HN-59-S	100	B, C, G, R, F, T, V

Hydrogeologic Setting

The NAWC is located in the Gettysburg-Newark Lowlands Section of the Piedmont Physiographic Province. The site and adjoining area are underlain by the Stockton Formation, which consists of sedimentary rocks of Triassic age. The Stockton Formation is divided into three lithologic units; the lower arkose, middle arkose, and upper shale members (Rima and others, 1962). The middle arkose member crops out at the site. At the NAWC, this unit consists of very fine- to medium-grained arkosic red sandstone interbedded with red shale, siltstone, and mudstone. Quartz 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 NAWC generally strike NE-SW and dip an average of 12° NW (Rima and others, 1962). Vertical and horizontal fractures are common.

Ground-water storage and movement within the Stockton Formation is through secondary openings such as interconnected fractures, bedding planes separations, and joints. Deeper wells may penetrate several water-bearing zones with different hydraulic properties that are under different hydraulic head. In this report, wells that penetrate more than one water-bearing zone are called multiaquifer wells. The static hydraulic head in a multiaquifer well is the result of the combined heads of all water-bearing zones penetrated. Where water-producing zones under different hydraulic head are interconnected by a borehole, water in that borehole will flow either up or down in the direction of lower head (Sloto and others, 1995).

At the NAWC, ground water in the upper part of the aquifer generally is under unconfined conditions, and ground water in deeper parts of the aquifer may be confined or partially confined. Local artesian conditions are common.

Borehole-Geophysical Logs

Geophysical logs provide information on location of fractures (caliper logs and borehole television surveys), water-producing and water-receiving zones, intervals of vertical fluid flow within the borehole (fluid-resistivity and fluid-temperature logs), quantification of vertical flow (heat-pulse-flowmeter measurements), lithologic correlation (gamma and single-point-resistance logs), and well construction (caliper and single-point-resistance logs) where unknown.

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 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, and water-receiving zones.

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, thorium-232, 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. Geophysical logging with a gamma probe can be conducted in the fluid-filled, dry, cased, or uncased parts of a borehole. However, casing does reduce the gamma response. The gamma log is used to correlate geologic units between wells (Keys, 1990).

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 water-producing zones (Keys, 1990).

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 are usually identified by a low-resistivity gradient between a water-producing and a water-receiving zone.

Fluid-temperature logs provide a continuous record of the temperature of the water in a borehole. Fluid-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 can be 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) poor seal integrity 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. During pumping, flow measurements are made after drawdown has stabilized. Otherwise, some of the measured flow will be derived from storage within the borehole rather than from water-bearing zones in the aquifer. Although the heat-pulse flowmeter is a calibrated probe, the data are primarily used as a relative indicator to identify water-producing zones.

Borehole television surveys were 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 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 logs and borehole television surveys is below 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 the former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

USGS borehole-identification number	U.S. Navy borehole-identification number	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
BK-2885	HN-54-S	69	19	9.51	2/11/97
BK-2886	HN-54-I	121	19	9.17	2/11/97
BK-2887	HN-54-D	222	19	9.46	2/11/97
BK-2888	HN-65-D	300	19.5	19.10	5/16/97
BK-2889	HN-65-I	200	19	19.97	5/19/97
BK-2890	HN-65-S	100	19	20.04	5/19/97
BK-2891	HN-14-I	113	19	16.24	9/16/97
BK-2892	HN-14-S	114	19	16.87	9/16/97
BK-2893	HN-59-I	98	19	15.37	9/17/97
BK-2894	HN-59-S	100	19	16.57	9/17/97

BK-2885 (HN-54-S)

The caliper log shows the total depth of the borehole is 69 ft and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 2). The static water level was 9.51 ft bls at the time of logging. The caliper log shows numerous fractures throughout the open-hole interval. The fluid-resistivity and fluid-temperature logs show changes in slope at 22 and 58 ft bls that correlate to fractures shown on the caliper log and indicate possible fluid-producing and fluid-receiving zones. Under nonpumping conditions, the heat-pulse flowmeter measured downward flow at 40 ft bls greater than 1 gal/min. The geophysical logs and the heat-pulse-flowmeter data suggest water enters the borehole through a fracture at 20 ft bls, moves downward, and exits the borehole through a fracture at approximately 58 ft bls. The driller's log shows the greatest water-producing zone in the borehole was encountered at approximately 67 ft bls. A screen and sand pack were placed at 55.5-71 ft bls to include the water-receiving fracture at 58 ft bls (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

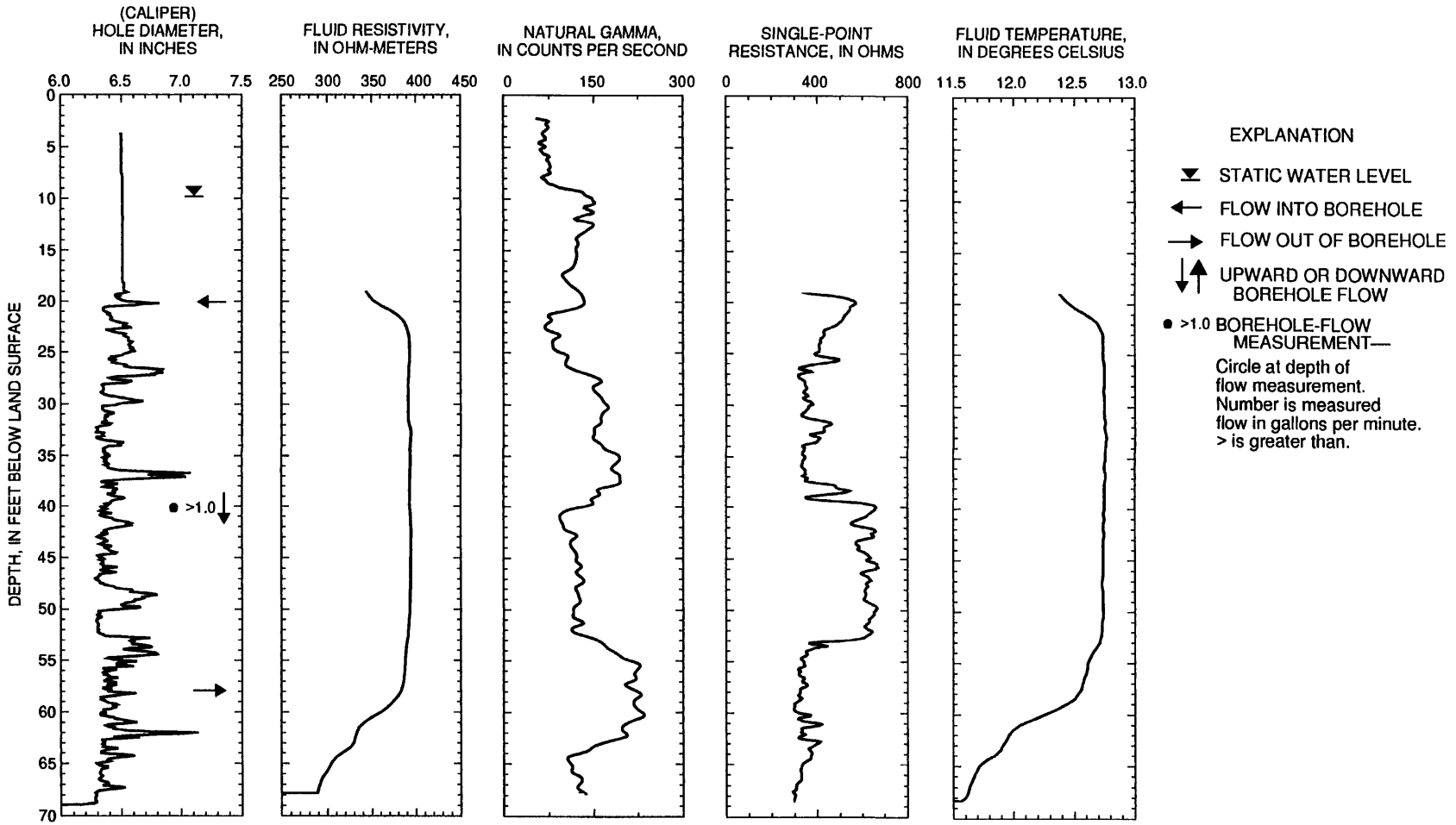

Figure 2. Borehole-geophysical logs for borehole BK-2885 (HN-54-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

BK-2886 (HN-54-I)

The caliper log shows the total depth of the borehole is 121 ft and it is cased with 6-in.-diameter casing to about 19 ft bls (fig. 3). The static water level was 9.17 ft bls at the time of logging. The caliper log shows major fractures at 29 and 44 ft bls plus numerous other fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 32, 40, and 114 ft bls that correlate to fractures on the caliper log and appear to be either fluid-producing or fluid-receiving zones. The fluid-temperature log shows changes in slope at 26 and 116 ft bls that correlate to fractures on the caliper log. Under nonpumping conditions, the heat-pulse flowmeter measured downward borehole flow at 50, 68, 86, and 102 ft bls (table 3). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through the fractures at about 26 ft bls, moves downward, and exits the borehole at 60, 82, 92, and 114 ft bls. The driller's log reports water-producing zones in the borehole were encountered at 16, 47, 95, and 115 ft bls. A screen and sand pack were placed at 107-124 ft bls to include the water-receiving fracture at 115 ft bls (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

Table 3. *Summary of heat-pulse-flowmeter measurements for borehole BK-2886 (HN-54-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

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

Depth (ft bls)	Flow rate under nonpumping conditions (gal/min)	Flow direction under nonpumping conditions
50	1.5	down
68	1.4	down
86	1.3	down
102	.94	down

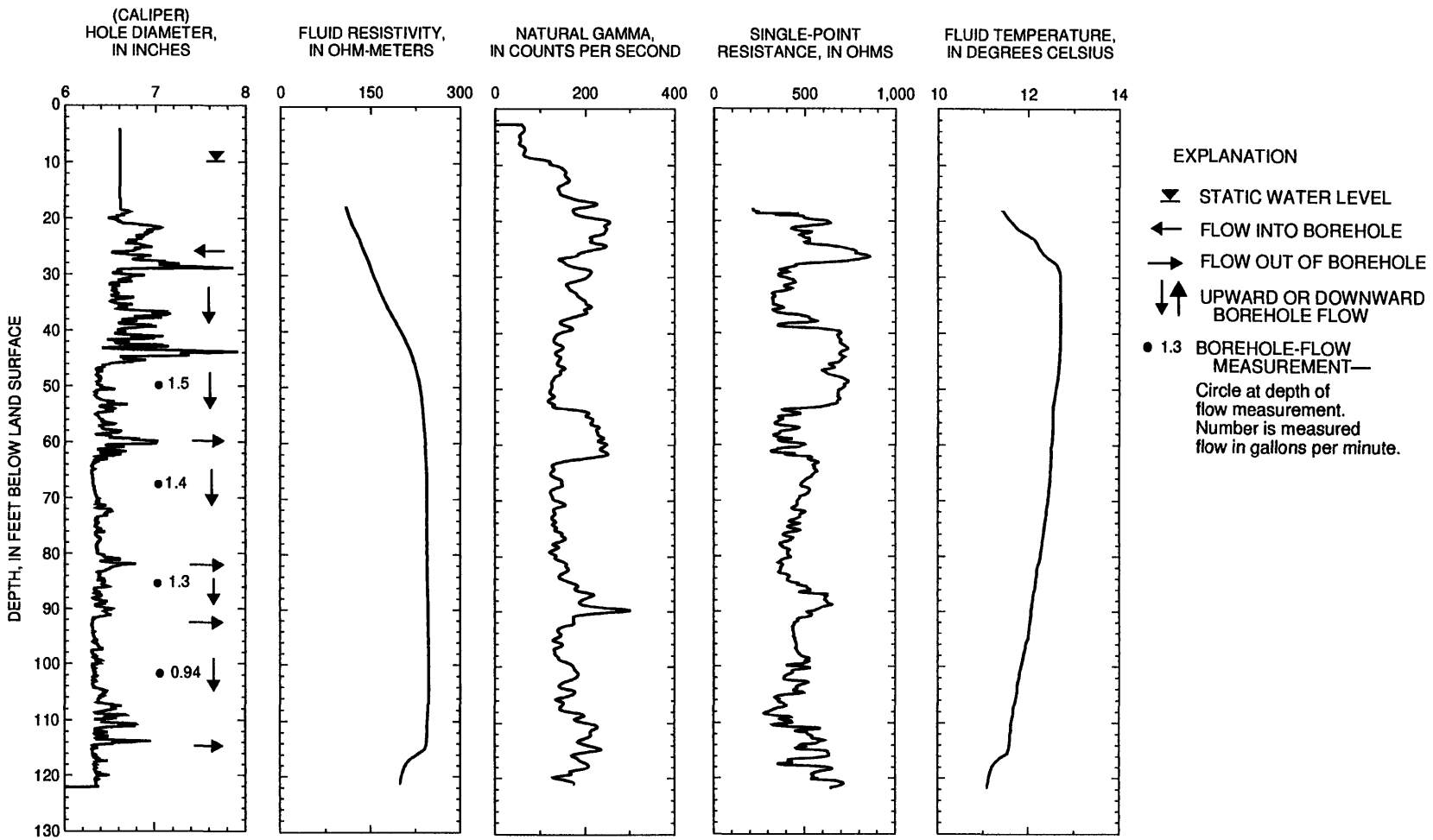

Figure 3. Borehole-geophysical logs for borehole BK-2886 (HN-54-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

BK-2887 (HN-54-D)

The caliper log shows the total depth of the borehole is 222 ft and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 4). The static water level was 9.46 ft bls at the time of logging. The caliper log shows major fractures at 164 and 195 ft bls plus numerous minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 28, 45, 60, 80, and 200 ft bls that approximately correlate to fractures shown on the caliper log and indicate possible fluid-producing or fluid-receiving zones. The fluid-temperature log shows changes in slope at 29, 45, 60, 164, and 202 ft bls. The natural-gamma log shows a siltstone unit with elevated gamma counts at 22-24 ft bls that might be used for stratigraphic correlation of geologic units with other wells. Under nonpumping conditions, the heat-pulse flowmeter measured downward borehole flow at 40, 50, 70, 108, and 150 ft bls and upward flow at 208 ft bls (table 4). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 20-30 ft bls, moves downward, and exits the borehole through fractures at 60, 164, and 198 ft bls. Also, water enters the borehole through fractures at 220 ft bls, moves upward, and exits the borehole at 195-201 ft bls. The driller's log shows water-producing zones were encountered at 19, 46, 79, 114, and 170 ft bls. A screen and sand pack was placed at 188-204 ft bls to include the water-receiving fractures at 195-201 ft bls (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

Table 4. *Summary of heat-pulse-flowmeter measurements for borehole BK-2887 (HN-54-D), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

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

Depth (ft bls)	Flow rate under nonpumping conditions (gal/min)	Flow direction under nonpumping conditions
40	1.5	down
50	1.4	down
70	.77	down
108	.77	down
150	.77	down
184	undetermined[1]	
208	.12	up

[1] Turbulence in borehole; unable to measure accurately.

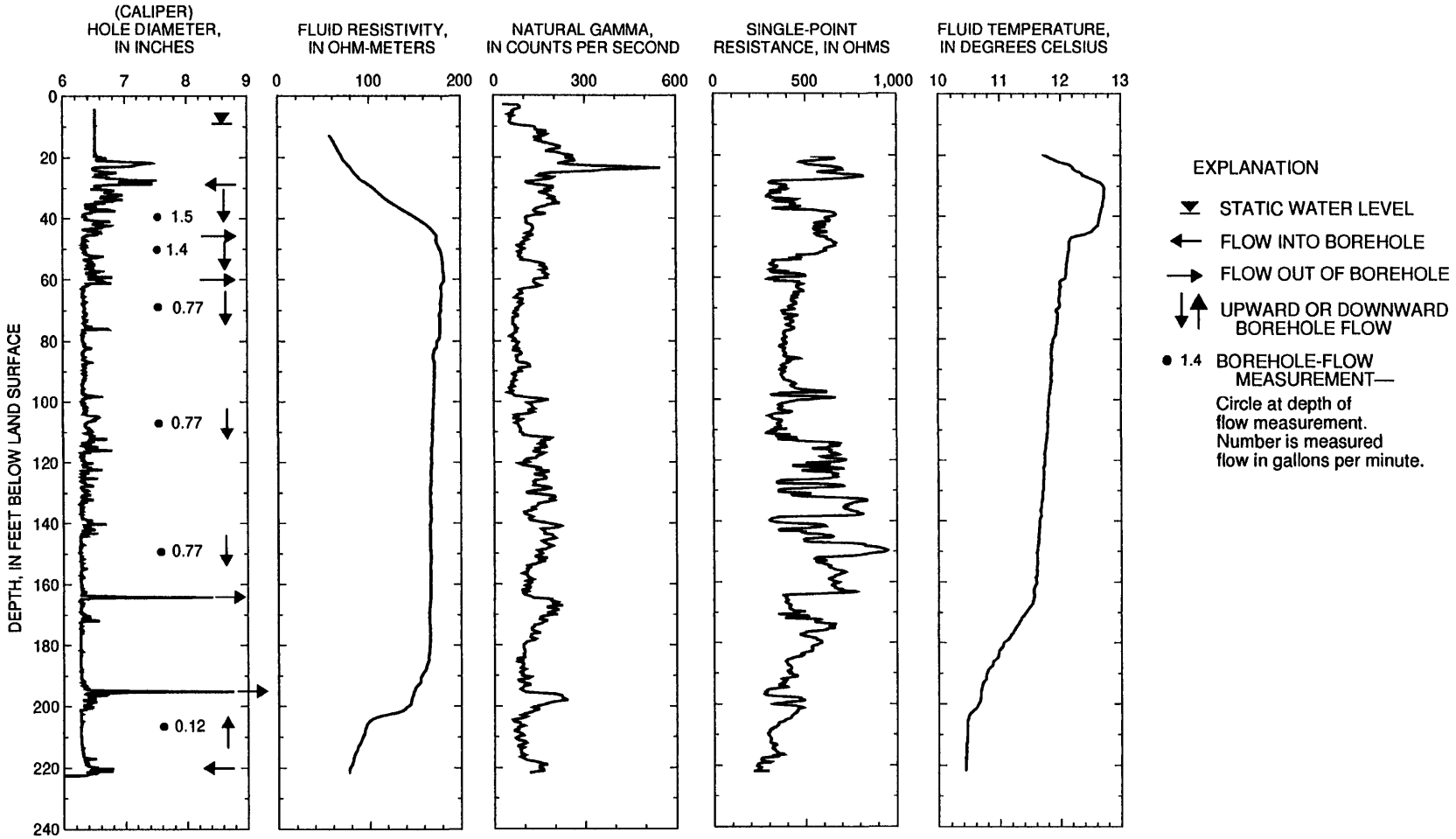

Figure 4. Borehole-geophysical logs for borehole BK-2887 (HN-54-D), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

BK-2888 (HN-65-D)

The caliper log shows the total depth of the borehole is 300 ft and it is cased with 6-in.-diameter casing to 19.5 ft bls (fig. 5). The static water level was 19.10 ft bls at the time of logging. The caliper log shows major fractures at 82 and 166-170 ft bls plus numerous other fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 40, 164, 172, 182, and 294 ft bls that correlate to fractures shown on the caliper log and indicate fluid-producing or fluid-receiving zones. The fluid-temperature log shows a change in slope at 42 ft bls, then almost no change in gradient with depth to 296 ft bls, which indicates borehole flow between these depths. The natural-gamma log shows a siltstone unit with elevated gamma readings at 139-142 ft bls that stratigraphically correlates with the natural-gamma spike at 139-142 ft bls in borehole BK-2889. This correlation indicates boreholes BK-2888 and BK-2889 are exactly on strike. Under nonpumping conditions, the heat-pulse flowmeter measured upward borehole flow at 30, 46, 76, 91, 114, 150, 178, 200, 230, 270, and 286 ft bls (table 5). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 292, 170, and 166 ft bls, moves upward, and exits the borehole through fractures at 94-104, 82, 42, and 23 ft bls. The driller's log reports water-producing zones were encountered at 86 and 166 ft bls. Screens were placed at 161-171 and 276-296 ft bls to include the water-producing fractures at 166 and 292 ft bls (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

Table 5. *Summary of heat-pulse-flowmeter measurements for borehole BK-2888 (HN-65-D), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

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

Depth (ft bls)	Flow rate under nonpumping conditions (gal/min)	Flow direction under nonpumping conditions
30	0.08	up
46	.24	up
76	.21	up
91	.36	up
114	.75	up
150	.80	up
178	.27	up
200	.30	up
230	.30	up
270	.37	up
286	.34	up

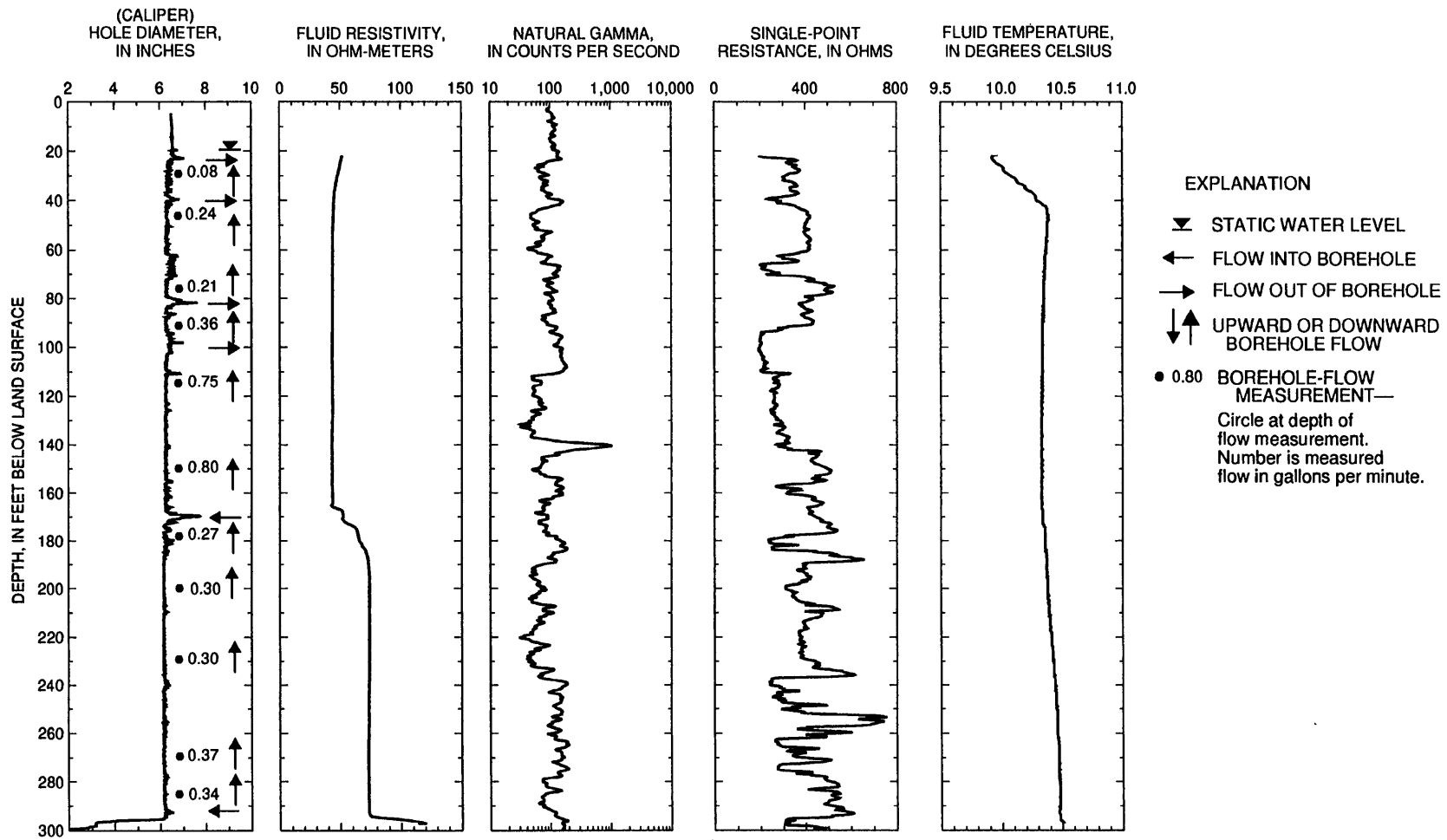

Figure 5. Borehole-geophysical logs for borehole BK-2888 (HN-65-D), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

BK-2889 (HN-65-I)

The caliper log shows the total depth of the borehole is 200 ft and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 6). The static water level was 19.97 ft bls at the time of logging. The caliper log shows major fractures at 56-58 ft bls plus numerous smaller fractures. The fluid-resistivity and fluid-temperature logs show changes in slope at 42, 118, and 196 ft bls that indicate fluid-producing or fluid-receiving zones. The natural-gamma log shows a siltstone unit with elevated gamma readings at 139-142 ft bls that stratigraphically correlates with the natural-gamma spike at 139-142 ft bls in borehole BK-2888. Under nonpumping conditions, the heat-pulse flowmeter measured downward borehole flow at 50, 76, and 106 ft bls and upward flow at 130 and 170 ft bls (table 6). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through a fracture at 42 ft bls, moves downward, and exits the borehole through a fracture at approximately 115 ft bls. Also, water enters the borehole at 195 ft bls, moves upward, and exits the borehole at 115 ft bls. The driller's log reports water is produced at 43 ft bls and possibly at 151 and 165 ft bls. A screen was placed at 40-50 and 105-120 ft bls to capture the water-producing and water-receiving fractures at 42 and 115 ft bls, respectively (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

Table 6. *Summary of heat-pulse-flowmeter measurements for borehole BK-2889 (HN-65-I), former Naval Air Warfare Center, Warminster Bucks County, Pennsylvania*

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

Depth (ft bls)	Flow rate under nonpumping conditions (gal/min)	Flow direction under nonpumping conditions
50	0.38	down
76	.32	down
106	.29	down
130	.08	up
170	.10	up

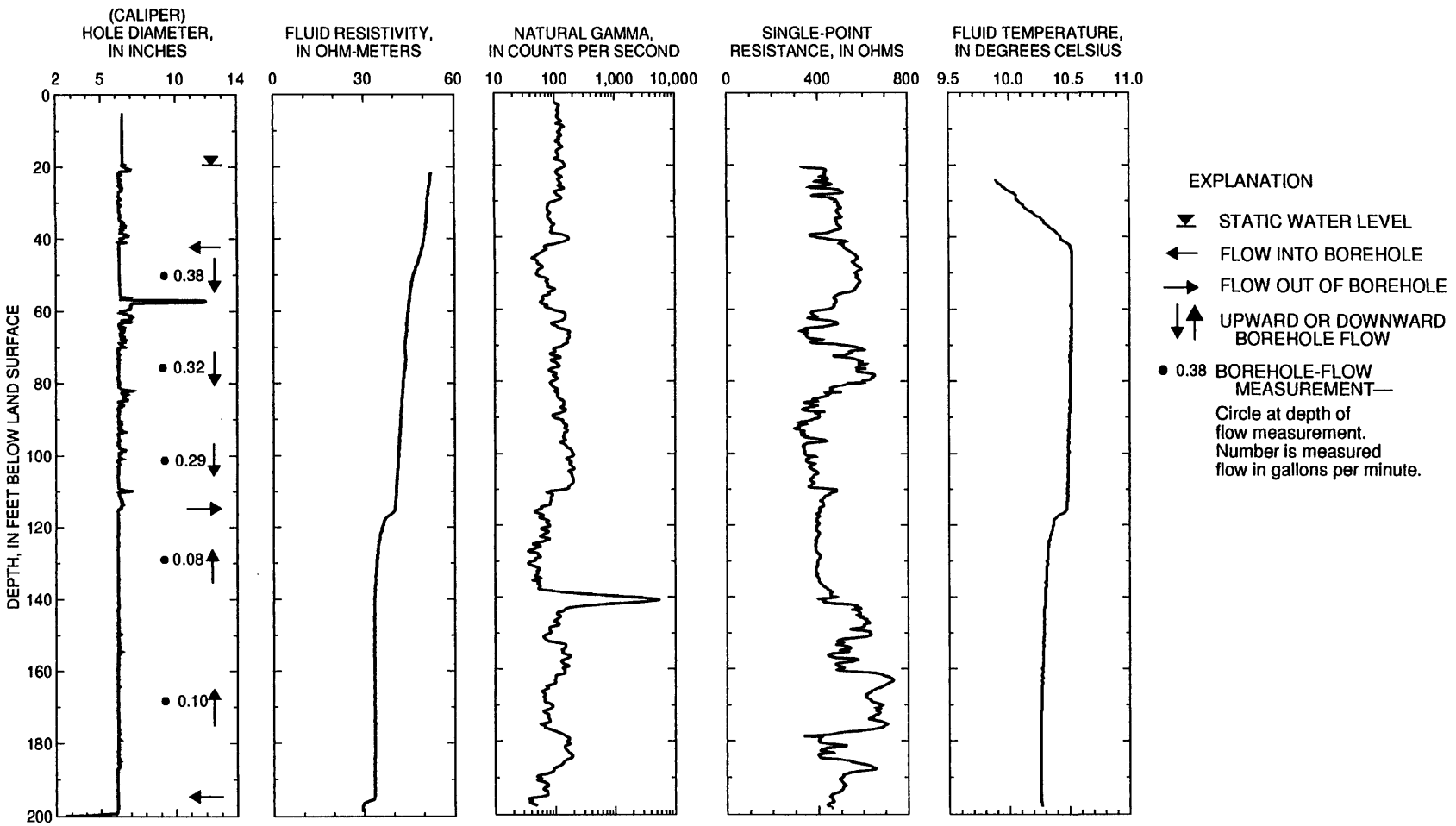

Figure 6. Borehole-geophysical logs for borehole BK-2889 (HN-65-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

BK-2890 (HN-65-S)

The caliper log shows the total depth of the borehole is 100 ft and it is cased with 6-in.-diameter casing to 19 ft bls (fig. 7). The static water level was 20.04 ft bls at the time of logging. The caliper log shows numerous minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 40 and 90 ft bls. The fluid-temperature log shows a change in slope at approximately 40 ft bls, indicating a fluid-producing zone. Under nonpumping conditions, the heat-pulse flowmeter measured upward borehole flow at 32, 50, 74, and 88 ft bls (table 7). The geophysical logs and the heat-pulse-flowmeter data indicate that water enters the borehole through fractures below 88 and at 38-41 ft bls, moves upward, and exits the borehole through fractures at 22-26 ft bls. The driller's log reports water was encountered at 83 ft bls; however, no evidence is seen at this depth on the geophysical logs. A screen was placed at 81-101 ft bls to include the reported water-producing fracture at 83 ft bls (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

Table 7. *Summary of heat-pulse-flowmeter measurements for borehole BK-2890 (HN-65-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

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

Depth (ft bls)	Flow rate under nonpumping conditions (gal/min)	Flow direction under nonpumping conditions
32	0.17	up
50	.07	up
74	.09	up
88	.07	up

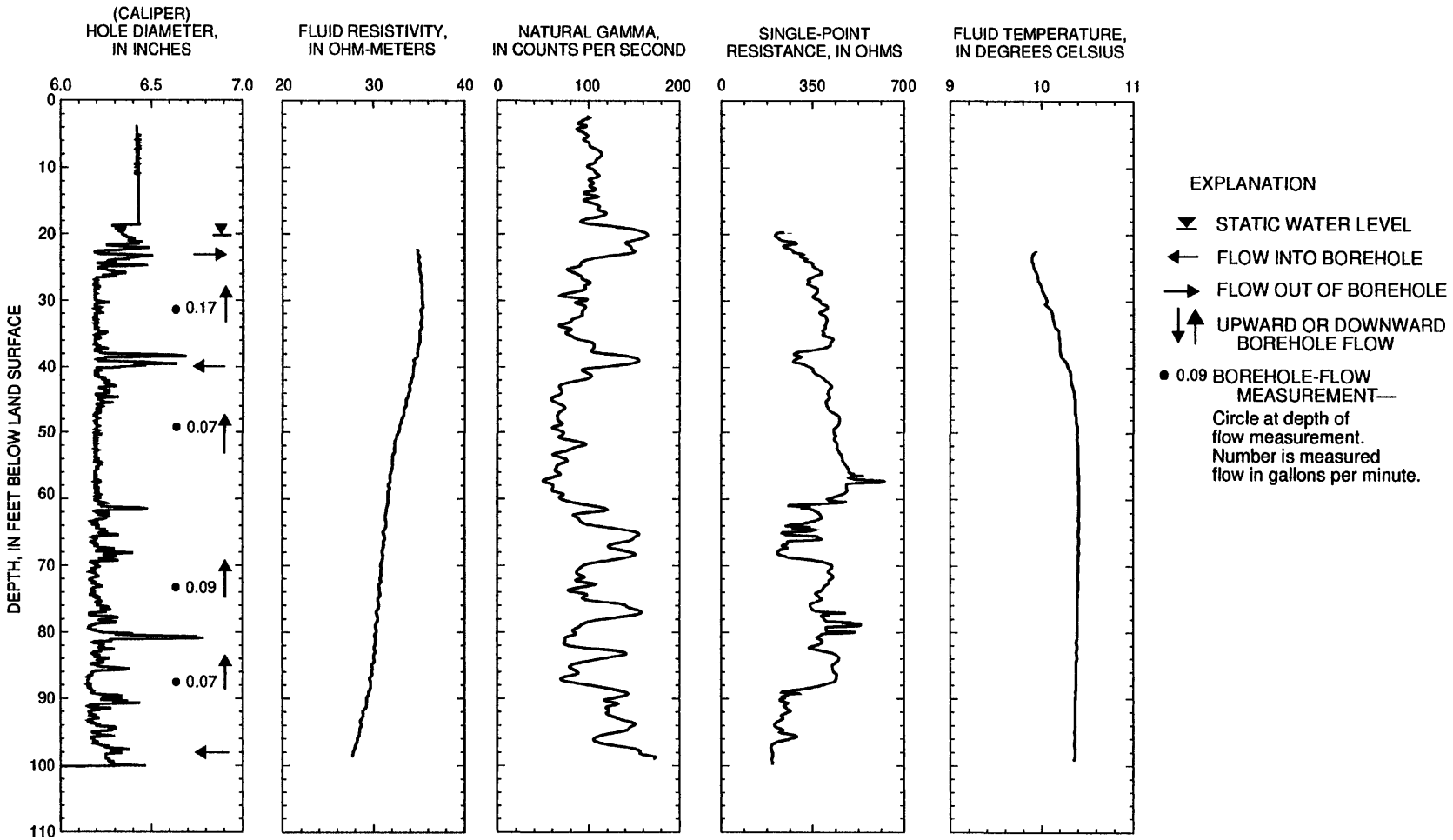

Figure 7. Borehole-geophysical logs for borehole BK-2890 (HN-65-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

BK-2891 (HN-14-I)

The caliper log shows the total depth of the borehole is 113 ft and it is cased with 10-in.-diameter casing to 19 ft bls (fig. 8). The static water level was 16.24 ft bls at the time of logging. The caliper log shows major fractures at 20, 31-33, and 91 ft bls plus numerous other fractures throughout the open-hole interval. The fluid-resistivity and fluid-temperature logs show changes in slope at 44 ft bls that correlate to minor fractures shown on the caliper log and are in proximity to a water-producing zone reported on the driller's log at 39 ft bls. Under nonpumping conditions, the heat-pulse flowmeter measured upward borehole flow at 41, 52, 59, and 88 ft bls and no flow at 102 ft bls (table 8). The borehole television survey shows the borehole water becomes cloudy at 99 ft bls indicating little or no borehole flow below that depth. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 90-96 ft bls, moves upward, and exits the borehole through fractures at 30-34 and 42 ft bls. The driller's log reports water was encountered at 39 and 59 ft bls and possibly at 78, 92, and 115 ft bls; the total yield was 5-6 gal/min. A screen was placed at 88-98 ft bls to include the water-producing fractures at 90-96 ft bls (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

Table 8. *Summary of heat-pulse-flowmeter measurements for borehole BK-2891 (HN-14-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

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

Depth (ft bls)	Flow rate under nonpumping conditions (gal/min)	Flow direction under nonpumping conditions
41	0.29	up
52	.71	up
59	.79	up
88	.73	up
102	no flow	

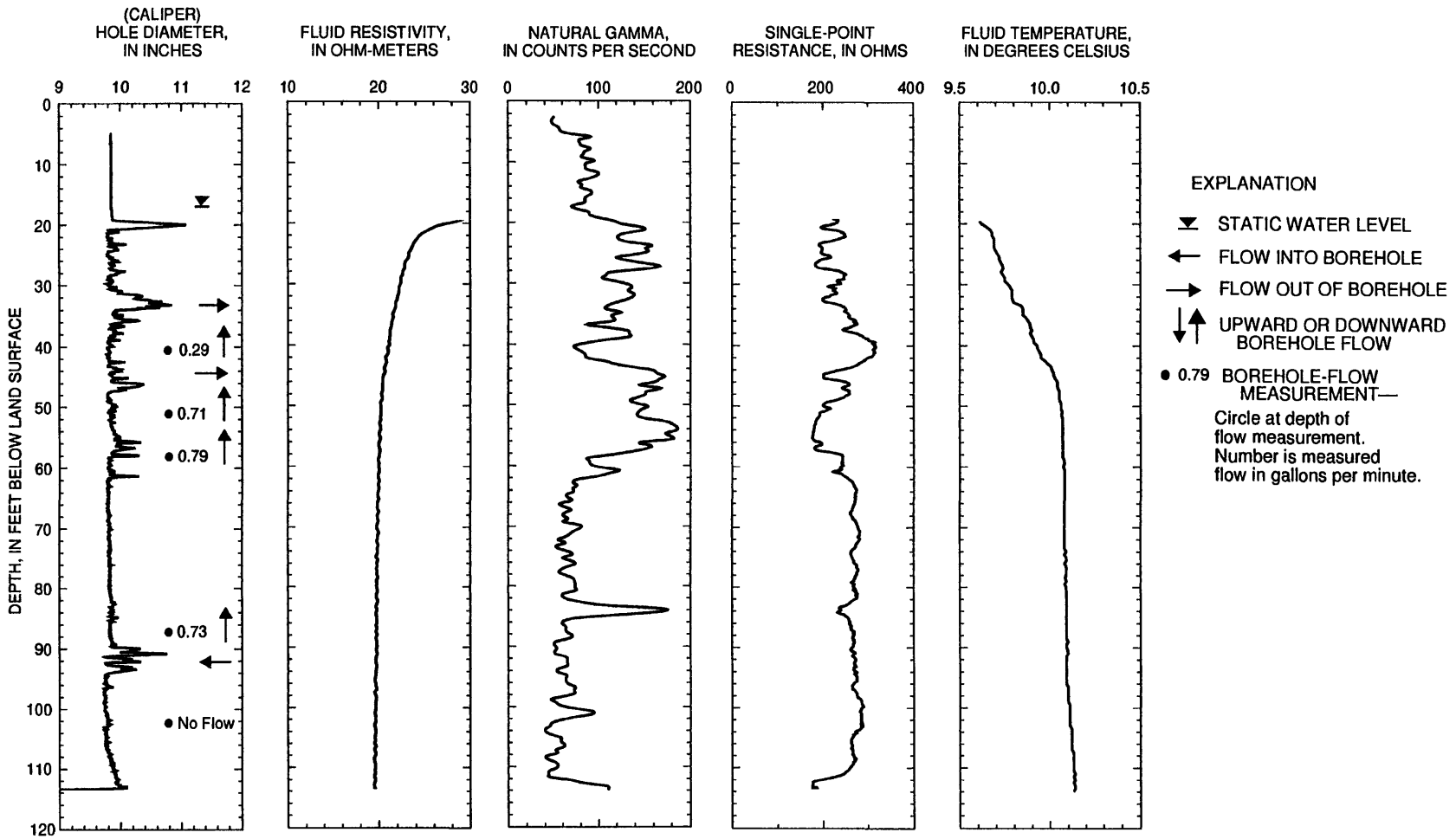

Figure 8. Borehole-geophysical logs for borehole BK-2891 (HN-14-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

BK-2892 (HN-14-S)

The caliper log shows the total depth of the borehole is 114 ft and it is cased with 10-in.-diameter casing to 19 ft bls (fig. 9). The static water level was 16.87 ft bls at the time of logging. The caliper log shows major fractures at 19, 22-23, 36, 38, and 61 ft bls. The fluid-resistivity and fluid-temperature logs show changes in slope at 38 ft bls that correlate to a fracture shown on the caliper log and a vertical fracture seen on the borehole television survey. Under nonpumping conditions, the heat-pulse flowmeter measured upward borehole flow at 42, 54, 70, 90, and 104 ft bls and no flow at 31 ft bls (table 9). The borehole television survey shows numerous vertical fractures down to approximately 50 ft bls. The geophysical logs, borehole television survey, and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 61 and 113 ft bls, moves upward, and exits the borehole through fractures seen on the borehole television survey at 34-38 ft bls. A screen was placed at 32-42 ft bls to include the water-receiving fracture at 36-38 ft bls (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

Table 9. *Summary of heat-pulse-flowmeter measurements for borehole BK-2892 (HN-14-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

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

Depth (ft bls)	Flow rate under nonpumping conditions (gal/min)	Flow direction under nonpumping conditions
31	no flow	
42	0.11	up
54	.13	up
70	.10	up
90	.08	up
104	.07	up

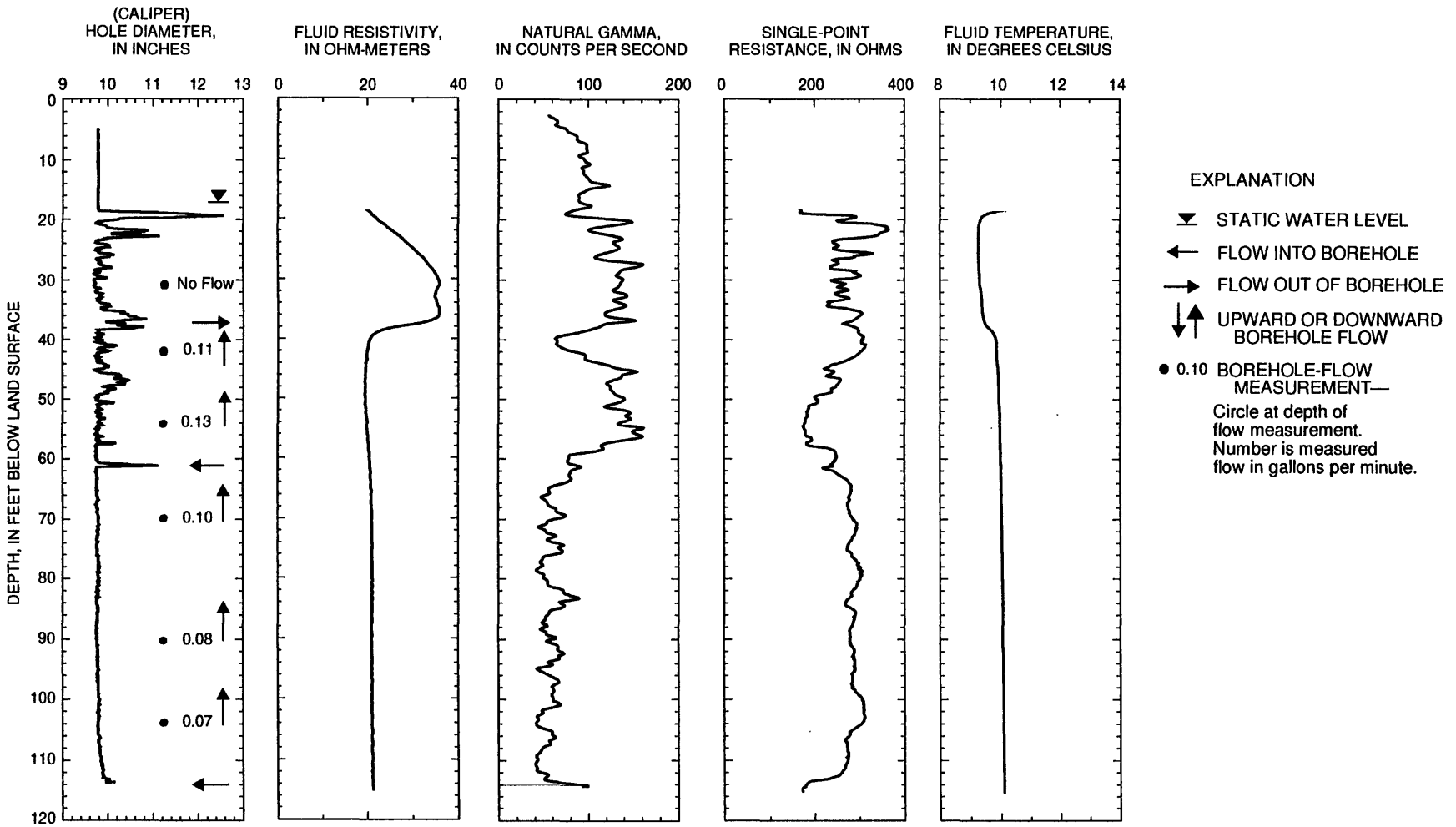

Figure 9. Borehole-geophysical logs for borehole BK-2892 (HN-14-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

BK-2893 (HN-59-I)

The caliper log shows the total depth of the borehole is 98 ft and it is cased with 10-in.-diameter casing to 19 ft bls (fig. 10). The static water level was 15.37 ft bls at the time of logging. The caliper log shows major fractures at 20 and 25 ft bls plus minor fractures throughout the open-hole interval. The fluid-resistivity log shows changes in slope at 25, 30, and 50 ft bls that may indicate water-producing fractures. The fluid-temperature log shows changes in slope at 50 and 92 ft bls that correlate with minor fractures shown on the caliper log. Under nonpumping conditions, the heat-pulse flowmeter measured upward borehole flow at 23, 33, and 70 ft bls and no flow at 85 ft bls (table 10). The borehole television survey shows the borehole water becomes extremely cloudy at about 70 ft bls. The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through minor fractures between 71-84 ft bls, moves upward, and exits the borehole through fractures at 20 and 25-28 ft bls. A screen was placed at 76-86 ft bls to include the water-producing fractures at 80-83 ft bls (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

Table 10. *Summary of heat-pulse-flowmeter measurements for borehole BK-2893 (HN-59-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

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

Depth (ft bls)	Flow rate under nonpumping conditions (gal/min)	Flow direction under nonpumping conditions
23	0.07	up
33	.22	up
70	.34	up
85	no flow	

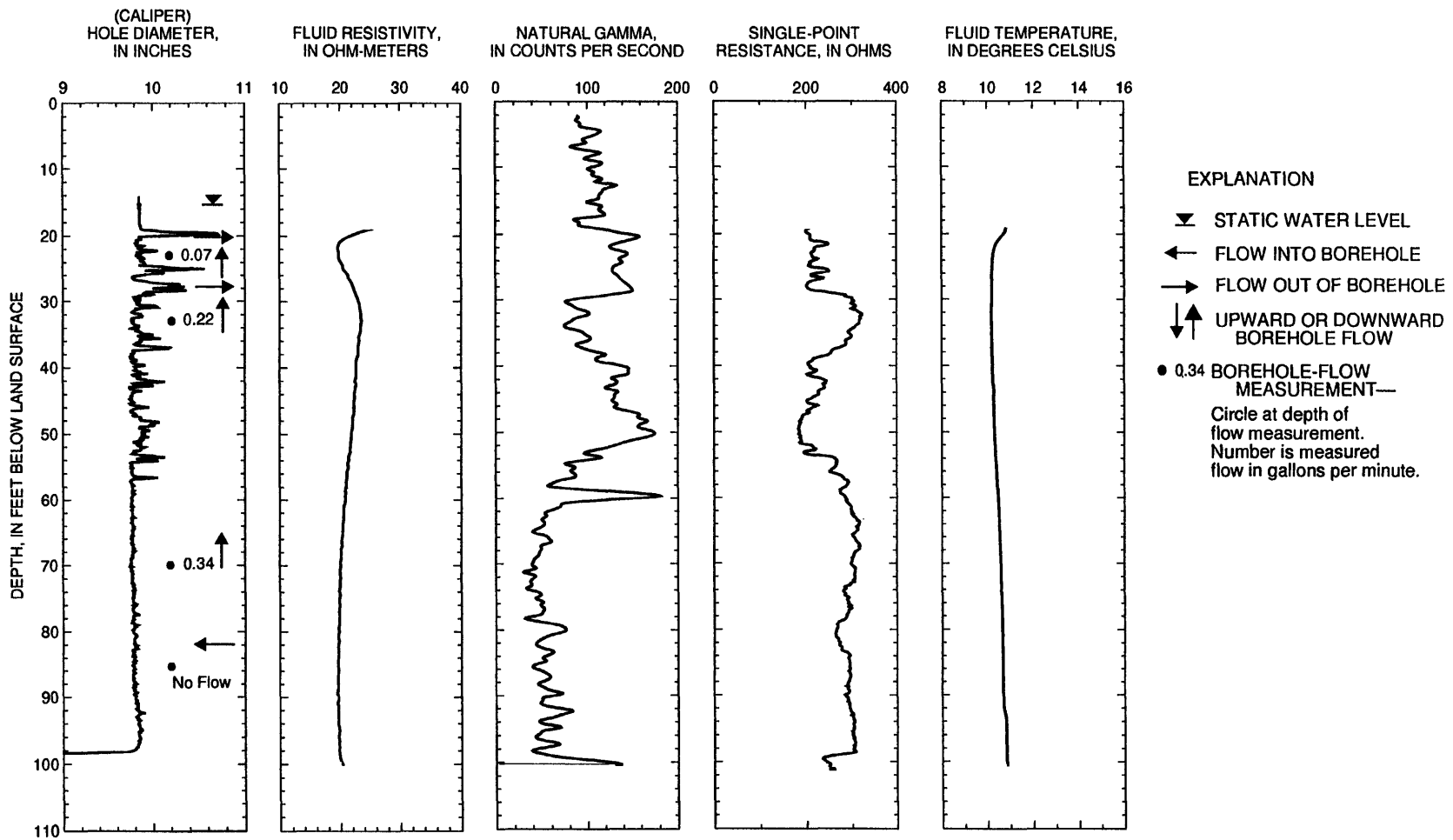

Figure 10. Borehole-geophysical logs for borehole BK-2893 (HN-59-I), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

BK-2894 (HN-59-S)

The caliper log shows the total depth of the borehole is 100 ft and it is cased with 10-in.-diameter casing to 19 ft bls (fig. 11). The static water level was 16.57 ft bls at the time of logging. The caliper log shows a major fracture at 20 ft bls plus numerous minor fractures throughout the open-hole interval. The fluid-resistivity log shows a change in slope at 34 ft bls that correlates to a fracture shown on the caliper log and indicates a water-producing or water-receiving zone. The fluid-temperature log shows changes in slope at 34, 58, and 98 ft bls. Under nonpumping conditions, the heat-pulse flowmeter measured upward borehole flow at 25 and 70 ft bls, downward flow at 46 ft bls, and no flow at 90 ft bls (table 11). The geophysical logs and the heat-pulse-flowmeter data indicate water enters the borehole through fractures at 36 ft bls, moves upward and downward, and exits the borehole through fractures at 20 and 50-58 ft bls. Also, water enters the borehole at 81 ft bls, moves upward, and exits the borehole through fractures at 50-58 ft bls. The driller's log reports water was encountered at 18 and 38 ft bls; total yield is approximately 3 gal/min. A screen was placed at 50-60 ft bls to include the water-receiving fractures at 50-58 ft bls (Don Whalen, Brown and Root Environmental, Inc., written commun., 1997).

Table 11. *Summary of heat-pulse-flowmeter measurements for borehole BK-2894 (HN-59-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania*

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

Depth (ft bls)	Flow rate under nonpumping conditions (gal/min)	Flow direction under nonpumping conditions
25	0.16	up
46	1.2	down
70	.18	up
90	no flow	

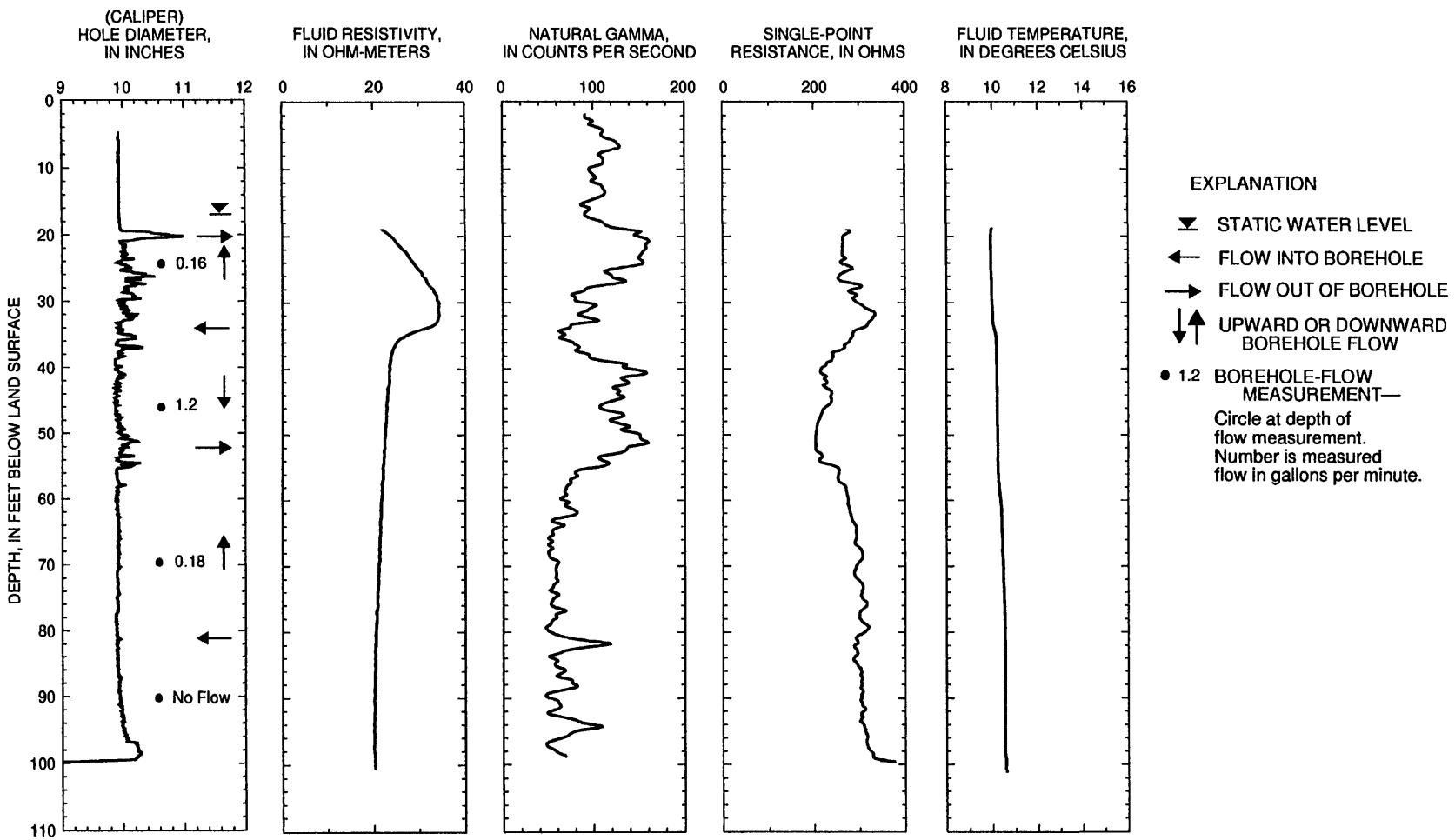

Figure 11. Borehole-geophysical logs for borehole BK-2894 (HN-59-S), former Naval Air Warfare Center, Warminster, Bucks County, Pennsylvania.

CONCLUSIONS

Water-producing zones, water-receiving zones, and intervals of vertical borehole flow were identified by the use of geophysical logs, heat-pulse-flowmeter measurements, borehole television surveys, and driller's logs. This enabled Brown and Root Environmental, Inc., to place well screens at selected water-producing intervals so that ground water from these intervals could be sampled.

The natural-gamma logs for boreholes BK-2888 and BK-2889 show a gamma spike (marker bed) at 139-143 ft bls. This marker bed occurs at the same depth below land surface in each borehole, indicating that BK-2888 and BK-2889 are exactly on geologic strike.

All boreholes where heat-pulse-flowmeter measurements were made showed borehole flow under nonpumping conditions. Generally, hydraulic characteristics are similar in boreholes within the same borehole cluster regardless of depth. For example, boreholes BK-2885, BK-2886, and BK-2887 are clustered together, have depths of 69, 121, and 222 ft, respectively, show water-producing zones between 20-45 ft bls, have downward flow of 1.0 gal/min or greater, and are all shallow. Boreholes BK-2891, BK-2892, BK-2893, and BK-2894 are in proximity to each other, have similar depths of 113, 114, 98, and 100 ft, respectively, and show water-producing zones between 60-114 ft bls, upward flow less than 1.0 gal/min, and water-receiving zones between 20-55 ft bls. Boreholes BK-2888 and BK-2890 have deeper water-producing zones and have a water-receiving zone between 25-100 ft bls.

Generally, water yield increases with depth to about 150 ft bls. The borehole television surveys show most boreholes have numerous horizontal and vertical fractures that generally decrease with depth. Heat-pulse-flowmeter data indicate all boreholes penetrate more than one water-bearing zone regardless of well depth. The boreholes near Area A are reported to produce approximately 3-8 gal/min along Lewis Drive and 5-20 gal/min at Ivyland Drive.

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