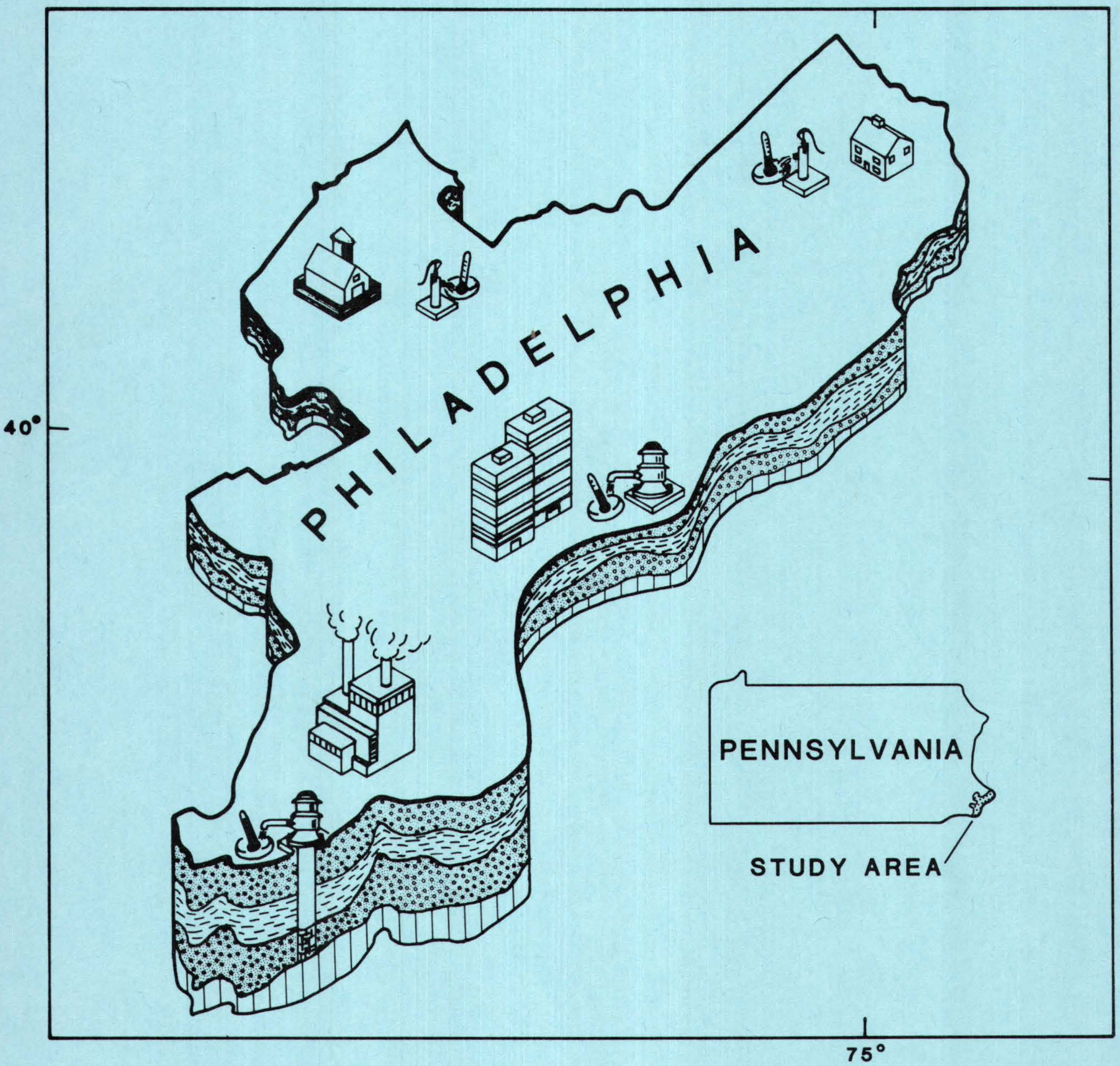
TEMPERATURE OF GROUND WATER AT PHILADELPHIA, PENNSYLVANIA, 1979-1981

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 84-4189



Prepared in cooperation with the
CITY OF PHILADELPHIA WATER DEPARTMENT

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By Gary N. Paulachok

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UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

Data given in this report are in inch-pound units except for temperature, which is in the International System of Units (SI). To convert to SI units, the following factors are used:

Multiply inch-pound unit	By	To obtain SI unit
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

To convert temperature in degrees Celsius (°C) to degrees Fahrenheit (°F), the following equation is used:

$$°F = (1.8)\ °C + 32$$

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ABSTRACT

Anthropogenic heat production has undoubtedly caused increased ground-water temperatures in many parts of Philadelphia, Pennsylvania, as shown by temperatures of 98 samples and logs of 40 wells measured during 1979-81. Most sample temperatures were higher than 12.6 degrees Celsius (the local mean annual air temperature), and many logs depict cooling trends with depth (anomalous gradients). Heating of surface and shallow-subsurface materials has likely caused the elevated temperatures and anomalous gradients. Solar radiation on widespread concrete and asphalt surfaces, fossil-fuel combustion, and radiant losses from buried pipelines containing steam and process chemicals are believed to be the chief sources of heat. Some heat from these and other sources is transferred to deeper zones, mainly by conduction. Temperatures in densely urbanized areas are commonly highest directly beneath the land surface and decrease progressively with depth. Temperatures in sparsely urbanized areas generally follow the natural geothermal gradient and increase downward at about that same rate.

INTRODUCTION

This report describes the temperature of ground water at Philadelphia, Pennsylvania. Data presented herein were collected during 1979-81 for a comprehensive study of the availability and quality of ground water there. That study was conducted by the U.S. Geological Survey, in cooperation with the City of Philadelphia Water Department. Background data on three drainage sumps and 828 water wells in Philadelphia, including those cited herein, are given in a companion report (Paulachok and others, 1984).

The author is indebted to the many firms and individuals who made their sumps or wells available for water-temperature measurements and geophysical logging.

DESCRIPTION OF STUDY AREA

The City of Philadelphia has a land area of 134.6 square miles in the Piedmont and Coastal Plain physiographic provinces of southeastern Pennsylvania (fig. 1). The Piedmont is a broad area northwest of the Fall Line, whereas the Coastal Plain part of Philadelphia forms a narrow band along the Delaware River. The Fall Line demarcates the landward limit of the Coastal Plain.

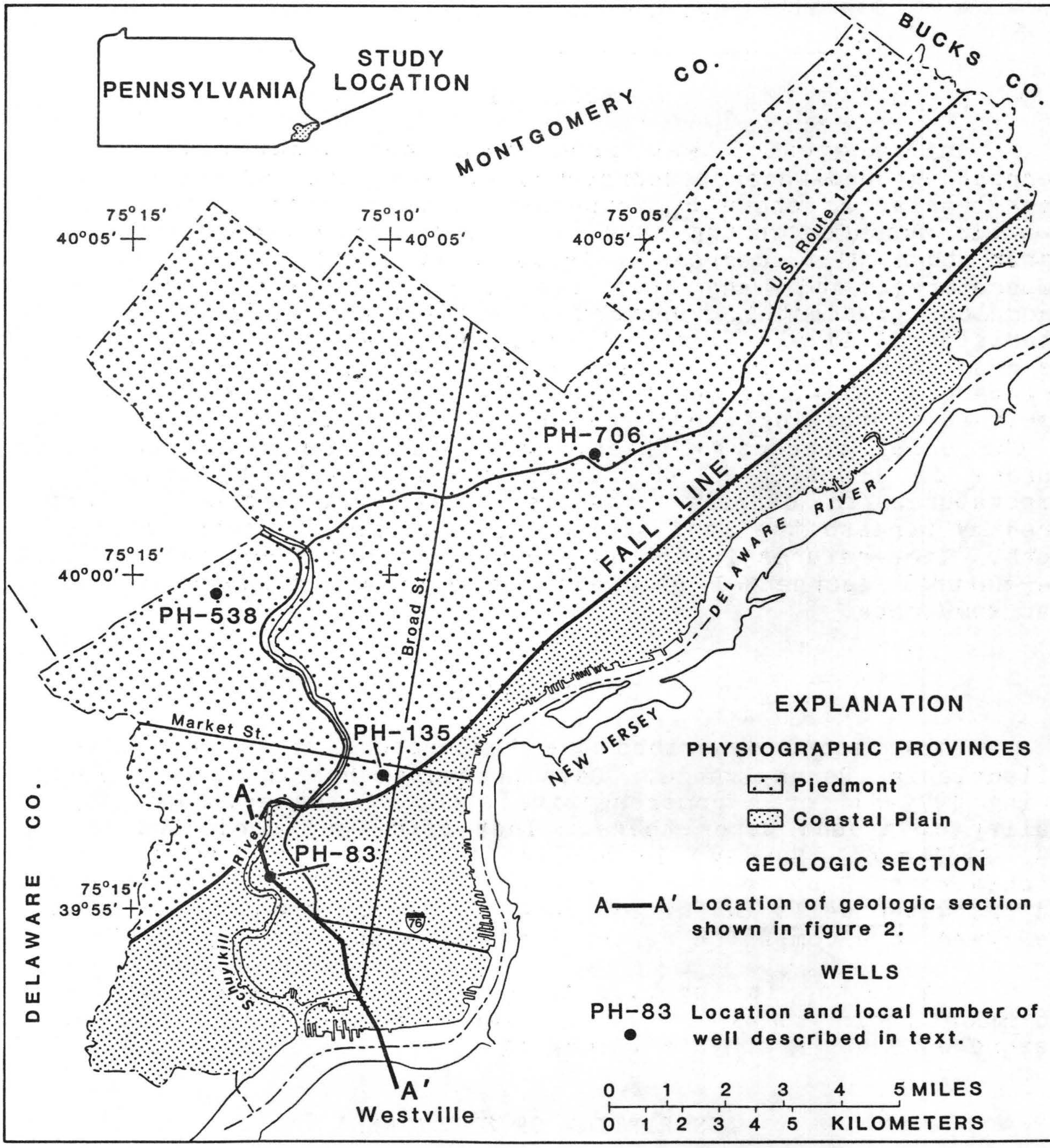

Figure 1.--Locations of physiographic provinces, generalized geologic section, and selected wells in Philadelphia.

Philadelphia, one of the oldest cities in the United States, is densely populated and extensively urbanized. According to the Federal Census of 1980 (U.S. Dept. of Commerce, 1982), the number of inhabitants was 1.7 million, or approximately 12,600 persons per square mile. Most of the land bordering the Delaware and lower Schuylkill Rivers is used for industrial purposes, whereas farther inland, commercial and residential areas predominate. Industrial, commercial, and residential sites account for 74 percent of the area; the remainder is used for recreation or resource production (Segal, David, Philadelphia City Planning Commission, oral commun., 1982).

The climate of the Philadelphia area is characterized by moderate temperatures and abundant precipitation. The local mean annual air temperature is 12.6°C (degrees Celsius). Generally, periods of extreme temperature last only a few days. The mean annual precipitation is 39.93 inches. Precipitation is distributed fairly evenly throughout the year; maximum amounts commonly occur during the late summer months.

HYDROGEOLOGY

Philadelphia is underlain by crystalline rocks of the Piedmont and by the younger unconsolidated sediments of the Coastal Plain. Figure 2 presents a generalized geologic section of the south Philadelphia area (fig. 1 shows location of section) and shows the southeastward dip of the strata. Table 1 gives the age and stratigraphic relationships of the various hydrogeologic units, and correlates the nomenclature used in this report with that of Greenman and others (1961) for the Coastal Plain of southeastern Pennsylvania.

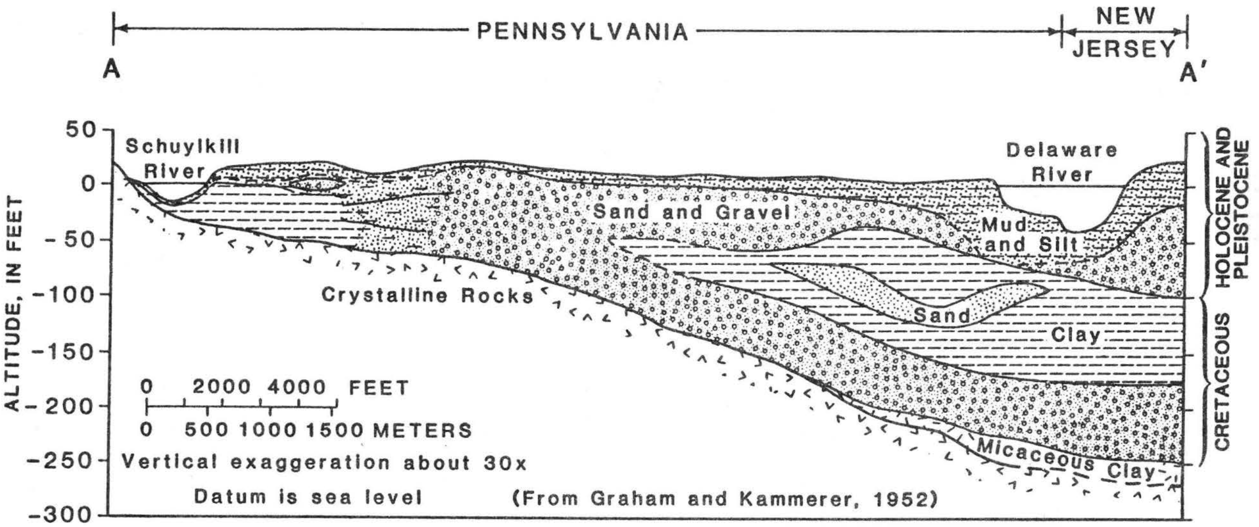

Figure 2.--Generalized geologic section, Philadelphia, Pennsylvania, to Westville, New Jersey.

Table 1.--Hydrogeologic units

SYSTEM	SERIES	HYDROGEOLOGIC UNIT			
		This report		Greenman and others (1961)	
Quaternary	Holocene	Alluvium		Alluvium	
Quaternary	Pleistocene	"Trenton gravel" (informal usage)		Cape May Formation	
				Pensauken Formation[1]	
Tertiary	Miocene	Bridgeton Formation			
Cretaceous	Upper Cretaceous	Potomac-Raritan-Magothy aquifer system	Upper clay unit	Raritan Formation	Upper clay member[1]
		Potomac-Raritan-Magothy aquifer system	Upper sand unit	Raritan Formation	Old Bridge Sand Member[1]
		Potomac-Raritan-Magothy aquifer system	Middle clay unit	Raritan Formation	Middle clay member
		Potomac-Raritan-Magothy aquifer system	Middle sand unit	Raritan Formation	Sayreville Sand Member
		Potomac-Raritan-Magothy aquifer system	Lower clay unit	Raritan Formation	Lower clay member
		Potomac-Raritan-Magothy aquifer system	Lower sand unit	Raritan Formation	Farrington Sand Member
	Lower Cretaceous	Potomac-Raritan-Magothy aquifer system	Lower sand unit		
Pre-Cretaceous		Crystalline rocks, Glenarm Group		Crystalline rocks, Glenarm Series[1]	

[1] Present usage by the U.S. Geological Survey: the Pensauken Formation is of Miocene age; the upper clay member and Old Bridge Sand Member are assigned to the Magothy Formation; and, the term "Glenarm Series" is obsolete.

The crystalline rocks consist chiefly of schist of the Wissahickon Formation of Late Proterozoic and early Paleozoic age, lesser amounts of quartzite of the Chickies Formation of Early Cambrian age, and scattered masses of gneissose rocks of uncertain age having granitic to gabbroic composition. These rocks crop out in the Piedmont and their surface slopes southeastward, forming the basement beneath the Coastal Plain sediments.

In Pennsylvania, the deepest Coastal Plain sediments, from oldest to youngest, are collectively called the Potomac Group, Raritan Formation, and Magothy Formation. These sediments are of Cretaceous age and form the Potomac-Raritan-Magothy aquifer system. The Cretaceous sediments belong chiefly to the Raritan Formation. The Magothy Formation has not been identified in Pennsylvania; some sediments of the Potomac Group, however, may be present there (Farlekas, G. M., U.S. Geological Survey, oral commun., 1983). The Potomac-Raritan-Magothy aquifer system consists of interbedded gravel, sand, silt, and clay units which are at or near the land surface in parts of Pennsylvania and New Jersey along the lower Delaware River. In Philadelphia, this aquifer system has been subdivided into the following units: lower sand, lower clay, middle sand, middle clay, upper sand, and upper clay. In much of their outcrop area, the Cretaceous sediments are overlain by Pleistocene sediments, chiefly the informally named "Trenton gravel" of Owens and Minard (1979), which in turn may be veneered by alluvium of Holocene age.

The Potomac-Raritan-Magothy aquifer system is equivalent to the Raritan Formation of Greenman and others (1961). The threefold division into "lower", "middle", and "upper" parts of this aquifer system in Pennsylvania has been adopted for use by the U.S. Geological Survey. However, individual hydrogeologic units may not be continuous or correlative with similar units in adjacent states. The Trenton gravel is equivalent to the Pleistocene sediments of Wisconsin age described by Greenman and others (1961).

In Philadelphia, the confined aquifer system generally includes the crystalline rocks where they are buried beneath the Coastal Plain sediments, and more importantly, the lower and middle sand units of the Potomac-Raritan-Magothy aquifer system. The unconfined aquifer system typically consists of the Wissahickon Formation in its outcrop area, the upper sand unit of the Potomac-Raritan-Magothy aquifer system, and the Trenton gravel. Locally, the Bridgeton Formation and the alluvium are not important aquifers.

Detailed information on the ground-water hydrology of Philadelphia and vicinity is given chiefly by Graham and Kammerer (1952), Greenman and others (1961), Biesecker and others (1968), Paulachok and others (1984), and Paulachok and Wood (1984).

GROUND-WATER TEMPERATURES AT PHILADELPHIA

Measurement Techniques

Water-sample temperatures and measurements of water temperature with depth (logs) were collected for the comprehensive study. In general, these data were collected only once. At sumps, sample temperatures were measured at the point of inflow; at wells, they were measured as close to the wellhead as possible. Temperatures were determined to the nearest 0.5°C with standardized mercury thermometers. Temperature logs were obtained with a vehicle-mounted, continuously recording logger at sites having vehicular access, whereas a portable, non-recording logger was used at sites lacking such access. Each logger was accurate to 0.1°C.

Natural Background

Temperatures of natural ground water (background) are fairly uniform throughout the year, and those of shallow ground water are generally equal to the local mean annual air temperature. Nevertheless, temperatures of shallow ground water fluctuate seasonally, due chiefly to heat conduction from the land surface; such fluctuations are commonly of about the same magnitude as those of surface-water bodies. Other fluctuations may result from temperature differences in circulating ground water. Because of the insulating properties of Earth materials, such natural fluctuations diminish rapidly with depth; annually, they are generally less than 0.5°C at depths of about 35 ft (feet) below land surface (Collins, 1925). Temperatures also increase naturally with depth at the rate of the geothermal gradient, which in the Philadelphia area, is approximately 1°C per 100 ft.

Ground-water temperatures are also influenced by natural heat conduction from the Earth's interior. Consequently, the temperatures of water at depths of 35 to 70 ft below land surface generally exceed the local mean annual air temperature by 1 to 2°C. Moreover, at depths greater than 70 ft, ground-water temperatures commonly follow the natural geothermal gradient and increase downward at about that same rate (Collins, 1925).

Prior to the widespread urbanization of Philadelphia, it is likely that shallow ground-water temperatures had an average value of approximately 12.5°C, and water temperatures at depths below about 70 ft probably increased with depth, following the natural geothermal gradient.

Anthropogenic Effects

The urbanization of Philadelphia has greatly affected ground-water temperatures and their spatial variations. Formerly vegetated open areas have been covered over by concrete and asphalt surfaces. Paving causes increases in ground-water temperatures and changes in their gradients by altering the thermal properties of the land surface, and by modifying important hydrologic controls on temperature including evapotranspiration and recharge. Heat lost from underground pipelines containing steam and process chemicals also causes temperatures of shallow ground water to increase as well as temperatures that decrease anomalously with depth.

The absorption and conduction of solar radiation by concrete and asphalt surfaces raises subsurface temperatures chiefly for two reasons: (1) unshaded solar radiation impinges directly on the paved ground in the absence of foliage, and (2) the paved surfaces store little moisture; consequently, evaporative cooling within them does not occur to the extent that it would within a moist soil. Much of Philadelphia is covered by paved ground which may conduct a substantial amount of surface heat into the subsurface and store it there. Also, because concrete and asphalt are good thermal conductors, they transfer downward more surface heat than does a loose, dry soil.

Fossil-fuel combustion and radiant losses from pipelines containing steam and process chemicals are also important local sources of heat. In densely urbanized areas, some heat from poorly insulated buildings may be conducted through the walls and floors into the contiguous ground and stored there. Heat losses from underground pipelines, chiefly the Steam Loop in parts of central and south Philadelphia, also have a strong local effect on subsurface temperatures. The Philadelphia Steam Loop consists of approximately 32 miles of insulated cast-steel pipe. In 1982, thermal energy with the heating equivalent of nearly 37,000 barrels of oil was lost by radiation from the Steam Loop to the subsurface (Wylie, J. J., Philadelphia Electric Company, oral commun., 1983). Heat lost from onsite steam-generation and distribution facilities outside the Steam Loop's service area, and that radiated by pipelines containing process chemicals at the two major oil refineries and numerous other industrial sites throughout Philadelphia may also result in locally high surface and shallow subsurface temperatures.

Earlier, Geraghty (1959) attributed the cause of anomalously high ground-water temperatures in southern New York City to urbanization. It is likely that above-normal temperatures are typical of ground water in urban areas, particularly that in industrialized localities.

Magnitudes

Temperatures of most of the 98 ground-water samples from sites in Philadelphia were higher than 12.6°C, the local mean annual air temperature. Temperatures of 41 samples from the crystalline rocks had a median value of 16.0°C, and ranged from 11.0°C in water from the wooded and less-developed northwestern localities to 20.5°C in that from densely populated or industrialized areas. The histogram of temperatures (fig. 3a.) shows a nearly normal, symmetrical distribution.

Temperatures of 27 samples from the confined lower and middle sand units of the Potomac-Raritan-Magothy aquifer system had a median value of 16.0°C, and ranged from 14.0°C in water from deep sediments that are insulated from anthropogenic heat sources to 26.0°C in that from shallow deposits in industrialized parts of the outcrop area. Most sample temperatures ranged from 14.0°C to 20.0°C; consequently, the histogram (fig. 3b.) is skewed toward higher values.

Temperatures of 30 samples from the unconfined upper sand unit of the Potomac-Raritan-Magothy aquifer system and the Trenton gravel had a median value of 17.0°C, and ranged from 13.5°C in water from deeper sediments or areas remote from anthropogenic heat sources to 25.0°C in that from shallow deposits or sites near those sources. The histogram (fig. 3c.) shows a nearly normal distribution that is skewed slightly toward higher values.

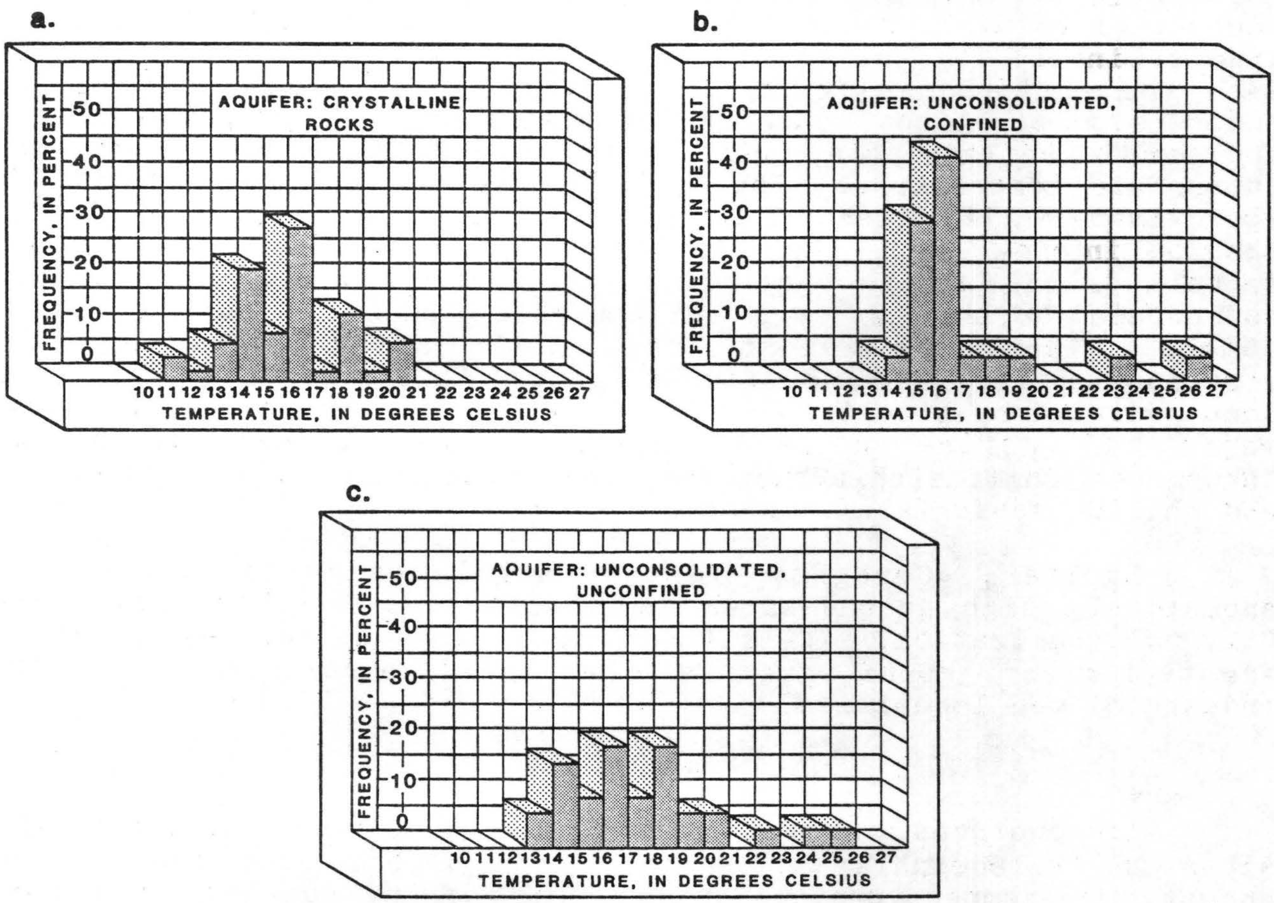

Figure 3.--Histograms of water-sample temperatures, 1979-80.

Table 2 summarizes statistical data on water-sample temperatures. The median values suggest a general decrease of temperature with depth. The standard deviations and coefficients of variation indicate that the temperatures of water in the shallow aquifers vary more than those of the deep aquifers. Temperatures in the shallow aquifers are less uniform because they are affected more by seasonal climatic variations and local heat production than are those in the deep aquifers.

Table 2.--Summary of data on water-sample temperatures.

	Temperature, in degrees Celsius				
Aquifer	Range	Median	Standard deviation	Coefficient of variation	Number of measurements
Unconsolidated, unconfined	13.5-25.0	17.0	2.9	0.17	30
Unconsolidated, confined	14.0-26.0	16.0	2.7	.16	27
Crystalline rocks	11.0-20.5	16.0	2.2	.14	41

The contours of figure 4 are based on 81 temperature measurements, two of which were made in nearby parts of Bucks and Delaware counties. Mean temperatures are depicted if more than one measurement was made at a site. The map shows that the lowest temperatures are in the wooded and less-urbanized northern and western localities, whereas the highest are in the densely urbanized north-central and south-central areas. Cells of anomalously warm water (20°C to 25°C) commonly occur at industrialized localities.

Gradients

Temperature logs of 40 water wells in Philadelphia indicate that anthropogenic heat production has significantly affected the distribution of water temperatures with depth. In many wells, water temperatures were highest directly beneath the land surface and decreased progressively with depth. Logs spanning depths from 20 to 580 ft depict temperatures at the water surface as high as 32°C, approximately 19°C higher than the local mean annual air temperature. These anomalous temperature gradients prevailed to

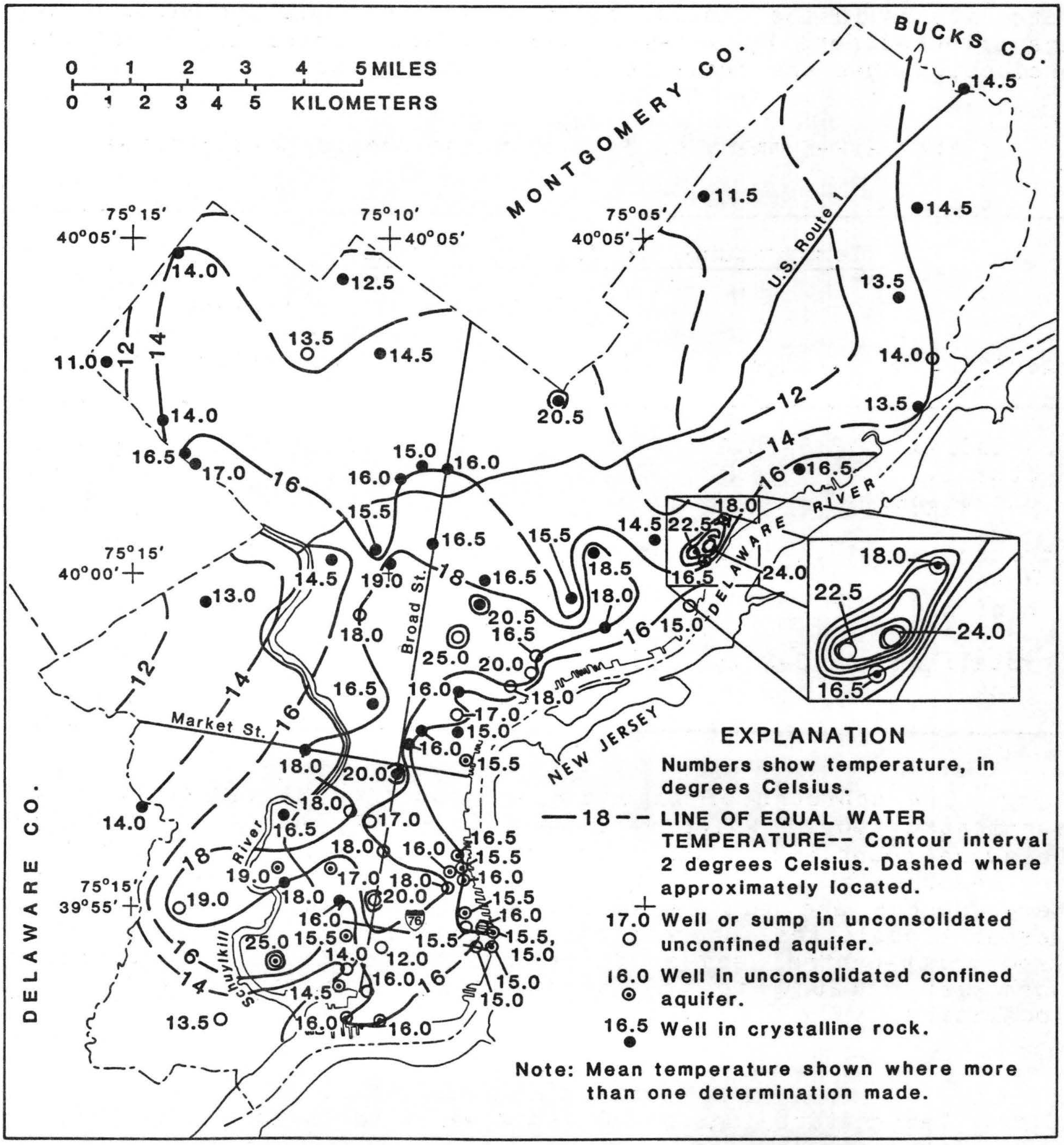

Figure 4.--Ground-water temperatures, 1979-80.

depths of 60 to 480 ft; below those depths, gradients typically began to resemble the natural geothermal gradient.

Because thermal gradients commonly induce vertical convection of water in large-diameter wells (Sammel, 1968), flow-velocity measurements were made in four of the logged wells with a brine ejector-detector system to determine if circulation of warm water from greater depths was the principal cause of the elevated shallow-subsurface temperatures and anomalous gradients. Because none of these measurements indicated any vertical movement of water, transport of heat through the aquifers from deeper zones toward the surface by convecting water is in general thought to be insignificant. The data on water temperatures and their gradients suggest that conduction downward from surface and shallow-subsurface sources is probably the chief mechanism of heat transfer.

Man's activities at and near the land surface greatly influence the distribution of ground-water temperatures with depth, as shown by the logs of Philadelphia County wells PH-135, PH-706, PH-538, and PH-83 (fig. 5.) Figure 1 shows the locations of these wells. All were unused for many years before they were logged, and vertical movement of water within them is likely to be negligible; therefore, their temperature logs are believed to represent a thermal equilibrium between the aquifer matrix and the ground water.

The logs of PH-135, PH-706, and PH-83 depict representative vertical distributions of temperature in densely commercialized, residential, and industrialized areas, respectively. Well PH-135 is in the densely urbanized central business district, an area served by the Philadelphia Steam Loop. Temperatures in PH-135 decline continuously from about 32°C near the water surface to 18°C at 185 ft, and probably continue to decline for some distance below that depth (fig. 5). Well PH-706 is in a residential neighborhood in northeast Philadelphia. Its water temperatures (fig. 5) decline at a progressively decreasing rate from more than 25°C at 30 ft to 13°C at 460 ft, and the curve of observed temperatures intersects the natural geothermal gradient curve at about 16°C and 210 ft of depth. Temperatures below 210 ft fall below those expected on the basis of the natural geothermal gradient. The cause of these cooler-than-typical temperatures is not understood, however, and is beyond the scope of this report. Well PH-83 is in the highly industrialized refinery area of south Philadelphia, a locality of intensive heat production. Its log (fig. 5) illustrates temperatures that decrease from more than 28°C at the water surface to slightly more than 18°C at 60 ft.

Logs of PH-135 and PH-83 show rates of temperature change that are much greater and opposite the sense of the natural geothermal gradient. The log of PH-706 indicates from 150 ft to 390 ft a rate of temperature change of about the same magnitude as the natural gradient, but of opposite sense. It also shows some

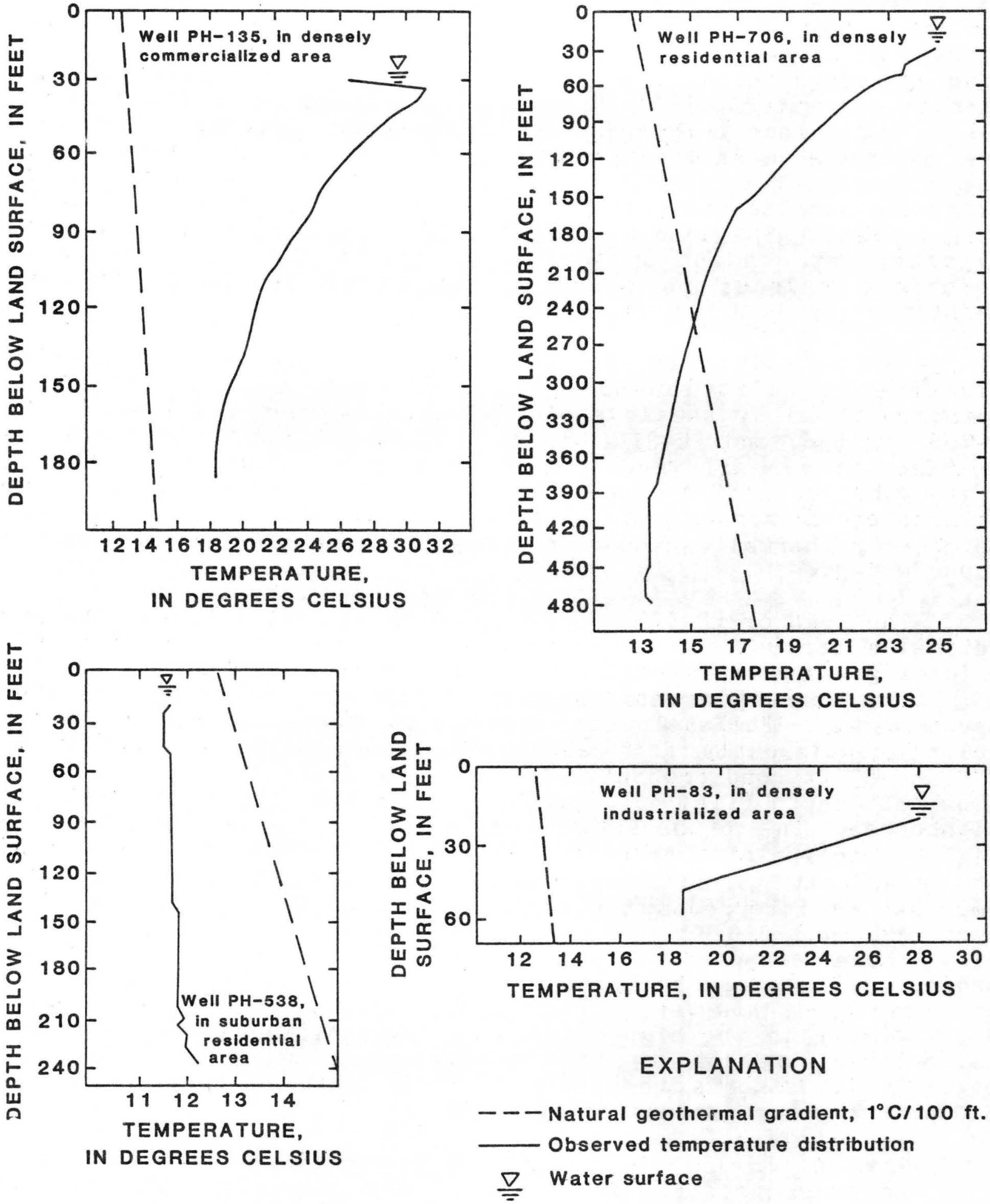

Figure 5.--Temperature logs of wells PH-135, PH-706, PH-538, and PH-83.

evidence of a change of gradient to the expected sense at 480 ft below land surface.

Well PH-538 is in a suburban residential neighborhood of west Philadelphia where comparatively little heat is produced. Its log depicts three zones of uniform temperatures that increase slightly with depth from 25 ft to 200 ft. Below 200 ft, temperatures increase at almost the same rate as the natural geothermal gradient. In general, vertical distributions of temperature closely following the natural gradient were atypical, and were present in only 13 of the 40 wells logged. Such gradients are to be expected where the natural heat flow predominates over that due to anthropogenic processes.

SUMMARY

This report describes the distribution of ground-water temperatures in Philadelphia, Pennsylvania, during 1979-81. Measurements of 98 samples show that ground-water temperatures in many localities are above the background level of 12.6°C, the local mean annual air temperature. This condition is undoubtedly attributable to anthropogenic heat production. Logs of 40 wells also represent the effects of heat from human activities, as many depict water temperatures that decrease anomalously with depth.

Heating of surface and shallow-subsurface materials, chiefly by solar radiation on widespread paved surfaces, fossil-fuel combustion, and radiant losses from buried pipelines containing steam and process chemicals has likely caused the elevated ground-water temperatures and anomalous gradients. Some heat from these and other sources is transferred to deeper zones, mainly by conduction.

Temperatures in densely urbanized areas are commonly highest directly beneath the land surface and decrease progressively with depth. Temperatures in sparsely urbanized areas generally follow the natural geothermal gradient and increase downward at about that same rate.

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